國家地震工程研究中心

NATIONAL CENTER FOR RESEARCH ON EARTHQUAKE ENGINEERING

Proceedings of the 10th JWWA/WRF/CTWWA Water System Seismic Conference

October 18-20, 2017, Tainan, Taiwan

Edited by

Nan-Tzer Hu and Shyh-Jiann Hwang

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President, Chinese Taiwan Water Works Association

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Conference Organized by

Chinese Taiwan Water Works Association (CTWWA)
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Taiwan Water Corporation, Sixth Branch Office
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October 2017

Preface

The goal of the Tenth JWWA/WRF/CTWWA Water System Seismic Conference aims at providing an avenue for practitioners and researchers to share practical and useful information generated from experience and research that could enhance water system safety and reliability against earthquakes. There are more than 100 registered attendees for the Conference with 31 from Japan, 10 from U.S., and the balance from Taiwan.

The Proceedings of the Conference contain all technical papers presented during the Conference. They are categorized into six topics: (1) pipe testing, analysis, and design, (2) seismic preparedness and emergency response, (3) evaluation of water system components, (4) experiences and lessons learnt, (5) assessment and information system, (6) pipeline enhancement strategy.

We would like to appreciate all participants to the Conference, and the authors who contribute their invaluable papers to the Proceedings. We do believe that through the sharing and friendship established in this event, we can promote further exchange and collaboration among Japan, U.S. and Taiwan to achieve improved seismic practices in water systems.

Nan-Tzer Hu
President
Chinese Taiwan Water Works Association

Shyh-Jiann Hwang
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2017.10.11, Taipei

Contents

Damage and Restoration of Drinking Water Systems Caused by 0206 Tainan Earthquake and Future Mitigation Measures

Nan-Tzer Hu

1. Overview of 0206 Earthquake's

At 03:57 local time (19:57 UTC) on 6 February 2016, an earthquake with a moment magnitude of 6.4 struck 28 km (17 mi) northeast of Pingtung City in southern Taiwan[1], in the Meinong District of Kaohsiung, Caoling of Yunlin County magnitude of 6, Tainan City, and Chiayi City areas of the earthquake level of 5. The earthquake struck at a depth of around 23 km (14 mi). Its comparatively shallow depth caused more intense reverberations on the surface[2]. The earthquake had a maximum intensity of VII (Very strong) on the Mercalli intensity scale, causing widespread damage and 117 deaths. Almost all of the deaths were caused by a collapsed residential building, named Weiguan Jinlong in Yongkang District, except two others, who were killed in Guiren District[3][4], both Districts are in Tainan City. Sixty-eight aftershocks have occurred[5]. The earthquake was the deadliest earthquake in Taiwan since the 921 earthquake in 1999.

The 6th branch office of Taiwan Water Corporation (TWC) immediately set up an emergency response team at 05:00 am, and recalled employees to inspect damage to water system infrastructure due to the earthquake. TWC found some transmission lines (1 meter or greater in diameter) were seriously damaged, thousands of distribution pipelines were damage due to shifting ground and soil liquefaction, resulting in water loss, water service interruptions, low pressure, contamination and sinkholes and/or large pools of water throughout the service area in the city.

The disaster has left 400,000 homes without water service. TWC dispatched several emergency repairing teams corporate with outsourcing contractors to repair leaky pipeline and buried new pipes, gradually reduced the number of households affected by the water-supply outage due to the earthquake until on the February 25th morning to restore water supply. Fig.1 shows restoration of water supply system in 0206 Earthquake in 2016.

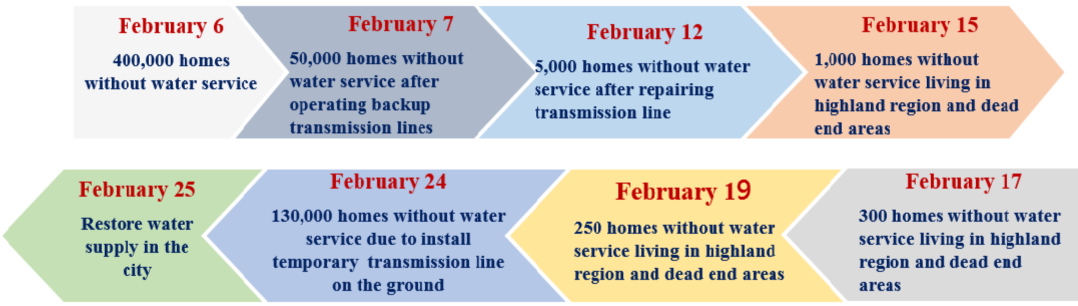

Fig.1 Restoration of water supply system in 0206 Earthque in 2016

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2. Emergency operation of Water Supply Systems in 0206 Earthquake

2.1 Emergency Water Supply Stations (Vehicle Transportation)

1. Emergency Water Supply Station (Water Supply Point):
   There are 142 Emergency Water Supply Station, generally one of these stations located within a 2km radius of consumer's home . Consumer can check the location of nearest Emergency Water Supply Station (Water Supply Point) from Public Notice or website of TWC and Tainan City Government.
2. Tour water supply: TWC uses water trucks to transport water to Emergency Water Supply Station (Water Supply Point). In accordance with the 22 vehicle route/stop for solid waste collection truck to send water tankers for providing patrol service.
3. Water tanker or Fire-fighting truck injected water into pipeline for supplying water to consumer's water tank.

2.2 Emergency Water Supply Operation

1. Due to the earthquake, Tainan Water Supply System had been seriously damaged, it needed time to restore water supply system gradually after repairing damaged water infracture , especially the damaged 2,000mm(in diameter) transmission line which was located under the collapsed 17-story Weiguan Jinlong Building (see Fig.2). TWC used backup 1,750 mm transmission line to transfer water and laying 1,350 mm emergency temporary transmission pipe on the ground (see Fig.3 and Fig.5) by reducing pressure to supply water. Owing that the total volume of water is insufficient and water pressure is low, the consumers living in highland region and dead end areas are still suffering water shortage problem.
2. Highland region : By operating the valves during night time to supply water .
3. Dead end areas : By using Water tanker or Fire-fighting truck injected water into pipeline for supplying water to consumer's water tank(see Fig.4).

Fig.2 The collapsed 17-story Weiguan Jinlong residential building

Fig.3 1,350 mm emergency temporary transmission pipe on the ground

Fig.4 Water tanker injected water into pipeline for supplying water to consumer’s water tank

2.3. Repairing Pipelines

1. After inspection, there were about 7,948 cases of reporting water interruption, and about 4,710 leaky pipes (72 cases are larger than 300mm in diameter). The repairing teams cooperated with outsourcing contractors were dispatched immediately to fix leaky pipes.
2. Yongda Road damaged 2,000mm (in diameter) pipe:
   After the Tainan City Government has cleaned up the collapsed Weiguan Jinlong Building, Repairing teams of TWC rushed to repair the pipe and completed at 24:00 on February 24th then restore water supply.
3. Xinhua Zhongxiao Road damaged 2,000mm (in diameter) pipe :
   The damaged pipe was constructed by pipe jacking method and was under 8 meters from the ground, total length of 1,200 meters. After inspection it was found there were 7 cracks in the pipe. It was repaired at 00 : 30 on February 24th.
   Location of damaged 2,000mm pipe and

Fig.5 Location of damaged 2,000mm pipe and 1,350 mm temporary pipe

2.4 Communicating with the Public during the earthquake

Effective communication with employees, customers, and reporters is a key element of emergency response. When the crisis hits, our communication measures are following:

- Daily regular press releases are available on TWC website for information on water and water supply stations.
- Provide free Mobile Water Housekeeper APP for query service (see Fig.6).
- Established FB to provide user for consultation platform.
- Toll-free hotline at 1910.

Fig.6 Mobile Water Housekeeper APP

3. Lessons Learned from the 0206 earthquake

3.1 Establishing Forward Command Post:

Forward Command Posts shall be established on the spot of serious disaster areas. The post shall be headed by President of Taiwan Water Corporation and operated by TWC HQ to integrate TWC's all kind of resource to relief the disaster as soon as possible.

3.2 Water service message:

- Establish Line or Messages Group for government officials, elected representatives to inform emergency message at the first time.
- Set up the news media center to provide complete, accurate, and timely information.
- Tell the truth and express empathy.
- Acknowledge uncertainty and offer to get back with more information later.

3.3 Continuously strengthen the supply system and take aseismic measures.

3.4 Improve the restoration time needed for highland region and dead end areas.

4. What To Do Next

- Constructing Nan-hua dual transmission line system
- Improving plans for water supply in Highland region
- Developing smart water networks across the system
- Surveying seismic and geologic hazards across the system
- Replacing aging pipe remains a big source for work
- Seismic vulnerability and condition assessment for large diameter pipeline
- Capacity building and institutional strengthening for water loss control
- Enhance training for emergency management capacity

5. Conclusion

- Location on the seismic area that we cannot predict, but we can do our best to strengthen the water system and do well prepared to face the coming hazards.
- In response to the challenges, we need to improve the old facilities, establish supporting and backup system.
- Different environments face different disasters, we suggest focusing on the most critical threats and engaging in the proper solutions.

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Lessons Learned from Damage to Drinking Water Supply System in the 2016 Kumamoto Earthquake in Japan

Masakatsu Miyajima

ABSTRACT

This study is focusing on damage to drinking water supply system in the 2016 Kumamoto Earthquake and the lessons learned are given. Mw 6.2 earthquake struck in and around Kumamoto City in Japan at a depth about 11 km at 21:26 JST on April 14, 2016. Around twenty eight hours later, at 01:25 JST on April 16, an Mw 7.0 stronger earthquake occurred in the same area at a depth of about 12 km. More than 8,000 houses were totally collapsed. Total fatality after the main shock was 49 dead with 1 missing. The main shock triggered many geo-hazards such as landslides, surface faulting and liquefaction. Drinking water supply system were heavily damaged by not only strong ground motion but also large ground deformation induced by the geo-hazards.

Damage analysis was conducted and the following findings are clarified.

1. The damage rate of pipelines of Kumamoto City is 0.08 cases/km. This value is similar to that of Sendai City in the 2011 Tohoku Earthquake, that is, 0.07 cases/km. The damage rate of Kobe City in the 1995 Kobe Earthquake was 0.32 cases/km and 0.30 cases/km in Nagaoka City in the 2004 Niigata-ken Chu-etsu Earthquake. These earthquakes recorded JMA seismic intensity 7. This difference seems to depend on percentage of installation length of seismic resistant pipe.
2. Pipe length of liquefied area is about 0.8% of the total length in Kumamoto City. The damage rate of pipelines in liquefied area was however about ten times of that in non-liquefied area.
3. The pipelines crossed a surface faulting suffered severe damage. The countermeasure for pipeline crossed a fault is necessary in the future.
4. Damage to air valve also affected suspension of water supply. The damage was caused by not only strong ground motion but also abrupt increase of water pressure in a pipe. The cause of abrupt increase of water pressure in a pipe just after an earthquake should be clarified.

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INTRODUCTION

Two strong earthquakes affected Kumamoto City and the nearby towns and villages. The first earthquake which was identified as the fore shock occurred on April 14, 2016, 9:26 PM in local time with a moment magnitude Mw=6.2. The epicenter was located at 32.849° N, 130.635° E at a depth of 11km. The second event identified as the main shock occurred on April 16, 2016, 1:25 AM in local time with a moment magnitude Mw=7.0. The epicenter of this earthquake was located at 32.791° N, 130.754° E, with a focal depth of 12km. A JMA (Japan Meteorological Agency) seismic intensity of 7, that is, the maximum grade of JMA scale was recorded at Mashiki Town in Kumamoto Prefecture in the fore shock and at Mashiki Town and Nishihara Village in Kumamoto Prefecture in the main shock.

Total fatality after the main shock was 49 dead with 1 missing. Number of totally collapsed houses was 8,369, partially collapsed houses 32,478 and slightly collapsed houses 146,382, respectively. The main shock triggered many geo-hazards such as landslides, surface faulting and liquefaction. Drinking water supply system were heavily damaged by not only strong ground motion but also large ground deformation induced by the geo-hazards. This paper introduced an outline of the damage to drinking water supply system by this earthquake and the damage analysis done to the pipelines buried in liquefied areas. Finally the lessons learned from this earthquake are given.

OUTLINE OF EARTHQUAKE AND DAMAGE TO WATER SUPPLY FACILITIES

Tables I and II list observation sites where large peak ground acceleration (PGA) and large peak ground velocity (PGV) were recorded, respectively. PGA and PGV listed in these tables are vector summation of horizontal two components. 9.25 m/s/s of PGA that is close to gravity acceleration was recorded at KiK-net Mashiki in the fore shock. Maximum PGV of 1.38 m/s was recorded at Mashiki-machi Miyazono, not same place as PGA, that is, at Kik-net Mashiki. In the main shock, accelerations greater than gravity were recorded at Ozu-chou Ozu, Minamiaso-mura, kawayo and Kik-net Mashiki. PGV more than 1 m/s was recorded at total six observation sites. The maximum PGV was 2.56 m/s recorded at Nishihara-mura Komori. These values were very large in comparison with those in the past earthquakes. It seems to be one of characteristics of near fault earthquake motions.

The piping length of drinking water supply in Kumamoto City is 3,238 km. The total number of pipe damages was 233, therefore, the damage rate was 0.07 per kilometer. As Figure 1 shows, the number of damage by pipe material was 0.63/km for SV (other joint), 0.39/km for CIP, 0.16/km for VP, 0.12/km for SP (welded joint), and 0.04/km for DIP (other joint).

TABLE I. LARGE PEAK GROUND ACCELERATION IN THE 2016 KUMAMOTO CITY

	Site Name	PGA(m/s/s)	Site Name	PGV(m/s)
1	KiK-net Mashiki	9.25	Mashiki-machi, Miyazono	1.38
2	Mashiki-machi, Miyazono	8.15	KiK-net Mashiki	0.92
3	Kumamoto nishi ku, Kasuga	7.36	K-net Kumamoto	0.72

TABLE II. LARGE PEAK GROUND VELOCITY IN THE 2016 KUMAMOTO CITY

	Site Name	PGA(m/s)	Site Name	PGV(m/s)
1	Ozumachi, Ozu	17.54	Nishihara-mura, Komori	2.56
2	KiK-net Mashiki	13.14	Mashiki-machi, Miyazono	1.82
3	Minamiaso-mura, Kawayou	12.92	Minamiaso-mura, Kawayou	1.39

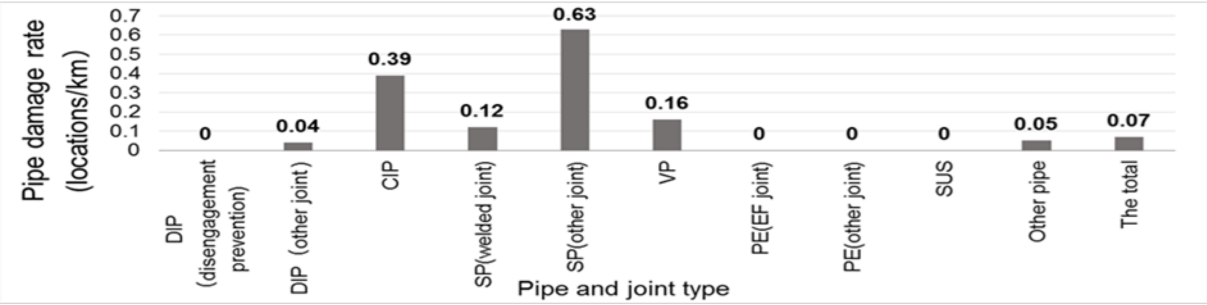

Figure 1. Pipe damage tare by pipe material in Kumamoto City

DAMAGE TO PIPELINE BURIED IN LIQUEFACTION AREA

Liquefaction occurred in and around Kumamoto City. The damage rate of drinking water pipeline in the areas where sand volcano densely appeared was evaluated in Kumamoto City. The pipe length in the liquefied areas was 26.7km. This length is about 0.8% of the total length in Kumamoto City. It indicates that the liquefaction occurred in Kumamoto City was not extensive. The damage rate of pipelines in liquefied area was 0.64/km because that the number of pipe damage was 17. The damage rate in liquefied area was about ten times of that in non-liquefied area.

DAMAGE TO AIR VALVE

Table III shows the number of locations of damage and damage rates of pipes and valves in Kumamoto City. This table indicates that damage to valves such as air valves was not small compared with damage to pipes in the 2016 Kumamoto earthquake. The number of damage to air valves in each prefecture in the 2016 Kumamoto earthquake is shown in Figure 2. This figure explains that the damage was concentrated in Kumamoto Prefecture and Oita Prefecture where the epicenter was located and near. On the other hand, air valve damage has also occurred in areas relatively far from the epicenter such as Saga City in Saga Prefecture and Nobeoka City in Miyazaki Prefecture. It seems that the damage was caused by not only strong ground motion but also abrupt increase of water pressure in a pipe. The cause of abrupt increase of water pressure in a pipe just after an earthquake should be clarified.

TABLE III. DAMAGE TO PIPELINE AND VALVES [1]

	Number of damage	Damage rate (locations/km)
Pipes	233	0.07
Valves	144	0.04

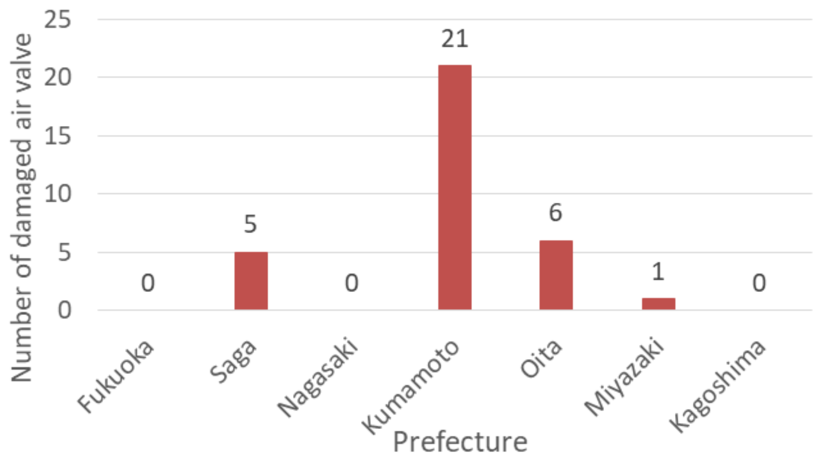

Figure 2. Number of damage to air valve in each prefecture

CONCLUDING REMARKS

Damage analysis was conducted and the following findings are clarified.

1. The damage rate of pipelines of Kumamoto City is 0.08 cases/km. This value is similar to that of Sendai City in the 2011 Tohoku Earthquake, that is, 0.07 cases/km. The damage rate of Kobe City in the 1995 Kobe Earthquake was 0.32 cases/km and 0.30 cases/km in Nagaoka City in the 2004 Niigata-ken Chu-etsu Earthquake. These earthquakes recorded JMA seismic intensity 7. This difference seems to depend on percentage of installation length of seismic resistant pipe.
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ACKNOWLEDGMENTS

I would like to extend our gratitude to the Kumamoto City Water and Sewerage Waterworks Bureau for their data provision as well as to the water utilities in Kyushu region that answered our questionnaire survey on damage to air valves.

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Developing a Seismic Resilient Pipe Network Using Performance Based Seismic Design Procedures

Craig A. Davis

ABSTRACT

The Los Angeles Water System is implementing a Seismic Resilience Program which comprehensively covers all aspects of water system business. A key component to the program is developing a seismic resilient pipe network. A seismic resilient pipe network is designed and constructed to accommodate damage with ability to continue providing water or limit water outage times tolerable to community recovery efforts. The challenges to creating a seismic resilient network is described through the four subsystems making up a water system, namely the supply, treatment, transmission, and distribution subsystems and how each must operate consistently given the numerous earthquake hazards using a performance-based design approach. The resilience of each subsystem is critical to supporting community resilience and are important for providing water delivery, quality, quantity, fire protection, and functionality services. Assessing the risks for fire following earthquake and identifying critical facilities and their locations throughout the city are important to defining the resilient pipe layout.

INTRODUCTION

The Los Angeles Department of Water and Power (LADWP) Water System is undertaking a seismic resilience program as outlined in [1] and [2]. As part of the program, these two documents recommended developing a Seismic Resilient Pipe Network (SRPN) recognizing it is a long-term mitigation effort with a commitment for using seismically resilient pipes across the city. A focus is given to improving the pipe network because most other components have been updated using modern seismic design over the past 40 years and were proven effective in the 1994 Northridge earthquake. However, to ensure consistency for design and construction across the entire system, the LADWP is also proposing the development of system-wide and component level seismic performance and design criteria.

The intent of a SRPN is to improve the existing network knowing earthquake damage cannot cost-effectively be completely prevented in the near-term, but may be better controlled with a focus of providing improved customer service. A resilient network places seismically robust pipes at key locations and alignments to help increase the probability of continuous water delivery and reduce the time to restore areas suffering a loss of water services after an earthquake. Seismically robust pipes are designed to accommodate earthquake forces meeting defined performance criteria. Damaged portions of the water system preventing flow capabilities can be isolated from the earthquake resistant pipes to increase service restoration rates.

This paper proposes methodologies for developing a SRPN for the Los Angeles Water System. The first section defines a SRPN. The following section presents a performance based seismic design procedure applicable to the water system. This information provides the basis forming the framework and criteria for transforming the existing transmission and distribution networks into a SRPN, which is described in the last section. The performance based seismic design and SRPN concepts are applicable to other water systems.

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The LADWP was founded in 1902 and is the largest municipal utility in the United States. It provides critical water and power services to support the local economy and wellbeing as well as in support of the supply of goods and products throughout the United States and the Pacific rim. Los Angeles covers an area of 1,214 km^2 with a population of about 4 million people. Water supply is obtained from local groundwater (12%), the Los Angeles Aqueduct (29%), purchased water from the Metropolitan Water District of Southern California (57%), and recycled water (2%); percentages are 2011-2015 averages. The transmission and distribution networks have over 12,000 km of pipe and contain numerous tanks, reservoirs, pump and regulating stations. Water quality is maintained with treatment plants, chloramination and chlorination stations.

DEFINITION: SEISMIC RESILIENT PIPE NETWORK

A SRPN is designed and constructed to accommodate damage with the ability to continue providing water services, or limit outage times tolerable to community recovery efforts [3]. To meet this definition, the existing Los Angeles water pipe network must be transformed into a SRPN using seismically robust pipes along strategic alignments in a manner allowing a post-earthquake damaged system to restore the water services meeting defined target performance criteria.

To further clarify this definition, a SRPN is made up of the entire set of pipes in the transmission and distribution subsystems within the Los Angeles Water System. It is not defined as only those pipes within the system considered to be seismically resistant or resilient. A SRPN considers how all the pipes perform in earthquakes and their resulting interactions which may impact the ability to provide post-earthquake water services.

The above definition underpins the need for robustness and reliability of complex infrastructure systems. An important distinction is made between the terms robust (or resistant) and resilient, both of which are important to understanding a SRPN. Robust describes the resisting of change or the effects of disturbance as compared to resilience describing the adaptation to the impact [4]. Seismically robust pipes are designed to accommodate earthquake forces meeting defined performance criteria. Seismically robust pipes are necessary components for a resilient network. The network resilience is created by its ability to accommodate damage and adapt to providing critical water services to the community.

PERFORMANCE BASED SEISMIC DESIGN

A SRPN must be designed and constructed consistent with all other components to ensure a resilient water system. To develop a resilient water system, a performance based seismic design methodology is necessary for assessing overall system operability and functionality following earthquakes. Performance-based seismic design is a process in which the performance of the system and/or components being designed is evaluated over the entire range of possible loadings rather than for one or more discrete intensities or events. Figure 1 presents the key steps in this iterative process as proposed for implementation by the LADWP Water System. The process identifies the initial target performance objectives for a very large and complicated water system built within an extremely complex environment of seismic hazards throughout Los Angeles.

At the system level, performance objectives articulate the targeted response and recovery of water system services relative to the probability of seismic hazards affecting the system. This defined system level performance can then be used to establish design criteria for system layout and each component making up the system. Design criteria must also meet minimum regulations dictated by local, state, and federal agencies.

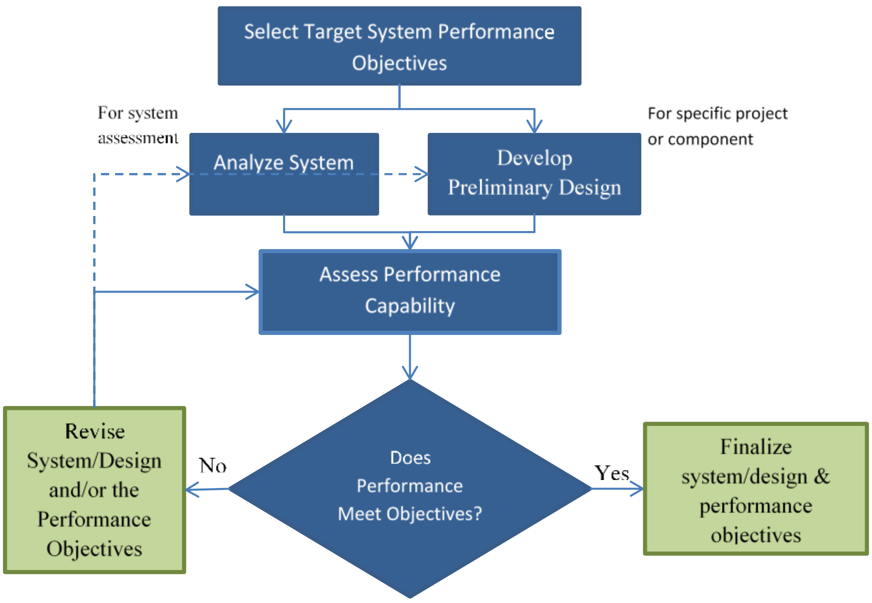

Figure 1. Performance based seismic design flow diagram (revised from [5]).

As shown in Figure 1, using the target performance objectives, a preliminary system layout (e.g., portion of a pressure zone) or component design (e.g., tank or building) will be developed. This step could also entail simply evaluating the existing system layout or an existing component to defined earthquake hazards. The hazards are to include, but not limited to, shaking intensity and permanent ground deformations. Permanent ground deformations include fault rupture, liquefaction induced settlement and lateral spreading, landslides, ground settlement, soft clay cyclic mobility, and other potential movements that may affect the system or component. Results of the assessment are compared to the performance objectives to determine if the performance capability meets or exceeds the target objectives. If the evaluated performance falls short of the target objectives (path “No” in Figure 1), then the design or system layout requires modification. In some cases, the load conditions may impose such large demands that the performance objectives cannot be economically met. In such cases the target performance objectives may need to be revisited and in special cases modified with approval of senior management. These modifications should be accounted for in system level response and recovery plans and incorporated into other city resilience plans to ensure the public is aware of certain extreme situations and are adequately prepared. Once the design is found to meet or exceed the performance objectives (path “Yes” in Figure 1), the objectives and system layout and/or component design is finalized.

Performance Criteria

Table 1 identifies the draft target performance criteria under consideration for implementation by the Los Angeles Water System. Using the hazard return period in Table 1, earthquakes expected to return within this timeframe are to be used to develop scenarios from which system level analysis will be performed to assess service restoration times. The complex seismic environment the LADWP operates within has about 40 different faults which may result in earthquakes for each of the levels identified in Table 1. The system performance criteria are defined to reflect increasing acceptable loss of services with earthquake size and rarity of the event. Performance criteria for Level 4 events target the containment of service losses and restore them in a manner to prevent unacceptable results in the aftermath of such extreme events.

Table 1. Draft target performance criteria for the Los Angeles Water System (under modification)

Level	Hazard Return Period Criteria	Target Water System Performance
1	100 years	Limited damage to water system, no casualties, few to no water service losses. All customer services operational within about 3 days.
2	500 years[1]	Life safety and property protection. All customer services operational within about 20 days, except water quantity; rationing may extend up to 30 days.
3	2,500 years[1]	Life safety and property protection. All customer services operational within about 30 days, except water quantity; rationing may extend up to 60 days.
4	>2,475 up to about 10,000 years; including major to great earthquakes[2]	Life safety and property protection. All customer services operational within about 45 days, except water quantity; rationing may extend up to 12 months.

[1]Highly active faults such as the San Andreas Fault have great earthquakes of M_w>7.8 within these return periods, for which the performance criteria are proposed to meet Level 4.
[2]http://www.geo.mtu.edu/UPSeis/magnitude.html

System Performance

The target water system performance objectives are identified in terms of life safety, property protection, and post-earthquake services based on the size of events defined in Table 1 [2][6]. Life safety and property protection are target objectives for all the levels presented in Table 1; These are self-explanatory and defined elsewhere [6]. The water service recoveries through the pipe network are described by five basic categories [6][7]:

Water Delivery: This service is achieved when the system can distribute water to customers, but the water delivered may not meet quality standards (requires tap water purification notice), pre-event volumes (requires water rationing), fire flow requirements (impacting firefighting capabilities), or pre-event functionality (system performance is inhibited).

Water Quality: This service is achieved when water quality at customer connections meets pre-event standards. Potable water meets health standards (tap water purification notices removed), including minimum pressures to ensure contaminants don't enter the system.

Water Quantity: This service is achieved when water flow to customers meets pre-event volumes (water rationing removed).

Fire Protection: This service is achieved when the system can provide pressure and flow of a suitable magnitude and duration to fight fires.

Functionality: This service is achieved when the system functions are performed at pre-event reliability, including pressure (system performance constraints resulting from the earthquake are removed/resolved).

A portion of the system, having restored water delivery, quality, quantity, and fire protection services, is considered operable (system has operability), but it may not be fully functional, meaning some performance constraints remain in the system (e.g., some trunk lines, reservoirs, or tanks may be damaged and out of service). The system has full functionality restored once all the system components can perform as intended before the event. Operability is the accumulation of water delivery, quality, quantity, and fire protection services and is a measure of the system's ability to support community resilience [6]. Functionality is a measure of the system's resilience and can be quantified using [8].

The post-earthquake support for community resilience, through operability, can be further defined by disaggregating the public safety, social, economic, and general livelihood aspects the water system services provide. Critical A customers are defined as those who need water services in support of actions for life safety and public health associated with post-earthquake emergency response and recovery. Critical B customers are defined as those who need water services in support of actions for crucial community resilience activities. Critical A and Critical B customers generally require a more rapid service restoration to ensure resilient community recovery and are currently being identified through a collaborative effort with many agencies and community input.

Figure 2 shows example draft restoration curves for each of the above described services for Level 2 performance criteria presented in Table 1. The details outlining the establishment of each service objective is not presented herein due to space limitations.

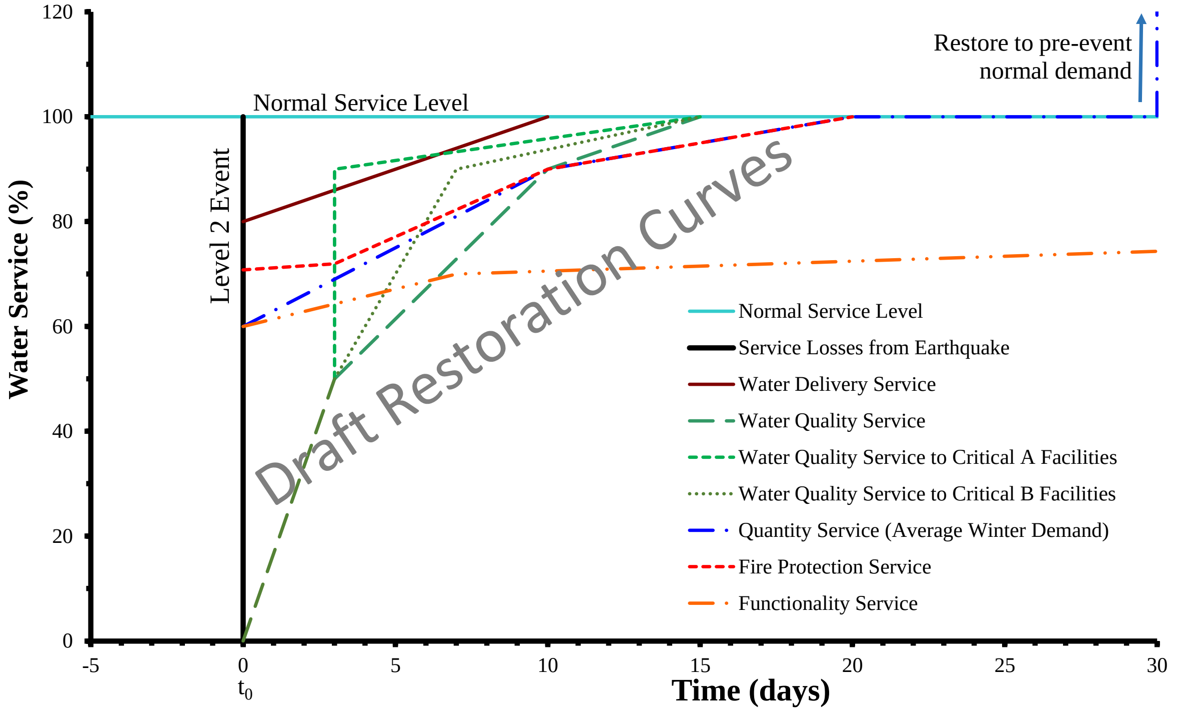

Figure 2. Draft service restoration curves for Level 2 events.

Table 2. Major water subsystems.

Subsystems	**Description**	**Typical Facilities/Components**
Raw Water Supply Systems	Systems providing raw water for local storage or treatment including local catchment, groundwater, rivers, natural and manmade lakes and reservoirs, aqueducts.	Reservoirs, pump stations, wells, pipelines, canals, tunnels, dams, levees, raw water intersystem connections. This may also include pertinent storm water capture facilities.
Treatment Systems	Systems for treating and disinfecting water to make it potable for safe use by customers.	Treatment plants, ultraviolet treatment processes, filtration systems, settling basins, chlorination stations, and other chemical stations (fluoridation, hypo-chlorination, chloramine, etc.).
Transmission Systems	Systems for conveying raw or treated water. Raw water transmission systems convey water from a local supply or storage source to a treatment point. Treated water transmission systems, often referred to as trunk line systems, convey water from a treatment or potable storage point to a distribution area.	Medium to large diameter pipes, tunnels, reservoirs and tanks, pumping stations, valves and regulating stations. This also includes treated water intersystem connections.
Potable Water Distribution Systems	Networks for distributing water to domestic, commercial, business, industrial, and other customers.	All pumping stations, regulating stations, tanks and reservoirs, valves, and piping (20”≤ diameter) not defined as part of other subsystems forming a network from connections at the transmission systems to points of service (meters).
Recycled Water Systems	Systems for producing, disinfecting, conveying, and distributing recycled water to customers.	Treatment plants, pumping stations, regulating stations, tanks, valves, and piping.

For the purposes of assessing the water system using the performance-based seismic design criteria, the water system consists of five major subsystems as described in Table 2. The water systems’ earthquake performance is not only dependent on the seismic robustness of each component from which it is made, but also on the systemic design, layout, and inter-links of each subsystem identified in Table 2. Each subsystem plays an essential role to achieve the performance criteria presented in Table 1; however, the importance of each may change for different earthquakes as identified by Levels 1 to 4 in Table 1. The SRPN consists of the piping networks in the transmission and potable water distribution subsystems.

Component Performance

Each subsystem defined in Table 2 is made up of many components shown in the right column. These are in addition to the numerous buildings and structures used for water system headquarters, operations, and maintenance facilities. Each component must be designed and constructed in a manner to provide the system performance targeted in Table 1. Figure 3 presents a design flow diagram for components. Using this process, the design of each component is expected to aggregate to the desired system-level performance; analyses are needed to confirm this assumption.

Each component is to have a designated Criticality Category I, II, III, or IV as defined in Table 3. Component performance objectives are established through definitions of maximum tolerable damage. Table 4 is a matrix showing the targeted maximum level of damage which may be tolerated for different Criticality Categories and hazard return periods. Hazard return periods effectively represent event intensity. Consider an earthquake exposing the water system to 475-year return period intensity hazards. Components designed to Criticality Category II will be expected to suffer a “Moderate” level of damage and those designed to category IV a “Minor” level of damage. Each designation of minor, moderate, high, and severe damage have corresponding definitions like FEMA [5], but are not included herein due to space restrictions.

Designs for Criticality Category III and IV components are to be checked against Level 4 earthquake scenario hazards. This requires the scenarios to be developed for use at the design level. The purpose for this check is to ensure the most cost-effective design and construction is achieved for the benefit of the community. This is to be accomplished per the notes at bottom of Tables 3 and 4, identifying alternatives are to be investigated and recommendations presented to the project oversight committee (senior management) for approval. The information presented should include cost differentials resulting from the Level 4 event hazards and the potential consequences to providing post-earthquake water system services for not mitigating impacts from the Level 4 events.

Pipeline Component Performance and Design

As shown in Figures 3 and 4, pipelines have special considerations to develop a SRPN. Pipelines providing water service for multiple uses must be classified using the highest Criticality Category in Table 3 based on its intended use. Pipeline systems connecting to Critical A or Critical B customers need to have a reliable set of components, utilizing the same Criticality Category for every component making up the piping system, through the entire transmission and distribution supply chain from source to tap (i.e., a reliable line of distribution and transmission pipes which can be isolated). Where pipe connections and branches come from a higher Criticality Category pipeline to serve a lower Criticality Category, the branch pipe needs to be designed as the higher Criticality Category or be equipped with isolation capabilities which may be operated in the event of damage. In addition, pipelines and pipe systems are to be designed for the higher Criticality Category for which service is provided downstream from the supply or water treatment source to the point of service.

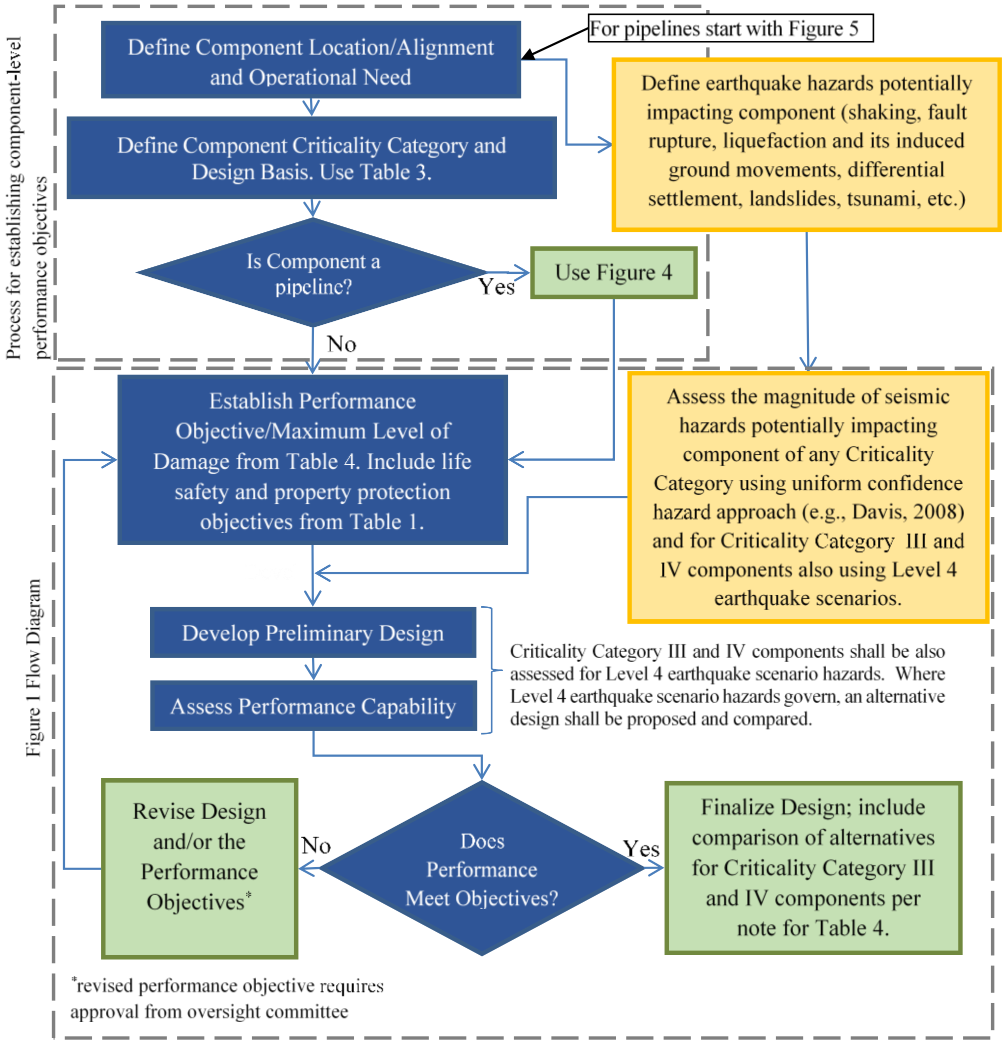

Figure 3. Component design flow diagram.

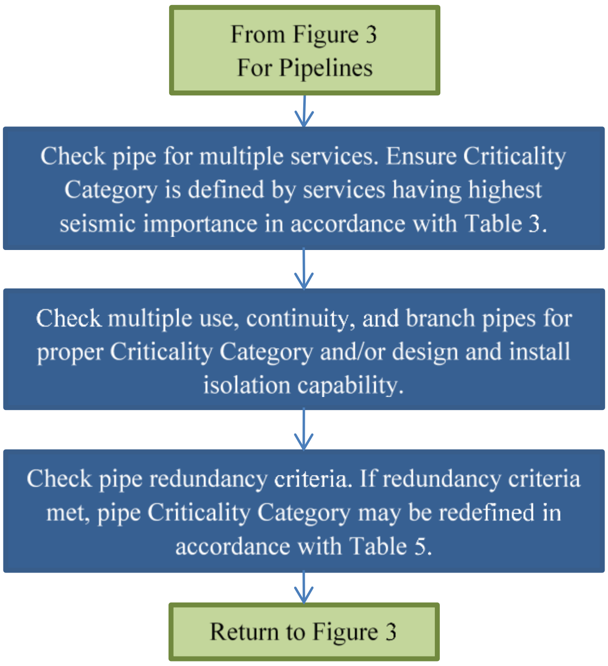

Figure 4. Pipeline component partial flow diagram for establishing performance objectives.

Table 3. Water system component criticality categories (summary descriptions).

Criticality Category	Description	Design basis hazard return period (years)
I	Components that present very low hazard to human life in the event of failure. Not needed for post-earthquake system performance, response, or recovery.	72
II	Normal and ordinary components not used for water storage, pumping, treatment or disinfection. They provide water for typical residential, commercial, and industrial use within the system and include all components not identified in Criticality Categories I, III, and IV.	475
III	Components, mainly pipelines, providing water to services that represent a substantial hazard or mass disruption to human life in the event of failure. These components may also result in significant social or economic impacts in the event of failure.	975*
IV	Components needed to provide water to essential facilities for post-earthquake response, public health, and safety. This includes components needed for primary post-earthquake firefighting. These components are intended to remain functional during and following an earthquake.	2,475*

*Note: Also check against Level 4 earthquake scenario hazards, see Table 4 and Figure 3.

Table 4. Maximum level of component damage to be tolerated based on Criticality Categories (modified from [5]).

Increasing Performance

Increasing Event Intensity

		Criticality Category			
		I	II	III	IV
Level 4 Event Scenario*		Severe	High to Severe	High	Moderate to High
Hazard Return Period (yrs)	2,475	High to Severe	High	Moderate to High	Moderate
	975	High	Moderate to High	Moderate	Minor to Moderate
	475	Moderate to High	Moderate	Minor to Moderate	Minor
	72	Moderate	Minor to Moderate	Minor	None

*Note: Resistance to damage for Level 4 events is to be checked for Criticality Categories III and IV components. Alternatives are to be investigated and recommendations presented to the project oversight committee for approval, including cost differentials resulting from the Level 4 event hazards and the potential consequences to services for not mitigating impacts from the Level 4 events.

Redundancy provides an increase in confidence, is a desirable resilience feature, and is encouraged to improve cost-effective reliability of water delivery. Two redundant Criticality Category II pipes provide an overall 99% confidence level of one pipe not being damaged when exposed to 475 year return period hazards. This increased confidence can be utilized for design efficiency by: (1) designating a primary pipe, of all the redundant pipes, to provide the minimum needed flow to meet post-earthquake operational needs, and to be designed for the highest required Criticality Category as defined in Table 3; and (2) reducing the seismic design criteria for redundant pipes in accordance with Table 5. Table 5 presents the recommended reclassification of pipe Criticality Category based on the redundancy level L_R. This redundancy factor shall not be applied to any pipes which:

1. Otherwise are required to have a higher Criticality Category based on life safety or other factors presented in Table 3,
2. Are exposed to common cause failures, such as:
    a. A leak or break in one pipe may lead to damage on other redundant pipes,

   b. Pipes are exposed to the same permanent ground deformation hazards (i.e., pipes cross same fault, landslides, liquefaction zones, etc.).
3. There are foreseeable plans to remove the designated primary redundant pipe from operation, in which case multiple redundant pipes shall be designated to be the same highest-level Criticality Category for their intended use.

Table 5. Criticality Categories for redundant pipes.

	L_R		
Criticality Category as defined in Table 3	0	1	2
I	I	I	I
II	II	II	II
III	III	II	II
IV	IV	III	II

DEVELOPING A SEISMIC RESILIENT PIPE NETWORK

A seismic resilient network targets water provision to critical areas and locations when needed by the community for disaster recovery. The SRPN is to improve the post-earthquake provision of services to at least the most critical services and facilities in the city and aid in meeting the system performance criteria. Developing a seismic resilient network must start with an overall vision of what the entire system could look like in the future. The following summary and Figure 5 identify aspects needed for developing a seismic resilient pipe network, originally outlined in [9].

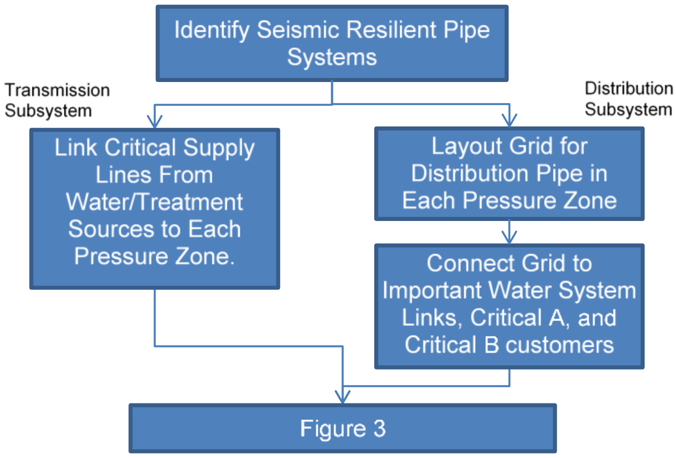

Figure 5. Work flow process for developing a seismic resilient pipe network.

Figure 5 shows the work flow process for laying out a system-wide SRPN. To develop a SRPN, resilient piping systems, using robust pipe, must be identified. These resilient piping systems must have a defined resistance, or fragility, to the different earthquake hazards. For consistency over the long-duration needed to develop a SRPN, standards for seismic resilient pipe systems are needed, including those for seismic resilient pipe design, testing, and installation. Seismic resilient pipe systems include Earthquake Resistant Ductile Iron Pipe (ERDIP), High Density PolyEthylene (HDPE), specially designed welded steel pipe, PolyVinylChloride (PVC) and others providing sufficient robustness against design level ground deformations.

Figure 5 shows the development of resilient transmission and distribution subsystems in parallel, because both can be improved to develop a SRPN simultaneously. The seismic design of each subsystem is critical to supporting community resilience. Each subsystem must have an initial draft layout incorporating the SRPN attributes described below. Using the draft layouts, the performance based design procedure (Figure 3) will be applied to (1) assess the system to determine if the target performance objectives can be met, and (2) identify pipe component level designs. This is applied across the entire water system with due consideration of the many variables dictating the SRPN layout. The SRPN layout may change with geographic and topologic location consistent with the diversity of the communities served. The following subsections provide guidance on transmission and distribution networks for the LADWP. These are intended for initial SRPN layout, from which scenario earthquake evaluations are to be undertaken in accordance with Figure 1 to see if the performance objectives are met; modifications may be needed in portions of the water system.

A SRPN should possess the following attributes and capabilities:

- Robust piping systems capable of resisting the seismic hazards for which they may be exposed, including: shaking, surface fault rupture, liquefaction induced settlement and lateral spreading, landslides, cyclic mobility, and other known earthquake hazards.
- Transmit bulk water to each pressure zone meeting minimum flow requirements established by performance objectives, proposed herein as average winter demand.
- Ability to rapidly isolate seismically reliable pipes from more vulnerable pipes which may leak and drain potions of system following an earthquake.
- Distribute potable water to critical customers within days after an earthquake, and in accordance with defined target performance objectives.
- Provide water flow to areas in need of fire suppression soon after an earthquake, consistent with the fire following earthquake risk and the Fire Department’s equipment capability for relaying water.
- Support post-earthquake emergency water accessibility to customers who may not have potable water at their tap.
- Connects important links within the water transmission and distribution subsystems with seismically robust pipes. Critical links include, but are not limited to:
    - Transmission lines, regardless of the trunk line Criticality Category
    - Inter-system pumping connections (to pump between pressure zones)
    - Key water supply sources (tanks, reservoirs, ground water, treatment plants, inter-system connections to other agencies, etc.)
    - Pump and regulating stations

Seismic Resilient Transmission Pipe Network

The Los Angeles transmission subsystems are proposed to have at least one continuous transmission line (or supply chain) which can provide the entire service area within a pressure zone with a minimum of average winter day demand (AWD) following strong to major earthquakes. They also need capability of being isolated from other pipes which may suffer damage in the same earthquakes. Figure 6 shows an initial draft for a seismic resilient water transmission pipe network for the entire city; these pipes are Criticality Category IV and will provide every pressure zone with a reliable set of components within the transmission subsystem designed with uniform confidence [10] to exposed seismic hazards which meet or exceed the performance criterion. All transmission components needed to flow water along these lines should meet the same minimum design requirements. This map will be used as a basis for further developing the seismic resilient transmission system. Not all pipes in Figure 6 are identified as being Criticality Category IV, however, all transmission pipes shall be designed for earthquake hazards in accordance with the performance based design procedure. Figure 6 represents the minimum number of Criticality Category IV pipes needed to make up a SRPN.

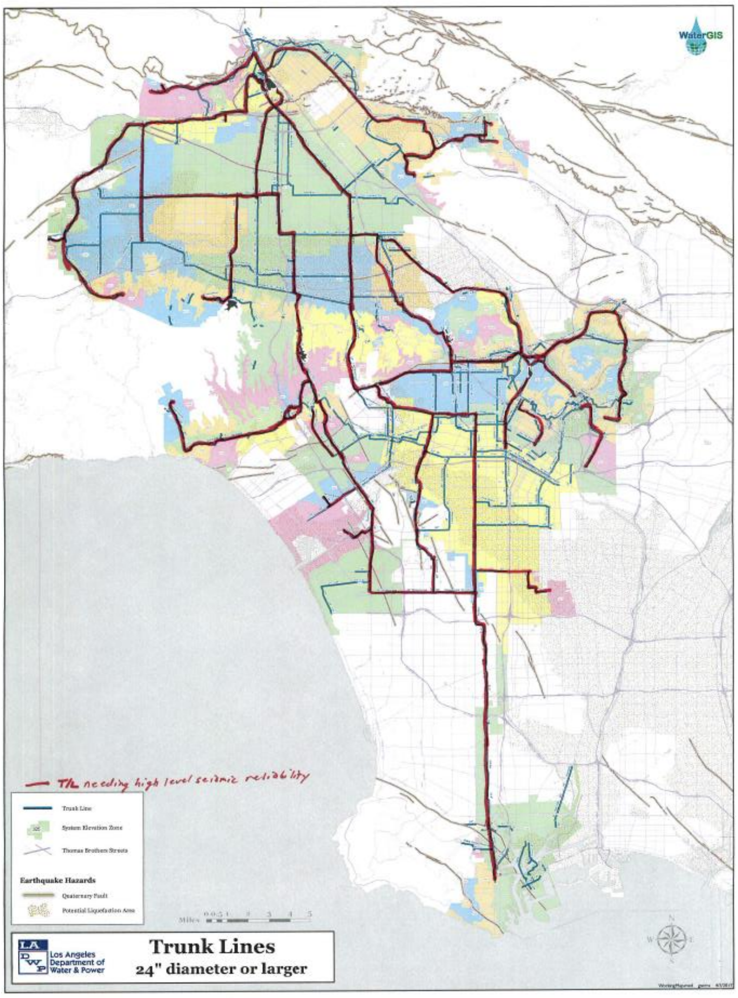

Figure 6. Draft LADWP Resilient Transmission Pipe Network (red lines are seismic reliable pipes with Criticality Category IV, blue lines are pipes with other Criticality Categories).

Seismic Resilient Distribution Pipe Network

A seismic resilient distribution pipe network can be developed using a concept of an arterial grid of robust pipes. This grid will provide an arterial subnetwork, embedded within the overall network of pipes having much higher reliability for conveying water throughout the pressure zone following strong to major earthquakes. From this grid, robust pipes will link to important system components, Critical A and Critical B customers and services. Important system links are outlined above. Following the performance based seismic design procedure, the design levels for each pipe component can be defined based on how it fits into SRPN layout and the earthquake hazards each is exposed. Conceptually, the grid dimensions made of seismically robust pipe may be determined to meet firefighting demand and/or emergency water distribution criteria. Based on fire department capability to relay water, a reasonable maximum grid dimension seems to be about 3.2 km by 3.2 km.

Implementation

Critical pipeline assets in the transmission and distribution subsystems need to be identified and mapped. These would represent the minimum layout of pipelines needed to achieve a SRPN. Figure 6 shows an initial effort for the transmission subsystem. Similar maps need to be prepared for the distribution subsystem for each pressure zone. It is advantageous and recommended to implement the development of a SRPN as part of the asset management and pipe replacement programs. As the critical pipes are prioritized for replacement from the asset management program, they should be designed and constructed using appropriate seismic robustness to build out the SRPN. To aid in the seismic design for distribution pipe, hazard maps for permanent ground deformations across faults, landslide, and liquefaction hazard zones can be developed across the city. Short and long-term plans need to be developed with stakeholder input, including resource and budget requirements to execute the priorities, updated periodically. The complete SRPN build-out will take decades, and possibly as long as the pipe replacement rate which currently is about 120 years; however, incremental improvement will be attained with each new pipe installation.

SUMMARY

A methodology for developing a seismic resilient pipe network (SRPN) for the Los Angeles Department of Water and Power (LADWP) has been presented. The SRPN is defined to include all 12,000 km of pipe making up the transmission and distribution subsystems and account for the interaction of all pipes and their seismic fragilities following an earthquake to provide water services in accordance with established performance objectives. A performance based seismic design procedure was presented for application to supply, treatment, transmission, and distribution systems as well as the facilities and buildings used for operation and maintenance. Target performance criteria based on four earthquake levels were proposed. The need for system-wide and component level performance criteria was described and related to development of a SRPN. System performance objectives for water delivery, quality, quantity, fire protection and functionality services are in need of being developed for all four earthquake levels. Attributes of a SRPN are summarized. Initial application of these procedures, incorporating the attributes, were applied to the LADWP transmission subsystem. Similar application will be applied to the distribution network in all pressure zones.

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Verification of Design Method of Pipeline Crossing Fault with Earthquake Resistant Ductile Iron Pipe using Large-scale Split-box Test

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ABSTRACT

This paper describes a safety verification result of the design method of a pipeline crossing fault using Earthquake Resistant Ductile Iron Pipe (ERDIP). In order to confirm the performance limit of the joint and pipeline behavior, we performed ultimate four-point bending tests and a fault rupture test using the test equipment at Cornell University in the U.S.

Consequently, no leakage immediately occurred even though the test pipes exceeded the design performance limit of the joint. Thus, the result showed that a pipeline design method based on the performance limit of the ERDIP joint can result in a satisfactory advantage. The following are the details of the test results.

(a) Four-point bending test: A joint bending test was performed on the ERDIP joint (DN150, GX-type) under water pressure of 0.55 MPa. No leakage was found until the joint deflection of 12.2°. Subsequently, first leakage was confirmed over 12.2°. Consequently, the test result shows that there was no leakage until the joint deflection of 1.5 times larger than the maximum joint deflection angle (i.e., 8°).

(b) Large-scale fault rupture test: ERDIP (DN150, GX-type) under water pressure of 0.55 MPa was installed in a test sand box divided into two sections. The fault displacement was simulated by moving one side of the divided test box. Six joints were placed in the sand box. Both ends of the pipeline were fixed to the box. Normally, an actual chain structure pipeline is installed under less severe conditions than those under which this test was performed. Consequently, no leakage immediately occurred even though the test pipes exceeded the design performance limit of the joint by the fault rupture.

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INTRODUCTION

It has been reported that there are approximately 2,000 faults in Japan. The 2016 Kumamoto Earthquake was caused by the movement of the Futagawa-Hinagu fault zone [1]. A surface earthquake fault whose maximum displacement was approximately 2 m caused significant damage to houses and infrastructure[2].

We previously reported the verification of the design method of a pipeline that crosses a fault using pipeline behavior analyses and large-scale split-box test with Earthquake Resistant Ductile Iron Pipes (ERDIPs) [3]. An ERDIP pipeline is capable of absorbing the large ground displacements that occur during severe earthquakes owing to the movement of its joint (extension, contraction, and deflection) and the use of the joint locking system. The pipeline is thus referred to as a “chain structure pipeline.” The existing ERDIP pipelines have been exposed to several severe earthquakes such as the 1995 Kobe Earthquake, the 2011 Great East Japan Earthquake, and the 2016 Kumamoto Earthquake and there has been no documentation of their failure in the last 40 years.

ERDIP has been used for measures against earthquakes on the western coast of North America, which is an earthquake-prone zone. In recent years, pipeline design for measures against fault displacement has become necessary, because there are many active faults in the area. The design displacement of a fault is determined by the past fault activities in general; however, we have to know whether the pipeline behavior during a fault movement becomes more excessive than assumed in order to be prepared in case the actual fault displacement is greater than the design displacement. Therefore, we conducted a four-point bending test and a large-scale split-box test under severe conditions wherein a bending moment or displacement exceeds the joint performance. We report the result of these examinations.

STRUCTURE OF ERDIP AND ITS BEHAVIOR

Figure 1 shows a cut-away view of a GX-type joint, which is a type of ERDIP joint investigated in the present study. The bell of an ERDIP is equipped with a locking ring and rubber gasket to prevent water leakage. The spigot is inserted into the bell past the rubber gasket and the locking ring. The spigot end has a special feature called spigot projection, which bears against the locking ring to resist pullout of the spigot from the bell.

Figure 2 shows the behavior of a GX-type joint. Table I presents the performance parameters of the joint. The joint is capable of extending/contracting by 1% of its standard pipe length (e.g., 5 m in the case of DN150). When the joint is fully extended, the spigot projection and locking ring lock tightly together to prevent leakage resulting from the pullout of the joint. The pipeline is thus referred to as a “chain structure pipeline” (Figure 3).

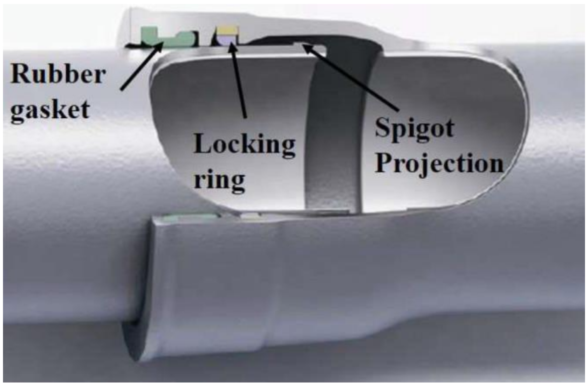

Figure 1. Cut-away view of a GX-type joint

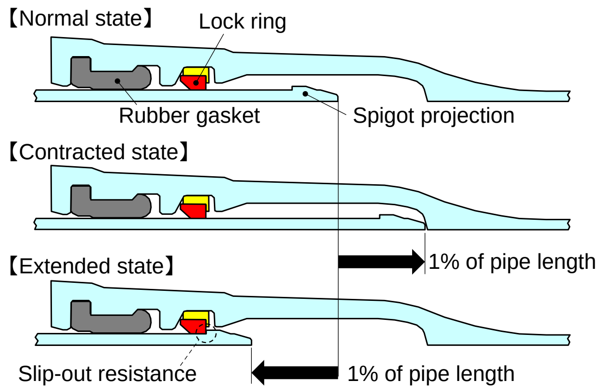

Figure 2. Behavior of a GX-type joint

TABLE I. PERFORMANCE OF GX-TYPE JOINT

Property	Performance
Pullout resistance	3D kN (D : nominal diameter [mm])
Amount of extension/ contraction	± 1% of pipe length
Deflection angle	8°

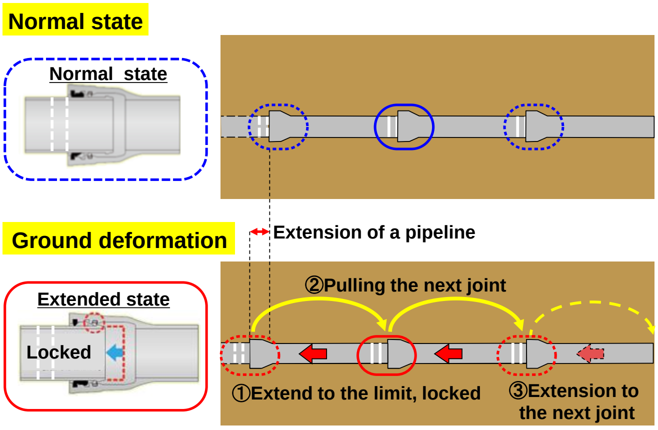

Figure 3. Behavior of a chain structure pipeline

FOUR-POINT BENDING TEST

We conducted a four-point bending test to confirm the ERDIP joint behavior in case the bending moment applied to the joint is larger than the limit performance of the ERDIP joint. The experiment was performed at the Cornell Large-scale Lifelines Testing Facility, which is part of the Bovay Laboratory Complex at Cornell University.

Materials and Methods

The four-point load test set-up for the 150 mm (6 in) GX-type ERDIP is shown in Figure 4. Figure 5 is a photograph of the bending specimen before the test. A bending moment load is applied to the pipe under pressurized conditions with water up to approximately 550 kPa (80 psi).

The specimen was initially set up at a fully inserted position. It was subsequently pressurized with water to approximately 550 kPa (80 psi) while allowing the joint to extend fully in response to the axial forces on the end caps. The internal pressure was adjusted continuously to maintain a nearly constant pressure for the rest of the test.

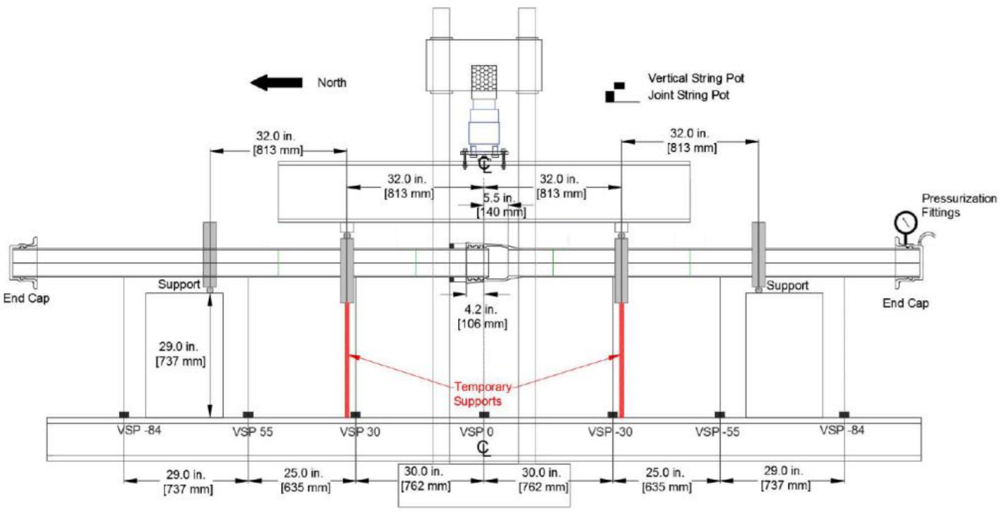

Figure 4. Four-point load test set-ups for the 6-in GX-type ERDIP

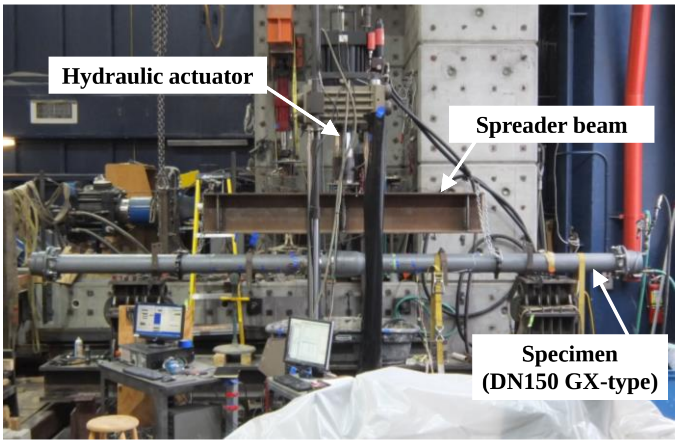

Figure 5. Bending specimen before the test

Results

The bending moment versus joint deflection relationship is shown in Figure 6. The bending moments owing to the pipe, water, and spreader beam weights are included in the bending moment versus the deflection calculations. Figure 7 shows the pipe specimen during and after the test. The results are as follows.

(1) No leakage occurred at 8°, which is the performance limit of GX-type joint.
(2) No leakage occurred at 12°, which is 1.5 times the performance limit of GX-type joint.
(3) The first leakage of approximately 0.4 l/min (0.1 gal/min) was observed at the deflection of 12.2°, corresponding to a small fluctuation in the pressure as shown in Figure 6.
(4) At the deflection of 14.3°, the pressure reduced to 410 kPa (60 psi), and the pipe leaked at a significant leakage rate of approximately 26.5 l/min (7 gal/min).
(5) The leakage stopped at the deflection of 16.6°, after which the pressure stabilized with very small pressure fluctuations.
(6) The test was stopped when the joint reached the joint deflection of 32°, as shown in the figure. The pipe was unloaded, thereby reducing the deflection to 29.2° after which the pipe was depressurized.

From the aforementioned results, no leakage immediately occurred even though the test pipes exceeded the design performance limit of the joint. Thus, the result showed that a pipeline design method based on the performance limit of the ERDIP joint can result in a satisfactory advantage.

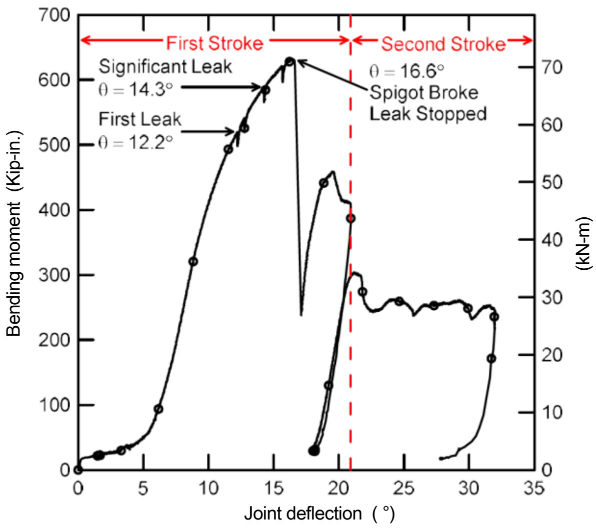

Figure 6. Bending moment versus joint deflection

[12.2°] [32°]

Figure 7. Bending specimen during and after the test

LARGE-SCALE SPLIT-BOX TEST

We conducted several large-scale split-box tests and confirmed that an ERDIP pipeline could absorb the fault displacement by the behavior of the chain structure pipeline [3].

In this study, we conducted a large-scale split-box test with an ERDIP joint under severe conditions wherein the ends of pipes were fixed to the split-box for the same purpose as the aforementioned four-point bending test. All the testing was performed in the large-scale test basin at the Cornell University Large-scale Lifelines Testing Facility.

Materials and Methods

Figure 8 shows the plan view of a large-scale split-box test for the 150 mm (6-in) GX-type ERDIP and Figure 9 shows the test equipment before the test. The dimensions of box were 12.1 m in length, 3.2 m in width, and 2.3 m in height. The pipe was placed on a bed of compacted sand, aligned, the instruments checked, and subsequently backfilled with compacted sand to a depth of cover of 30 in (762 mm) above the pipe crown. Table II shows the backfill sand conditions. The crossing angle between the fault and pipeline was 50°, and the box was moved to pull the pipe.

The number of joints in the boxes was six (S18, S15, S5, N5, N15, N18) and the specimen was initially set up at a fully inserted position as the amount of extension was 120 mm.

First, one of the two boxes was moved by 1.0 m using an actuator to simulate a fault displacement. At this time, all the joints in the boxes were fully extended. Second, one of the two boxes was moved by 1.1 m and we observed the pipeline behavior.

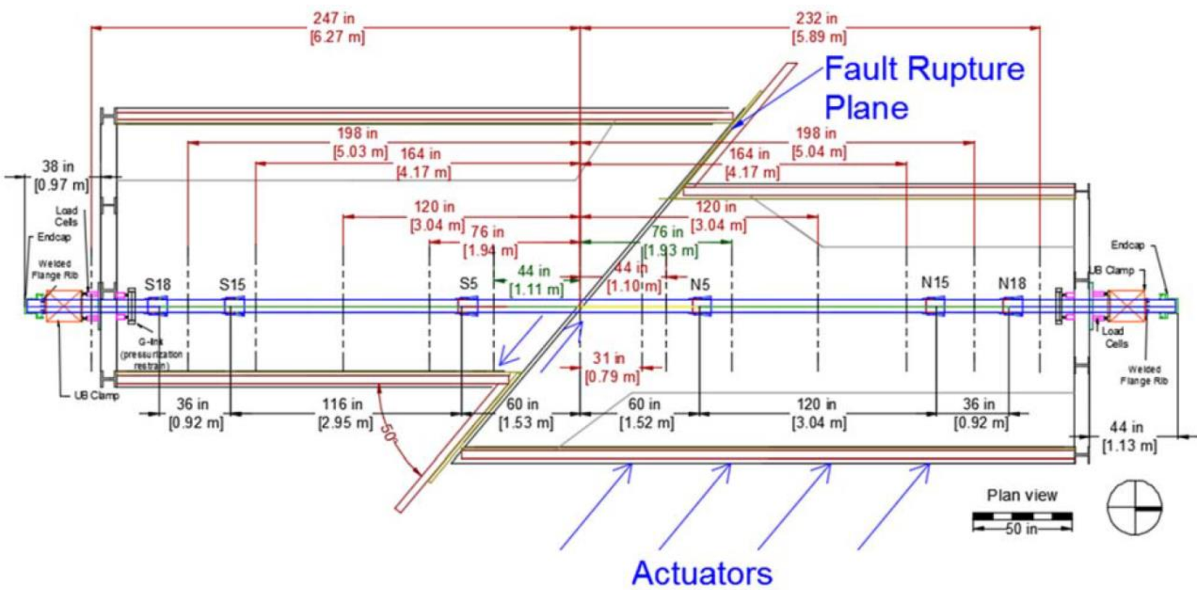

Figure 8. Large-scale split-box test set-ups for the 6-in GX-type ERDIP

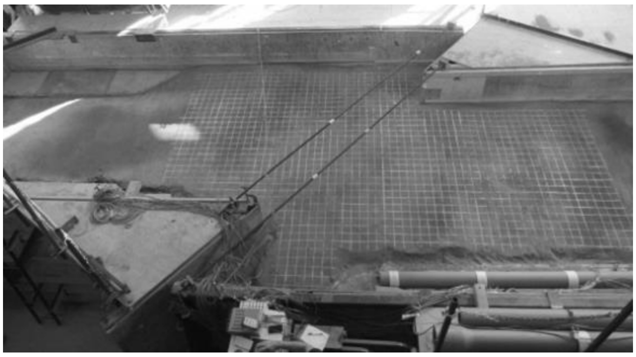

Figure 9. Large-scale split-box test set-ups for the 6-in GX-type ERDIP

TABLE II. BACKFILL SAND CONDITIONS

Items	Conditions
Type	Glacio-fluvial sand (produced by RMS Gravel Consisting)
Global average dry unit weight	16.6 kN/m^3 (105.6 lb/ft^3) with a standard deviation of 0.24 kN/m^3
Global average moisture content	3.7% with a standard deviation of 0.5%
50% particle diameter	0.59 mm
Coefficient of uniformity	3.35
Coefficient of curvature	0.83
Friction angle	42°

Results

Figures 10 and 11 show the test equipment and specimen, respectively, after the test. The behavior of the chain structure pipeline was observed such that the joints were extended and bent following the fault displacement.

Figure 12 shows the amount of joint extension versus fault displacement. Figure 13 shows the joint deflection versus fault displacement. The results are as follows.

(1) After the joints S5 and N5 located near the fault began to extend to their limits, the joints S15, N15, S18, and N18 on both sides of S5 and N5 began to extend to absorb the ground displacement. The behavior of the chain structure pipeline was observed.

(2) When the fault displacement was 0.96 m, all the joints in the boxes were fully extended. No leakage occurred in this step.

(3) When even larger displacement that exceeded the performance limit of the ERDIP was applied to the fully extended pipeline, joint S5 began to pull out. However, no leakage occurred immediately.

(4) When the fault displacement was 1.13 m, the amount of extension of joint S5 reached 210 mm. At this time, the end of the spigot passed the rubber gasket and leakage occurred.

According to the aforementioned results, we confirmed that the ERDIP pipeline could absorb large fault displacement well and no leakage occurred when the joint deflection and extended to a large extent. When both ends of the pipeline were fixed to the box and the fault displacement exceeded the performance limit of the joint, one of the joints began to pull out; however, no leakage occurred immediately. The water tightness performance of the ERDIP joint had a safety margin against pulling out.

Discussion

The pipeline used in the large-scale split-basin test could accommodate 28.5 in (725 mm) of axial extension, corresponding to an average tensile strain of 5.9% along the pipeline. Such extension is sufficiently large to accommodate the majority (more than 99%) of the liquefaction-induced lateral ground strains measured using high-resolution light detection and ranging (LiDAR) after each of the four major earthquakes during the recent Canterbury Earthquake Sequence (CES) in Christchurch, NZ [4]. These high-resolution LiDAR measurements provide a comprehensive basis for quantifying the ground strains caused by liquefaction on a regional basis for the first time. In order to place the CES ground strains in perspective, the levels of liquefaction-induced ground deformation measured in Christchurch exceeded those documented in San Francisco during the 1989 Loma Prieta earthquake and in the San Fernando Valley during the 1994 Northridge earthquake. They are comparable to the levels of most severe liquefaction-induced ground deformation documented during the 1906 San Francisco earthquake, which caused extensive damage to the San Francisco water distribution system. The tests confirm that the ERDIP joints can sustain large levels of ground deformation without leakage, the magnitude of which will vary depending on the ground deformation patterns and spacing of the joints.

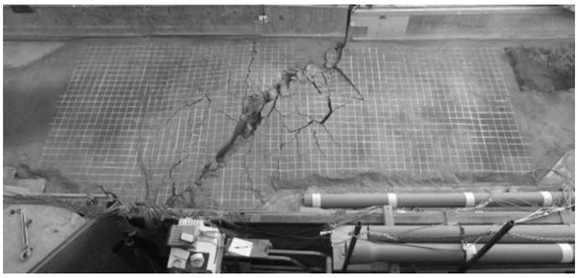

Figure 10. Test equipment after the test

Figure 11. Test specimen after the test

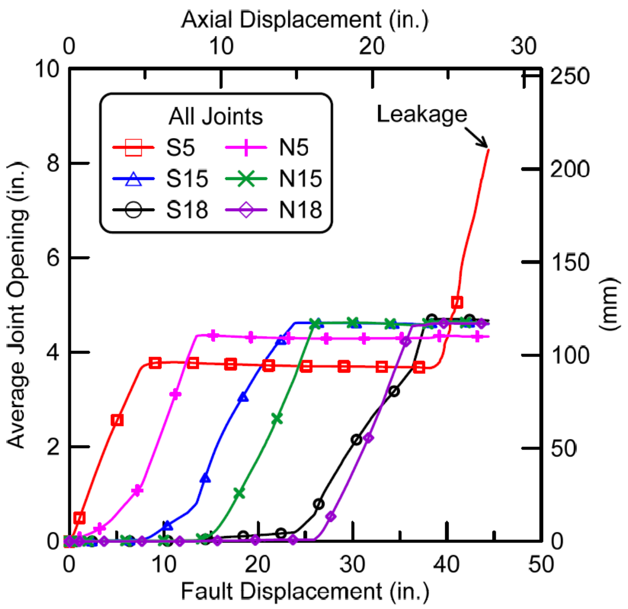

Figure 12. Amount of joint extension

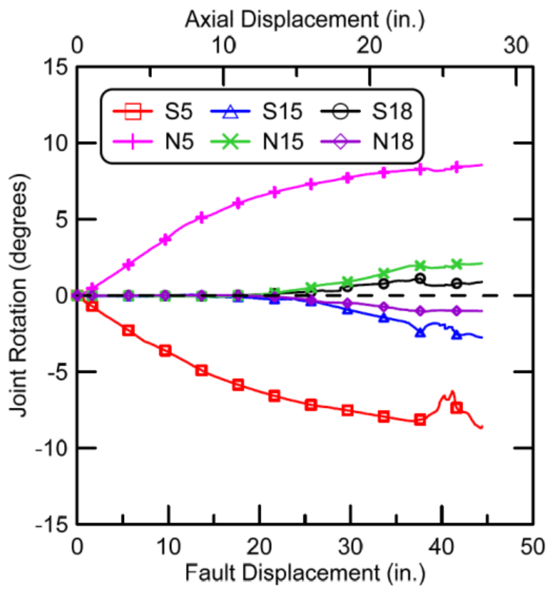

Figure 13. Joint deflection angle

CONCLUSION

In this study, we performed a four-point bending test and a large-scale split-box test using ERDIPs in order to observe the behavior of ERDIPs under severe conditions that exceed the performance limit of the joint. The following is a summary of the findings of this study.

(1) According to the result of the four-point bending test, it was not until the joint deflection reached 12.2° (which is approximately 1.5 times larger than the maximum joint deflection i.e., 8°) that no leakage was visually observed.

(2) According to the result of the large-scale split-box test, we confirmed that the ERDIP pipeline could absorb large fault displacement well and no leakage occurred when the joint deflected and extended to a large extent.

(3) According to the result of the large-scale split-box test, when both ends of the pipeline were fixed to the box and the fault displacement exceeded the performance limit of the joint, one of the joints began to pull out; however, no leakage occurred immediately. The precise performance of the ERDIP joint had a safety margin against pulling out.

(4) The aforementioned points (1) to (3) showed that a pipeline design method based on the performance limit of the ERDIP joint can result in a satisfactory advantage.

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Design Strategies of Transmission Trunks across Normal Fault-- A Case Study of Shanchiao Fault

Sheng-Shin Chu, Chin-Ling Huang and Kai-Ping Chang

ABSTRACT

According to the studies about active faults in metropolitan Taipei area, it has been indicated that Shanchiao Fault at the western rim of Taipei Basin is a highly active normal fault. Slip of the fault can cause deformation of shallower soil layers and lead to the destruction of infrastructures, residential building foundations and utility lines like transmission trunks near or across the influenced area.

Data on geological drilling and dating have been used to determine that a growth fault exists in the Shanchiao Fault. In an experiment, a sandbox model was built using noncohesive sandy soil to simulate the existence of a growth fault in the Shanchiao Fault and forecast the effect of the growth fault on shear-band development and ground differential deformation. The experimental results indicated that when a normal fault contains a growth fault at the offset of the base rock, the shear band develops upward beside the weak side of the shear band of the original-topped soil layer, and surfaces considerably faster than that of the single-topped layer. The offset ratio required is approximately one-third that of the single-cover soil layer.

The finite element method (FEM), finite difference method (FDM), and discrete element method (DEM) are usually used to analyze the fault deformation. However, when the normal fault is simulated, the new overlay was deposited after the fault slip; the finite element method (FEM) of the continuum is hard for normal fault analysis. In former study, a numerical simulation of the sandbox experiment was conducted using a discrete element method program, PFC2D, to simulate the upper-covering sand layer shear-band development pace and the scope of a growth normal fault slip. The simulation results indicated an outcome similar to that of the sandbox experiment.

According to the above test results, the Guandu(關渡) profile geometric simulation model established in this study, The PCF2D program was used to create a model for simulating SCF-8 and SCF-9 profiles and the shear-band propagation reached the particle surface in the final 1-m, 2-m, and 2.5-m slip of this growth normal fault numerical model. The simulation results can be applied to the design of construction projects near fault zones.

Keywords: Normal Fault; Shanchiao Fault; Discrete Element Method PFC2D; Transmission Trunks

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INTRODUCTION

The National Science and Technology Center for Disaster Reduction (NCDR) of Taiwan has analyzed for large-scale earthquake shocks in the Metropolitan Taipei area. The "Large-scale earthquake impact analysis in the Metropolitan Taipei area" (102- 104) conducted by NCDR for the "disaster impact" and "urban function failure", based on the existing technical deficiencies, the development of relevant assessment techniques to quantify the large-scale seismic shocks in Taipei, as a contingency plan basis and disaster prevention of a large-scale earthquake would hit.

The seismic focal mechanism is considered to be the Shanchiao Fault which is adjacent to the Metropolitan Taipei area. The magnitude of the earthquake is about 7.1, and the depth of the epicenter is about 10 km. The potential of the disability is also estimated. However, the NCDR's estimate of the above-mentioned water and electricity disability has not been conducted for Taipei Water Department (TWD), but TWD should establish its own earthquake-resistant assessment mechanism for the important equipment.

Fractured underground faults form transient and strong seismic waves that are transferred upward and laterally, causing strong ground motion (dynamic behavior) and permanent (or plastic) deformation of the ground surface (static behavior). These two mechanisms can cause severe damage to structures on the ground surface, particularly to those near the fault zone. Although the active reactions of structures induced by transient waves have been thoroughly investigated, ruptures near the ground surface caused by fault fracturing produce permanent or plastic deformation, thus severely distorting and damaging structures and utility pipelines.

As a result of the investigation of the devastating earthquake, it can be seen that the secondary disaster caused by the damage of the major traffic construction and the lifeline near the fault zone is the main cause of the loss of human life and property. The Metropolitan Taipei is the political and economic center of Taiwan, after Pleistocene, northern Taiwan was subject to the clockwise turning and westward extension effect of Okinawa trough, the east-west horizontal tension stress replaced the original compression stress and became the main tectonic stress that influences the crust deformation in northern Taiwan and therefore the thrust faults formed by compression stress during orogeny period has lost their activity mechanism and it is not possible to become active again in recent geologic period. However, according to the distribution map of Taiwan's active fault in 2010 published by the Central Geological Survey of the Ministry of Economic Affairs of Taiwan and a geological survey commissioned by Taiwan Power Company pointed out that this normal fault extends at least 40 km offshore as shown in Figure 1. Shanchiao Fault is a normal fault under the above-mentioned tensile stress in Taipei Basin area, therefore, Shanchiao Fault still remains its activity from the stress point of view.(Lin 2005)

Furthermore, the consequences of fault fractures in proximity to facilities such as reservoirs or nuclear power plants are even more catastrophic and these facilities cannot tolerate differential settlement. Therefore, the key design concept of crucial facilities is to avoid active faults. However, for linear facilities, such as roadways, utility lines, or transmission pipelines, it is impossible to avoid active faults because they must cross them to satisfy transportation and supply needs.

In order to improve the water supply system to New Tamsui residential area and the nearby area, TWD plan and construct a Dadu Transmission Trunks (Dadu line Project) which is a 1200mm water pipeline from the Dadu distribution reservoir to connect the Taiwan Water Company pipeline, and is expected to complete two work wells, a 2000 mm shield tunnel and 1200mm DIP in the shield tunnel, and also with the excavation, the total length of the shield tunnel is about 2,249 m. The construction site is located at the Guandu Plain in the northwestern margin of the Taipei Basin. According to the drilling survey of SCF-7, SCF-8 and SCF-9 conducted by the Central Geological

Survey(CGS) , National Taiwan University's Prof. Chen drawed the Guandu section of the Shanchiao fault (as shown in Fig. 2), and determined the position of the fault which is expected to pass the west side of the Dadu Transmission Trunk's 1k + 500 ~ 1k + 600 around. The impact of this activity of the fault has become a very worthy subject.

SURVEY OF RESEARCH REGIONAL TOPOGRAPHY AND GEOLOGY

Dadu line project is located in the Guandu Plain in the northwestern margin of the Taipei Basin. The topography is gentle and the altitude is between 0m-10m. The stratum is dominated by modern alluvial (the Songshan layer of the surface of the Taipei Basin) consist of the nonconsolidation of sand accumulation. Near the end of the pipeline is the Datun volcano area, the formation is mainly the Andesite volcanic breccia.

According to the survey data of the CGS in 2000 and 2010, there are a few faults get through this area, which are Xinzhuang fault, Jinshan fault and Shanchiao fault from the west to the east, and only the Shanchiao fault is the second type active fault, the others are Non-active. The Xinzhuang fault is about 0.2km passed on west of the site, the Shanchiao fault and Jinshan fault pass through the pipeline, and are covered by the Songshan layer of the basin.

Following a single rupture event of a normal fault, the sedimentary layer typically forms from the footing and hanging-wall sides of the normal fault. Because the sedimentary layers in both sides are sufficiently thick to become a single sedimentary layer, the sedimentary layer with the normal fault underneath is thus considered the growth normal fault (Roberts, Yielding et al. 1990). Several rupture events and sediment layers above the normal fault are also possible. Previous studies have indicated that the Shanchiao Fault is a growth normal fault based on drilling and dating information (Huang, Rubin et al. 2007, Chen, Lee et al. 2010). The growth fault sketch map is as shown in Fig.3.

METHODOLOGY

The authors conducted laboratory testing to explore the shear-band propagation in growth normal faults(Chu, Lin et al. 2013). Based on the test results, it is concluded that if there is any seismic activity of a growth normal fault with sandy material, with a smaller offset displacement from the fault tip, although the depositional thickness of the upper layer might be very thick, the shear band could still be propagated to the ground surface as shown in Fig.4.

Moreover, when the fault ruptures, both the rock mass (reverse fault, etc.) or the deposited soil (normal fault) will crack to form the shear zone or the fault zone belt. The strength of soil in this zone (fault gouge) should be weaker than that of general soil. Numerical simulation using continuum if does not consider this phenomenon, the soil strength properties will affect the impact of the simulation results biased the safety side and misjudgment fault rupture caused by future.

In order to properly simulate this phenomenon, the authors collected the literature found that use of discrete element method can do better than a continuum simulation on fault as a good performance of the discrete characteristics of the material. In recent years there have been many studies of fault modeling using this Discrete Element Method (DEM).(Seyferth and Henk 2006, Chang, Lee et al. 2013, Yang, Hu et al. 2014). In this study, the authors established numerical models using the discrete element method, PFC 2D that simulated geological boring profiles SCF-8 and SCF-9 located in the Guandu area, to compare the possible depths of the shear band in the sedimentation layer above the normal fault.

The authors hope that the stress and strain phenomena and distribution of the soil can be observed as the design basis of engineering and disaster mitigation, but the discrete element method can now observe the particle movement and pore change in the simulation area by using the observing circle or triangular mesh to infer stress changes. However, the application of the aforementioned in soil strain observation of the stimulation area is still inadequate. Because the extent of shear strain could not be shown in the PFC2D program. The shear bands were able to be distinguished by strain ellipse according to the analytical method of structural geology suggested by Ramsay (Ramsay and Huber 1983), using MATLAB software as a postprocessor to translate a grid-history text-data file which was produced through PFC2D simulation. The appropriate number of particles in the models comprised a square area, as shown in Fig. 5, which created a circular area in the center of the square. When the square is affected by single shears, the circle in the center becomes an ellipse, referred to as the finite strain ellipse, as shown in Fig. 6. The finite strain ellipse obtains the value of the shear strain of the original square affected by the shearing effect.

$$R = \frac{a}{b} \qquad (1) \qquad \Delta_A = \frac{A_{after}}{A_{before}} \qquad (2) \qquad \frac{a}{r} = R(1+\Delta_A) \qquad (3) \qquad \tan 2\theta' = -\frac{2}{\gamma}$$

(4)

where R is the ellipticity; a is the long radius of the finite strain ellipse; b is the short radius of the finite strain ellipse; Δ_A is the volume strain; A_{after} is the area of the original square; A_{before} is the area of the parallel square after shearing; r is the radius of the original circle; θ' is the dip angle of the finite strain ellipse; and γ is the shear strain, as shown in Fig. 6. The ellipticity is the ratios of the long and short axes of the finite strain ellipse. This physical quantity can be used to represent the probe affected by the shearing reaction. The larger the shearing force, the narrower and longer the finite strain ellipse is, and the greater the ellipticity is.

The finite strain ellipse can fully describe the conditions of objects being sheared. The ellipticity, shear strain γ, the dip angle of the finite strain ellipse, volume strain, and the relationships of maximum extension are shown in Table 1. In this study, ellipticity was primarily used to describe the level of reaction when the probe is sheared. Diverse ranges of ellipticity have various color reactions. In this reaction, the ellipticity range of 1.03 (light green color) or above indicated shearing bands.

RESULTS OF THE PFC2D SIMULATION OF GROWTH NORMAL FAULT PROFILES NEAR THE GUANDU AREA

The PCF2D program was used to create a model simulating SCF-8 and SCF-9 Guandu profiles, in which the microscopic coefficients of the numerical model are shown in Table 2. The model involved creating a normal fault by triggering a 1.06 m offset from the fault tip, and allowing a layer of particles to deposit a 0.68-m-thick layer above the footwall and a 1.74-m-thick layer above the hanging wall of the normal fault. A second 1.06 m offset was triggered from the fault tip to create another normal fault offset displacement, allowing another layer of particles to deposit a 0.68-m-thick layer above the footwall and another 1.74-m-thick layer above the hanging wall of the normal fault. The slip and deposition were repeated 205 times so that footwall sediments deposited over 139.4 m and hanging wall sediments deposited over 356.7 m to simulate the SCF-8 and SCF-9 profiles is shown in Fig. 8.

The shear-band propagation of Guandu profiles after slip 1.06m repeatly 205 times so that footwall sediments deposited over 139.4 m and hanging wall sediments deposited over 356.7 m is shown in Fig. 9.

According to the research of Wells and Coppersmith (Wells and Coppersmith 1994), the normal fault slip induced earthquake magnitude 7.1, the maximum displace is 2.6m based on empirical estimation as below:

$$\log(MD) = -5.90 + 0.89 * M \qquad (5)$$

The shear-band propagation of Guandu profiles after slip 2.0m and 2.5m repeatly 205 times so that footwall sediments deposited over 139.4 m and hanging wall sediments deposited over 356.7 m is shown in Fig. 10. and Fig. 11.

CONCLUSION AND DISCUSSION

The results of numerically simulating a growth normal fault around Guandu area indicated that with a depositional layer on top of the deformed normal fault, another 1.06m offset event from the normal fault tip can propagate the shear band to the ground surface with a width of 64m. In addition, the distance of the vertical projection from the fault line to the shear band is 69m as shown in Fig.12.

The results of numerically simulating around Guandu area indicated another 2.0m offset event from the normal fault tip can propagate the shear band to the ground surface with a width of 92m. The distance of the vertical projection from the fault line to the shear band is 42m. In addition, 2.0m offset event from the normal fault tip can propagate the shear band to the ground surface with a width of 93m. The distance of the vertical projection from the fault line to the shear band is 41m.

In a growth normal fault, the offset occurrence from the fault tip causes the shear band to continue from the end of the old shear band to develop upward. This explains why the shear band developed to the ground surface with a smaller offset ratio compared with a regular-normal fault.

The geotechnical and geological survey of the Shanchiao Fault indicated that it remains a highly-active normal fault. Drilling and dating information further proved the existence of a 100 to 700 m thick depositary layer on top of the normal fault, which accumulated after several rupture and deposition events. Although the fault tip might be deeply buried, based on the findings of this study for sandy material, the shear band with a small offset ratio at the growth normal fault tip could develop to the ground surface. Therefore, the ground deformation characteristics near Dadu line that are adjacent to a potential growth normal fault must be considered to avoid any catastrophic failures of the Transmission Trunks.

Table1 Definition of the finite strain ellipse

Finite strain ellipse							
ellipticity	1.0	1.5	2.0	2.5	3.0	3.5	4.0
γ	0%	41%(4%)	71%(7%)	95%(10%)	115%(13%)	133%(16%)	150%(>18%)
θ'	None	-39.2°	-35.2°	-32.3°	-30.0°	-28.1°	-26.6°
Max elongation	1.0	1.5	2.0	2.5	3.0	3.5	4.0
color(砂箱)	1.0~1.5	1.5~2.0	2.0~2.5	2.5~3.0	3.0~3.5	3.5~4.0	4.0~
color(剖面)	1.0~1.03	1.03~1.06	1.06~1.09	1.09~1.12	1.12~1.15	1.15~1.18	1.18~

Table2 The microscopic parameters of the numerical models

Parameters	Values
Ball radius/percentage of weight (m/%)	1.0m/(25%) 、0.9 m/(25%) 、0.8 m/(25%) 、0.7 m/(25%)
Normal stiffness of ball, k_n (N/m)	$k_n = k_{no}(\frac{v'}{v'_o})^{0.4}$; k_{no}=4.08_10^6 N/m
Shear stiffness of ball, k_s (N/m)	1/3k_n
Normal stiffness of wall	6.0_10^{12} N/m
Shear stiffness of wall	6.0_10^{12} N/m
Friction coefficient of between ball	0.577 (_ $= 30^o$)
Friction coefficient of between ball and side wall	0.0
Friction coefficient of between ball and base wall	0.364
Density of ball (kg/m³)	2600

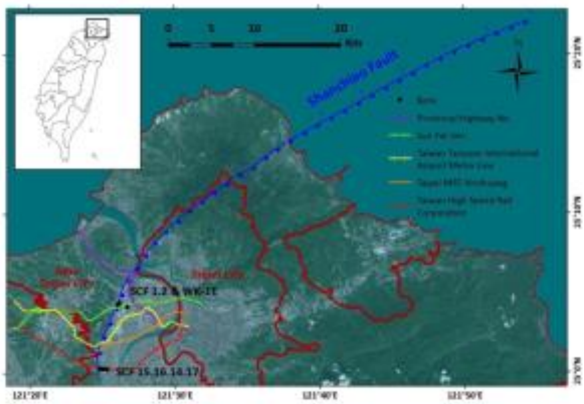


Fig. 1. Trace of Shanchiao Fault.

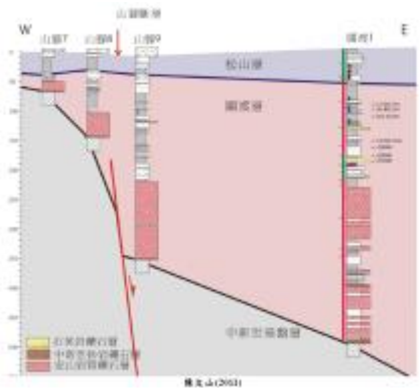


Fig.2. The borehole profile of the SCF-7, SCF-8, and SCF-9 (plotted by Chen, 2011)

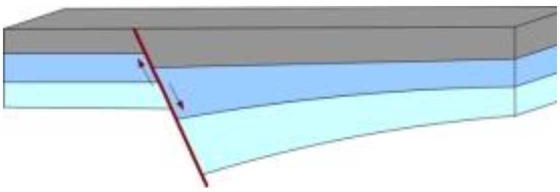


Fig.3. The sketch map of growth fault

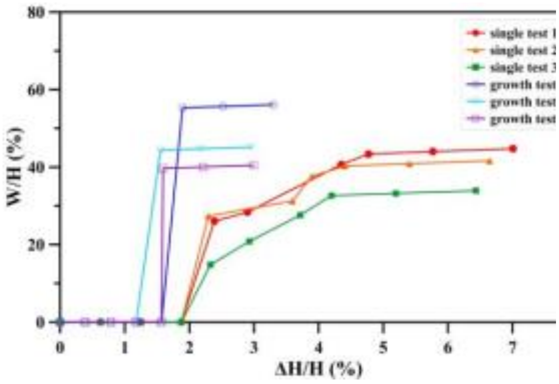


Fig. 4. Relationship of offset ratio (ΔH/H) and normalized influenced width (W/H) for Type 1 (single) and Type 2 (growth) tests.

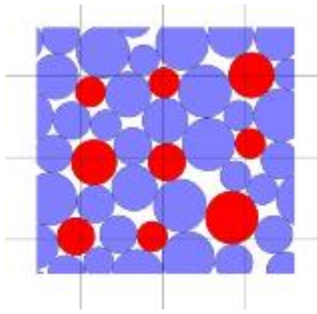


Fig. 5. The finite strain ellipse grid of PFC2D

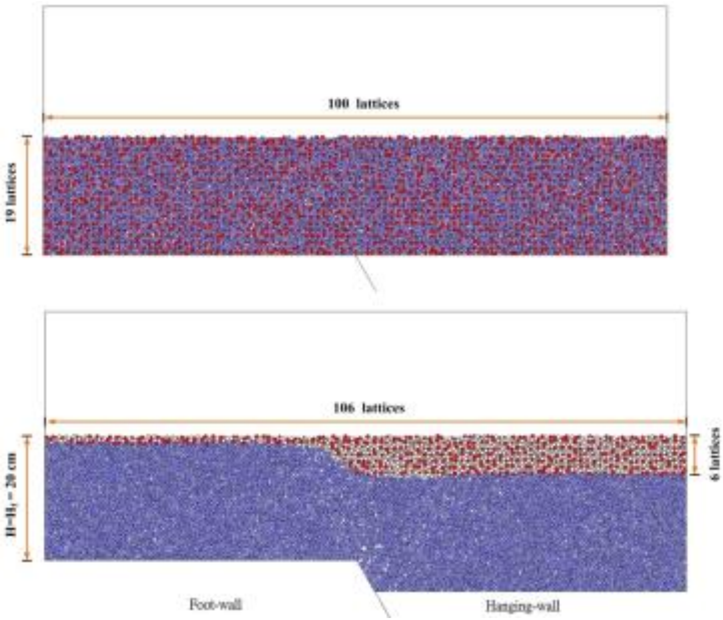


Fig. 6. The finite strain ellipse grid in normal growth fault model of PFC2D

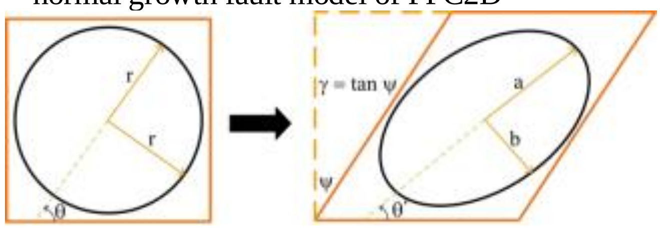
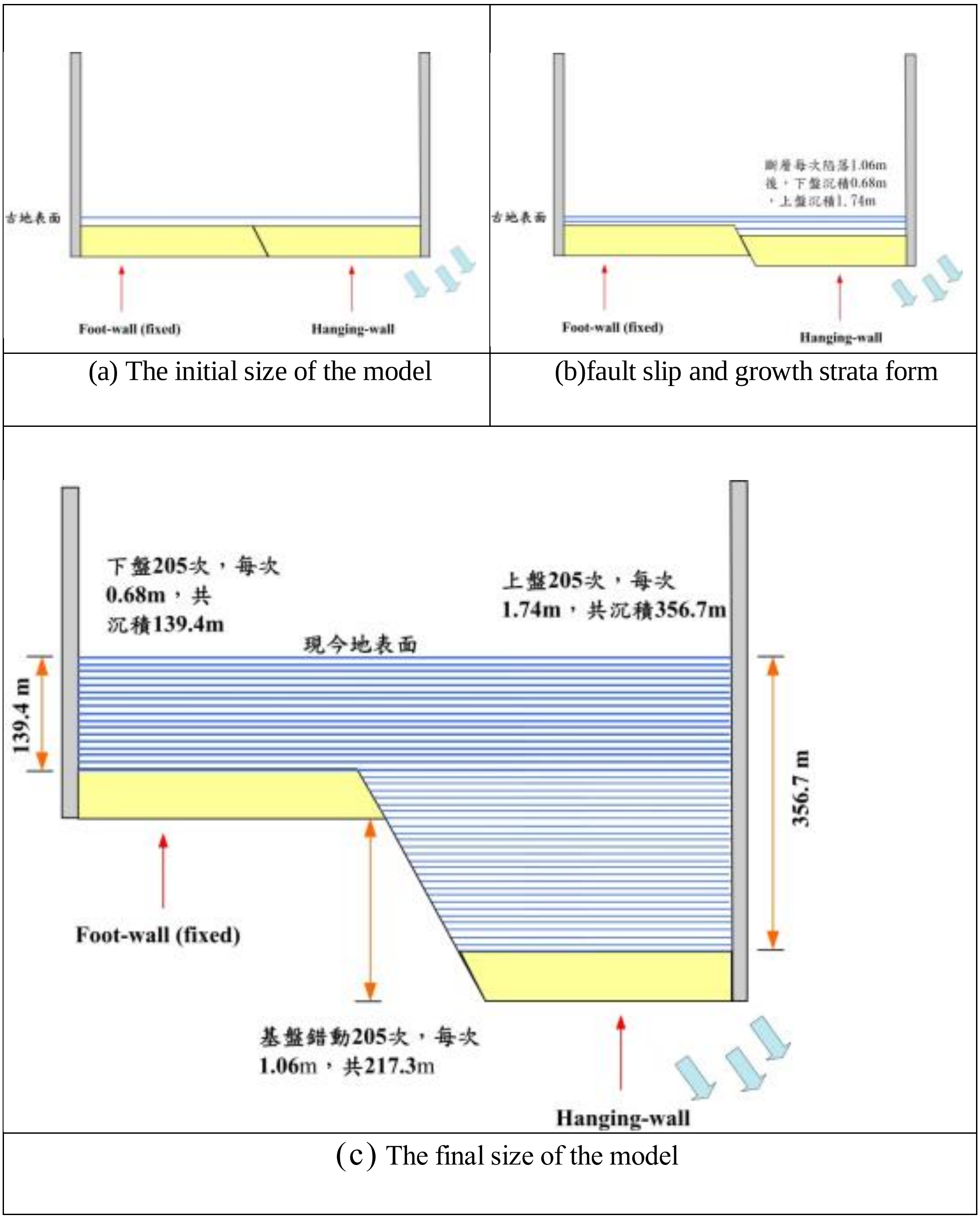


Fig. 7. Using ellipse to describe the shearing reaction of squares (modified from (Ramsay and Huber 1983)

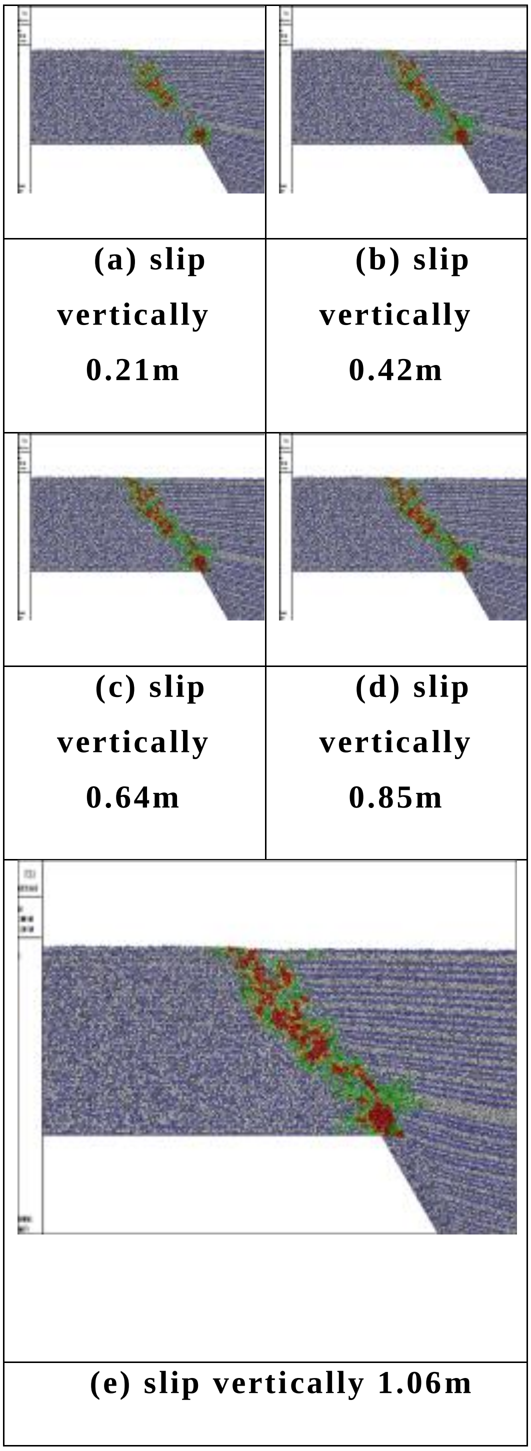


(a) The initial size of the model

(b)fault slip and growth strata form

(c) The final size of the model

Fig. 8. Guandu profile numerical simulation process and scale illustration



(a) slip vertically 0.21m

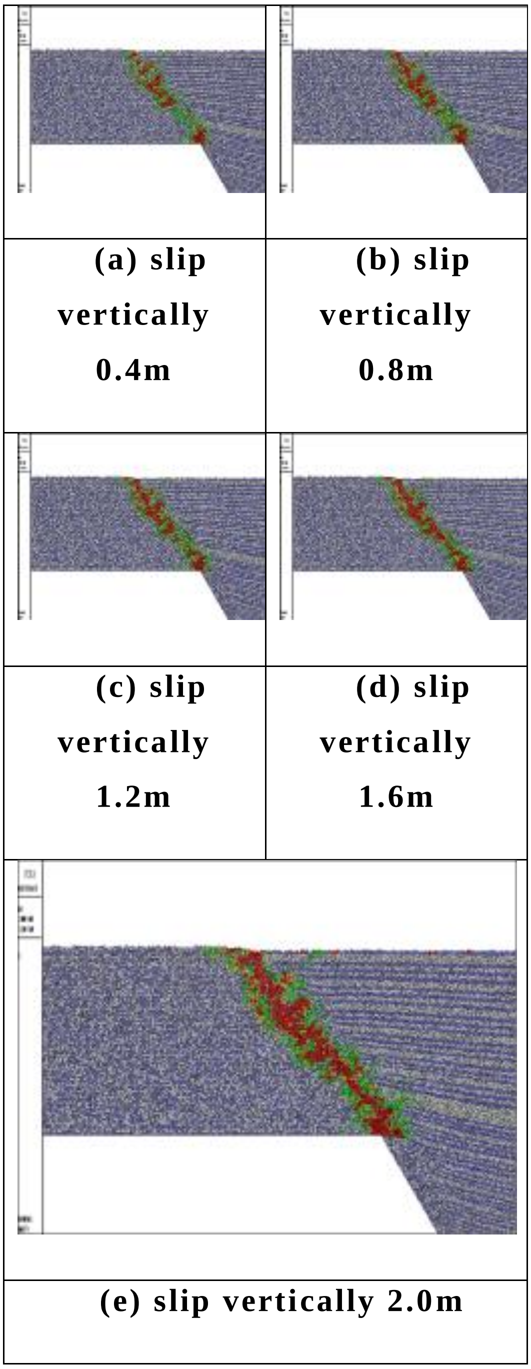
(b) slip vertically 0.42m

(c) slip vertically 0.64m

(d) slip vertically 0.85m

(e) slip vertically 1.06m

Fig. 9. Process of Guandu profile numerical simulation slip vertically 1.06m



(a) slip vertically 0.4m

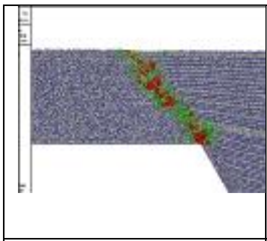
(b) slip vertically 0.8m

(c) slip vertically 1.2m

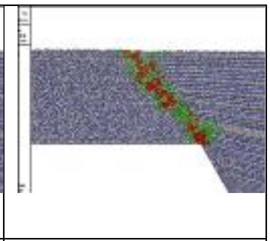
(d) slip vertically 1.6m

(e) slip vertically 2.0m

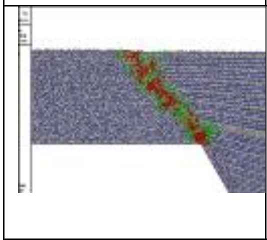
Fig. 10. Process of Guandu profile numerical simulation slip vertically 2.0m



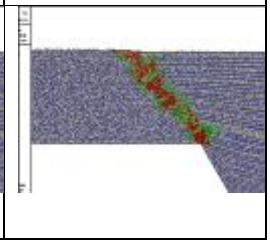
(a) slip vertically 0.5m



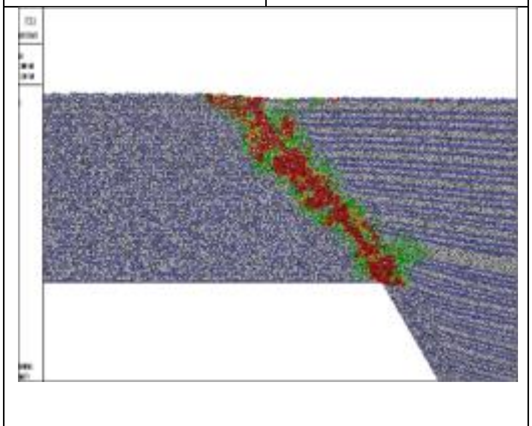
(b) slip vertically 1.0m



(c) slip vertically 1.5m



(d) slip vertically 2.0m



(e) slip vertically 2.5m

Fig. 11. Process of Guandu profile numerical simulation slip vertically 2.5m

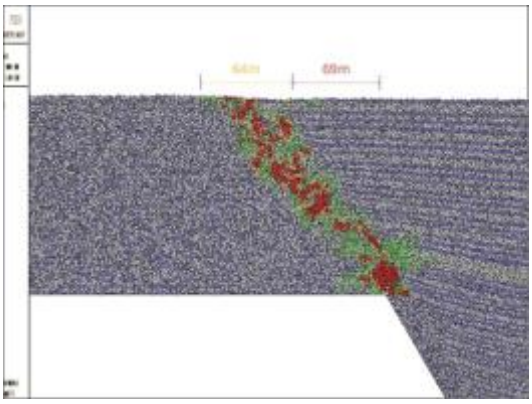


Fig. 12. The shear band propagation by the fault slipped of PFC2D Guandu profile model

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Performance Test of Steel Pipe for Crossing Fault in United States

Nobuhiro HASEGAWA, Hayato NAKAZONO, Brad P. Wham,

and Thomas D. O'Rourke.

ABSTRACT

This report describes the performance tests of Steel Pipe for crossing Fault (SPF), which is an "on fault earthquake-resistant countermeasure" pipe, conducted at Cornell University. In the test results, despite applying deformation of several times the design value, the pipe did not crack or leak and more than 80% of the pipe cross section where water can pass was secured in all the tests.

I. INTRODUCTION

There are about 2000 faults in Japan. Similarly, there are many huge active faults such as the San Andreas Fault on the West Coast of the United States. Particularly in California, large-scale earthquakes are expected in the future, and since many buried water pipelines cross faults, local water utility companies are studying fault countermeasures for underground waterworks pipelines.

Steel Pipe for crossing Fault (SPF) is a fault countermeasure for buried water pipelines. SPF is manufactured by processing steel pipes for waterworks into a special wavy shape (comparable to the wavy part of a bendable drinking straw) so that the fault displacement which occurs during an earthquake can be absorbed by concentrating the deformation on the wave-shaped section, rather than attempting to resist the deformation. We have conducted tests in Japan, including underground tests, and confirmed the performance of Steel Pipe for Crossing Faults.

This report will give an overview of Steel Pipe for Crossing Fault and describe the performance tests conducted at Cornell University.

II. OVERVIEW OF STEEL PIPE FOR CROSSING FAULT

Damage to Fault Crossing Pipeline

Figure 1 shows an example of damage to a buried steel pipeline (200A diameter steel pipe) crossing a fault in the Taiwan Earthquake of 1999. When a slip occurs at the fault plane, it is likely to be thought that the transverse pipeline undergoes shear deformation at the fault plane due to the shearing force of the ground.

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However, in the actual pipeline shown in Figure 1, bent portions (plastic hinges) formed at positions away from the fault plane, and the whole pipeline exhibited a Z-shaped bending deformation.

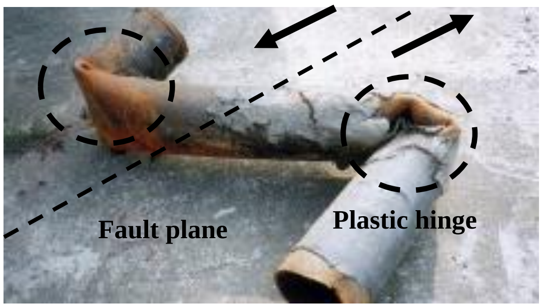


Figure 1. Damage to pipeline in fault cross-section

The pipe damage shown in Figure 1 is an example of damage to a buried steel pipeline crossing a fault. As shown in the figure, the pipe was bent plastically in the shape of the letter "Z." To identify the mechanism of Z-shaped plastic deformation, a finite element analysis of the pipeline-soil system shown in Figure 2 was done. The pipeline and soil were modeled with shell and solid elements, respectively, and forced displacement was given so that fault displacement occurred in the direction indicated by the arrow. In the analysis, as shown in Figure 2, buckling occurred symmetrically on both sides of the fault at a certain distance from the fault plane, and the cross section does not necessarily show deformation at the fault plane. These analytical results were consistent with the observation results shown in Figure 2.

The analytical results indicate that a pipeline will rotate about the fault plane if fault displacement occurs. When this occurs, soil shear force occurs along the fault plane, but since the stiffness of the pipe is sufficiently large compared with the soil shear force, buckling does not occur at the shear plane. However, because of fault displacement, rotating force acts on the pipe so that bending occurs on both sides of the fault plane at points certain distances from the fault plane. When the full plastic moment is reached at the points where the maximum bending moment occurs, buckling begins and plastic hinges are formed. As shown in Figure 2, bending deformation is concentrated only at these plastic hinges. Therefore, it was thought that the most effective countermeasure for fault displacement is to absorb the bending at the position where the maximum bending moment occurs. Based on this concept, we developed “Steel Pipe for crossing Fault,” which fully utilizes the elastoplastic deformability of steel pipes, as a structure that absorbs bending deformation.

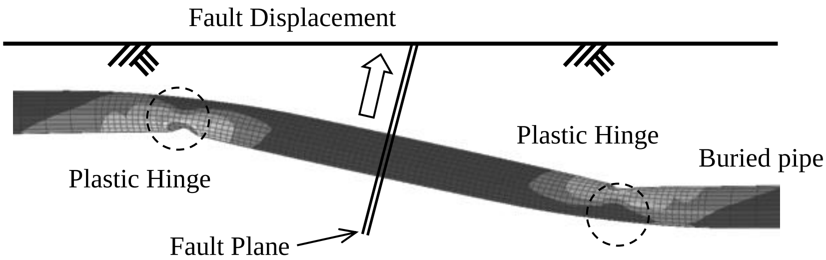


Figure 2. Deformation of buried pipeline caused by fault displacement

Basic Mechanism of Steel Pipe for Crossing Fault

As described above, the damage to a pipeline caused by fault displacement takes the form of concentrated local bending deformation at the positions where plastic hinges are formed. This suggests that the water flow function of the whole pipeline can be maintained if a mechanism which is capable of absorbing bending deformation corresponding to the fault displacement is provided at these positions. Therefore, as shown in Figure 3, short pipes with a convex part (hereinafter referred to as “wave-shaped section”) are prepared in advance as an initial deformation in the steel pipe, and by placing these wave-shaped sections at the positions of the maximum bending moment caused by fault displacement, it is considered possible to control the position of occurrence of deformation and the deformation mode.

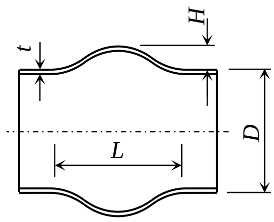


Figure 3. SPF wave-shaped section

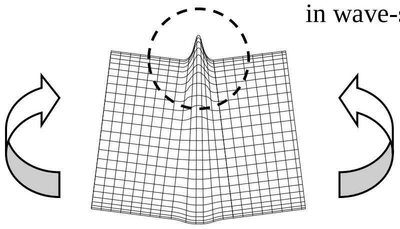


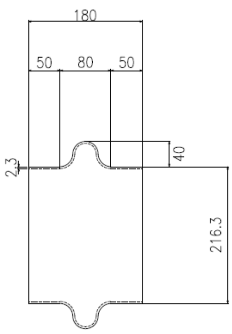
Figure 4. Deformation of wave-shaped section

Figure 4 schematically shows the deformation of the wave-shaped section. The upper side of the pipe (compression side) shows deformation such that the inner walls come into contact with each other when bending deformation occurs, while the lower side of the pipe (tension side) shows deformation in which the wave-shaped section extends and the convex part becomes flat. Since both deformation modes are simple, if the deformation range is restricted, it is possible to prevent the reduction of the water flow function due to blockage of the pipe cross section and cracks due to buckling. Furthermore, because the fault displacement necessarily acts in one direction, there is no concern of cracking due to low cycle fatigue.

Although the steel pipes in the wave-shaped sections deform plastically in order to absorb fault displacement of several meters as bending deformation, the pipeline can still deliver water without leakage after an earthquake. Since the water flow function can be maintained for a certain period of time until more urgent emergency/restoration work is completed, the survey, diagnosis and restoration of the wave-shaped sections can be handled after the disaster.

III. PERFORMANCE TESTS

In order to confirm the performance of Steel Pipe for crossing Fault, we carried out an axial compression test, axial tensile test, bending test and underground test at Cornell University (New York, USA). The geometry of the specimen used in the tests is shown in Figure 3-1.



OD : 213.6 mm

t : 2.3 mm

Material : SS400

Wave height : 40mm

Wave width : 80mm

Figure 3-1. Geometry of Steel Pipe for crossing Fault (SPF) specimen used in tests

Axial Compression Test

The axial compression test was carried out using the test equipment shown in Figure 3-2 to confirm the deformation capacity in the axial compression direction. In order to deform the specimen in the planar direction, a frame was made using molded steel. The specimen and actuator were installed in the frame, and the specimen was subjected to axial compression deformation.

Both ends were joined by flanges to apply pressure (0.55 MPa) to the specimen, and axial compression deformation was applied by using an actuator. The maximum stroke of the actuator was 100 mm, and it was possible to increase the amount of axial compressive deformation by replacing the actuator.

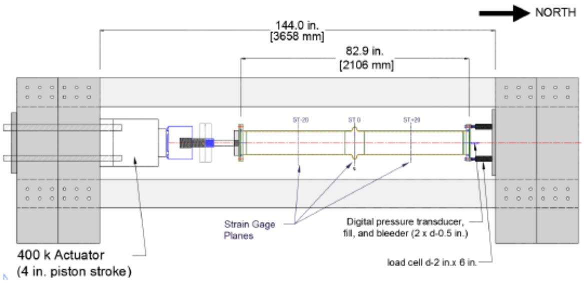


Figure 3-2. Test equipment (axial compression

Figure 3-3 is a deformation image of the allowable displacement of 47.2 mm (at the time of inner surface contact). This deformation is simple deformation in which the wave-shaped section gradually rises, and there were no cracks or leaks.

Figure 3-4 is a deformation image of the displacement of 86.4 mm, which is approximately twice as much as that at inner surface contact. After inner surface contact, the reaction force increased and the straight pipe part began to buckle, but it did not reach cracking and leaking.

Figures 3-5 and 3-6 compare the test results with the results of a FEM analysis. As these figure shows, the deformation is almost the same, and the lateral collapse phenomenon of the wave-shaped section can be reproduced in the FEM analysis.

Figure 3-3. Deformation image (at inner surface contact)

Figure 3-4. Deformation image (final)

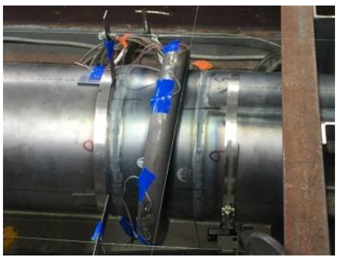


Figure 3-5. Deformation image (at inner surface contact)

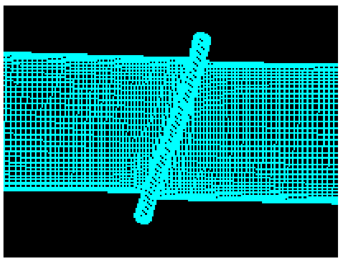


Figure 3-6. Deformation image (final)

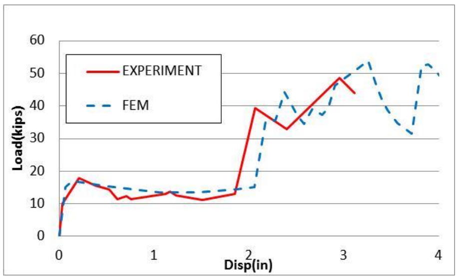


Figure 3-7. Relationship between load and displacement

Figure 3-7 shows the relationship between the load and displacement in the test and in the FEM analysis. The test and FEM analysis results show extremely good agreement. Since Steel Pipe for crossing Fault is made only of a single material (SS400) and the shape is simple, it can be expressed accurately by FEM analysis.

Axial Tensile Test

A demonstration test was carried out to confirm the deformation capacity in the tensile direction. Figure 3-8 shows the test setup. The equipment used in the axial tensile test was basically the same as in the axial compression test, but an adjustment jig was installed at the connection between the specimen and the actuator, and the maximum stroke of the actuator was 100 mm, but could be extended up to a maximum of 400 mm by replacement.

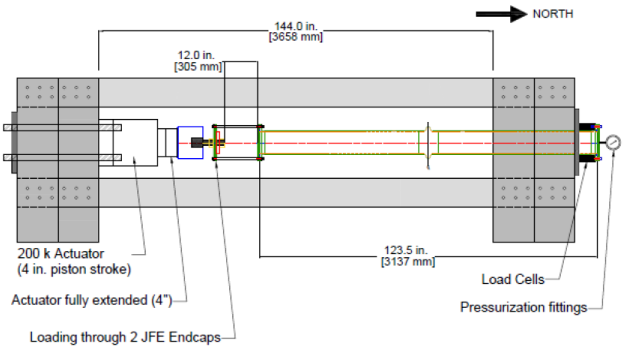


Figure 3-8. Test equipment (tensile

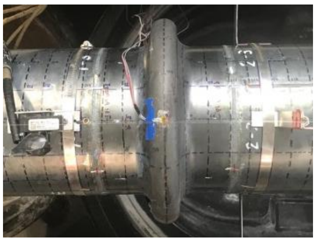


Figure 3-9. Initial state

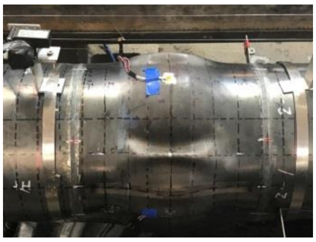


Figure 3-10. Maximum deformation

Figure 3-11. Break (Flange welded part)

The different conditions of the pipe are shown in Figure 3-9 to Figure 3-11. Figure 3-10 shows the final deformation of the wave-shaped section. As shown in the figure, as deformation progresses, the crest height gradually decreases and approaches the straight pipe. Due to the difference in the circumferential lengths of the wave-shaped part and the straight pipe part, creases appear at approximately equal intervals in the peripheral cross section. When pulled further from this state, the deformation in the wave-shaped section dissipates and the deformation moves to the straight pipe part. However, when the straight pipe part starts to expand, the deformation concentrates on the joint (welded part) with the flange. In this test, rupture occurred at the flange welded part on the south side.

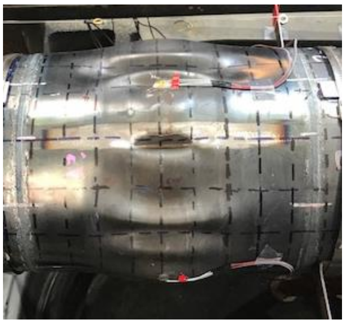


Figure 3-12. After deformation (test)

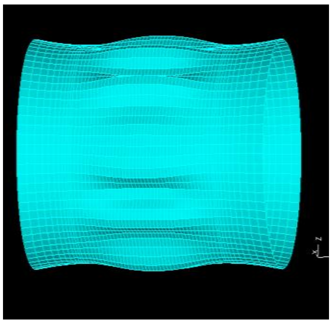


Figure 3-13. After deformation (FEM)

Figures 3-12 and 3-13 are comparisons of the deformation in the test and in the FEM analysis. As the figures show, the deformation is almost the same, and the actual deformation under axial tension can be reproduced sufficiently by FEM. Figure 3-14 shows the *P*-δ curve.

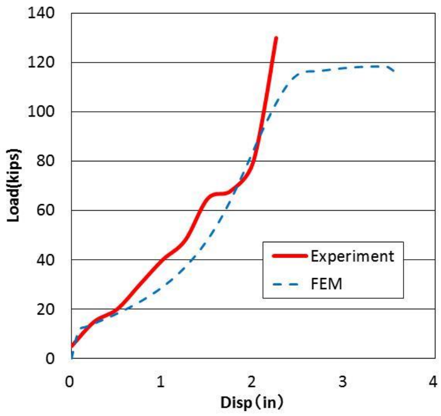


Figure 3-14. *P*-δ curve

Bending Test

In order to confirm the bending deformation capacity of the wave-shaped section, a four-point bending test was performed using the test equipment shown in Figure 3-15. This equipment has a structure in which the outer fulcrum part is movable upward, and all the fulcrums are pin fulcrums and there are no fixed parts. The maximum stroke of the test equipment in one stroke is 300 mm, and replacement is possible when the stroke exceeds this maximum.

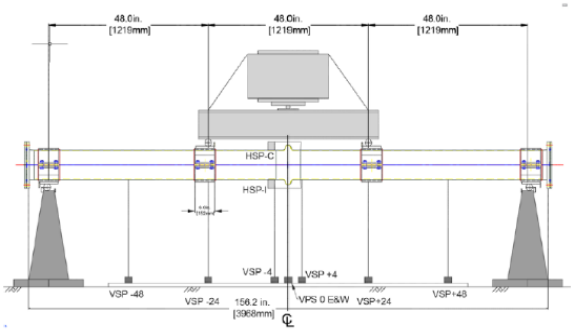


Figure 3-15. Test equipment (bending test)

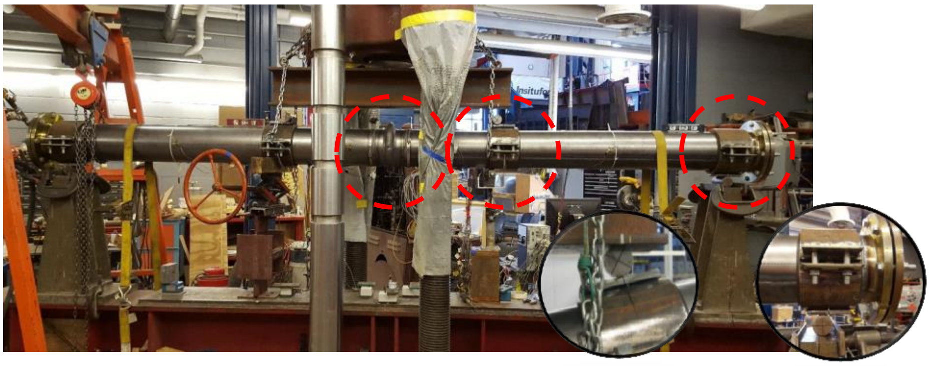


Figure 3-16: Actual setup of test equipment

The test results are shown in Figures 3-17 and 3-18. Figure 3-17 is a deformed image of the pipe with the allowable bending angle (18° at inner surface contact), showing that the upper wave-shaped section rises gradually and deforms uniformly on the left and right. Figure 3-18 shows the deformation at the stroke limit of the test equipment, when the bending angle reached 36.6° (about twice the allowable bending angle). Even in this state, the deformation of the wave-shaped section was almost symmetrical, and no cracks or leaks were found. Figures 3-19 and 3-20 show the deformation image of the FEM analysis. As shown in Figure 3-19, the deformation at the time of contact of the inner surfaces was almost symmetrical, but in the final deformation shown in Figure 3-20, the upper side of the wave-shaped section collapsed and started to deform irregularly.

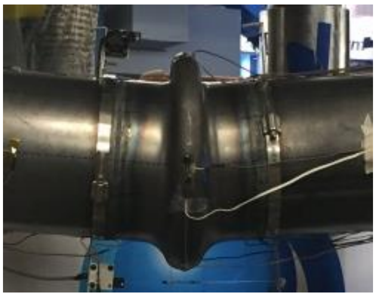


Figure 3-17. Deformation image (at inner surface contact)

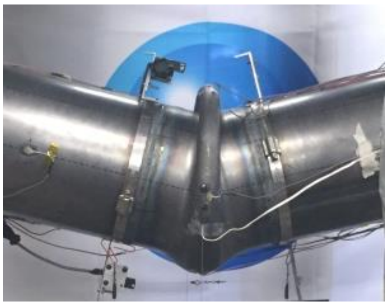


Figure 3-18. Deformation image (final)

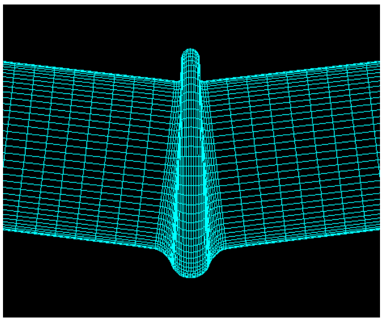


Figure 3-19. FEM deformation image (at inner surface contact)

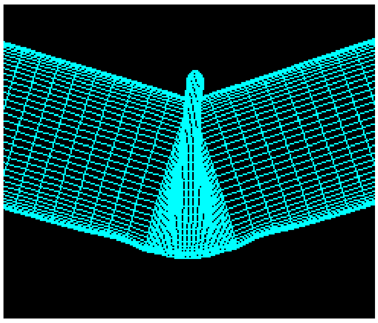


Figure 3-20. FEM deformation image (final)

Figure 3-21 shows the relationship between the bending moment M and bending angle θ. As shown in this figure, the analysis value and the experimental value were almost the same before contact of the inner surfaces, but after contact, the bending moment increased in the FEM analysis but converged to a constant value in the experiment.

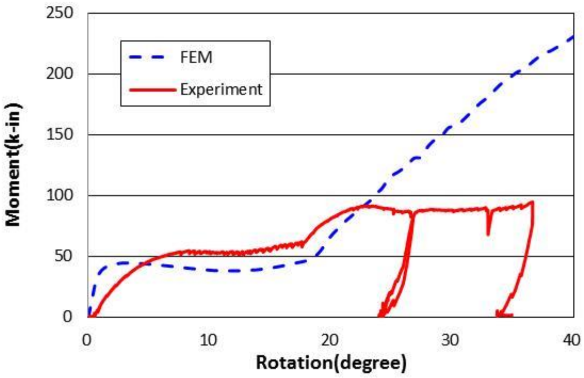


Figure 3-21. *M*-*θ* curve

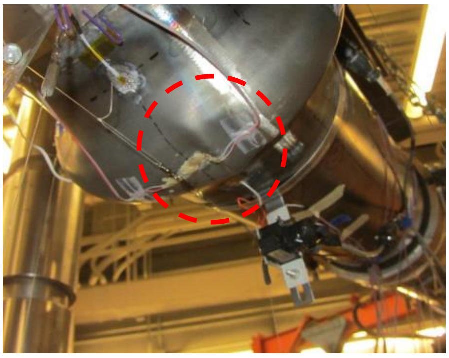


Figure 3-22. Generation of buckle (bending angle 23°)

Underground Test

In order to confirm the deformation capability of the wave-shaped section in the buried condition, an underground test was conducted using the equipment shown in the Figure 3-22. The installation interval of the wave-shaped sections was determined by a FEM analysis, which was carried out beforehand. The test equipment consisted of two soil tanks, one fixed and the other movable, as shown in the figure. Fault displacement (610 mm) was simulated by moving the movable soil tank in the direction of the fault angle (50°) by using actuators.

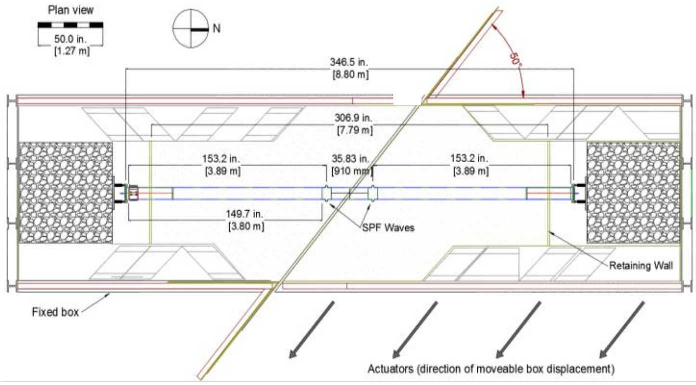


Figure 3-23. Test equipment (underground test)

Figure 3-23 shows the condition of a pipeline installed and backfilled in the test equipment. From this state, fault displacement was given along a fault plane with an angle of 50°.

Figure 3-24 shows the deformed state of the pipeline after applying fault displacement of 610 mm. As shown in figure, the pipeline bent at the wave-shaped sections equidistant from the fault plane and absorbed the fault displacement.

Figures 3-25 and 3-26 show the comparison of the condition before and after deformation. From these figures, it can also be confirmed that the wave-shaped sections absorbed the fault displacement efficiently. The bending angle of the wave-shaped section at final deformation was 42°, and cracks and leaks did not occur even when the pipe was deformed to approximately four times the allowable bending angle (inner surface contact angle of 9°).

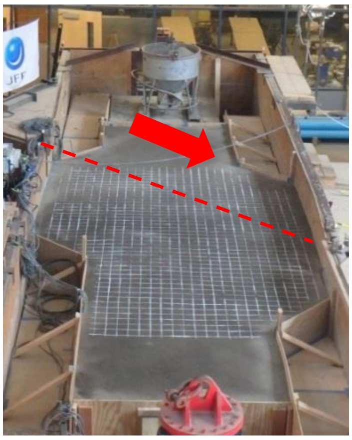


Figure 3-23. Before test

Figure 3-24. After test

Figure 3-25. Before deformation

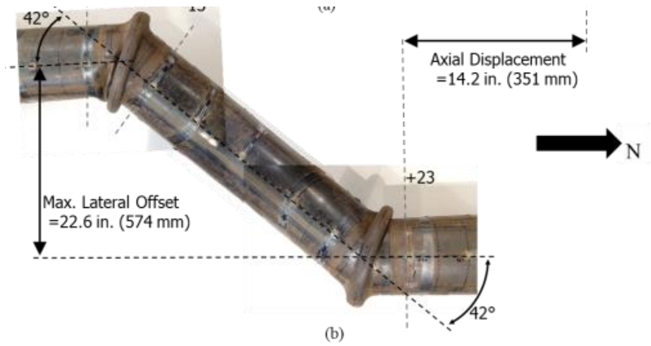


Figure 3-26. After deformation

As shown in Fig. 3-29, although the analytical value was slightly smaller than the experimental value, the first inner surface contact and the second inner surface contact were almost the same, and the curve was roughly traced after that. In analysis including the ground, the analysis value and the experimental value are often inconsistent due to the ambiguity of the ground condition. Here, however, the ground strength was extremely uniform, and the deformation of the pipeline was simple, as only the wave-shaped sections were deformed. This deformation behavior is considered to be a factor in the approximate agreement of the analysis value and the experimental value obtained in this test.

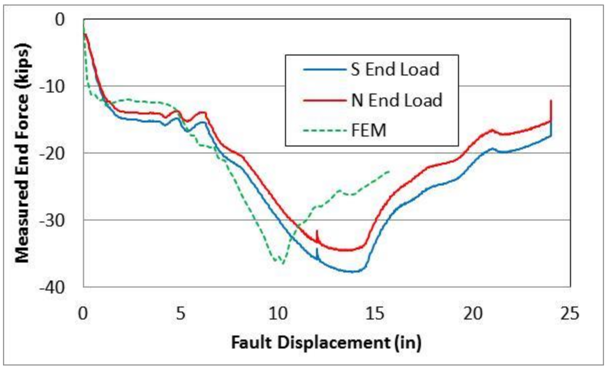


Figure 3-29. Relationship between fault displacement and reaction force

IV. SUMMARY

This report has introduced the results of axial compression, axial tensile, bending and underground tests of Steel Pipe for crossing Fault (SPF), which were conducted at Cornell University in the United States as performance tests of SPF.

In the axial compression test, even though the test pipeline was deformed to about twice the allowable value of inner contact displacement, deformation concentrated only on the wave-shaped section. Complex deformation behavior did not occur, and there were no cracks or leaks.

In the axial tensile test, deformation started in the wave-shaped section, and when the allowable deformation (50 mm) was exceeded, creases (buckling) occurred in the axial direction. However, as the straight pipe part began to elongate under increasing deformation, no cracks or water leakage occurred.

In the bending test, a four-point bending test was performed to an allowable bending angle (inner surface contact angle) of 18° and further to 36.6°, which is about twice the allowable bending angle. No complicated deformation was observed and no cracks or leaks were found.

In the underground experiment, simulated fault displacement of 610 mm was applied to a test pipeline at a fault angle of 50°. In the experimental results, the pipe was deformed to 42°, which was about 4 times the set allowable value of the inner contact angle (9°), but deformation was limited to only the wave-shaped sections, and cracks and leaks were not observed.

From all the test results, no cracks or leakage occurred, even when deformation of several times the allowable axial displacement and bending angle were applied, because the wave-shaped sections were designed with sufficient safety against the set tolerance. Thus, it is considered possible to absorb deformation due to fault displacement, even if unexpected deformation occurs, without failure of the pipeline.

Moreover, in a FEM analysis conducted under the same conditions as the tests, the experimental values and analytical values coincided with very high precision. Therefore, it can be concluded that reproducibility is high even under conditions such as different diameter and pipe thickness.

We hope that this method will be considered one effective option for countermeasures for pipelines crossing faults, and will lead to the construction of earthquake-resistant water pipelines in the United States.

REFERENCE

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Mitigating Risk to Underwater Crossings to Improve Water Supply Reliability: Two Case Studies

Serge Terentieff, Denise Cicala, Xavier Irias, and Raffi Moughamian

ABSTRACT

Isolated segments of the East Bay Municipal Utility District's (EBMUD) raw water aqueducts and large diameter transmission pipelines are at risk of breaking as a result of seismically-induced liquefaction at underwater crossings, which may significantly limit potable water supply for EBMUD's 1.4 million customers in the San Francisco East Bay Area. This paper examines two case studies that highlight alternative approaches that can be used to mitigate risk of failure: the first considers potential levee failures in the Sacramento-San Joaquin Delta (Delta), as a result of a low-probability seismic event that could result in structural damage to EBMUD's raw water aqueducts at river crossings; the second considers failure of transmission pipes that supply potable water to Alameda Island, a city of about 80,000 residents that depends solely on underwater pipeline crossings for its water supply.

The first case study is Mokelumne Aqueduct No. 3, a major pipeline that crosses three rivers. While the probability of seismic damage is relatively low, as Aqueduct No. 3 was seismically retrofitted in 2003, the consequence is high because the pipeline is a major supplier to 1.4 million customers. To mitigate the risk of structural failure to Aqueduct No. 3, and to the other older and nonretrofitted Mokelumne Aqueduct Nos. 1 and 2, EBMUD installed cross connections among these three raw water aqueducts at both ends of the Delta to allow damaged sections to be bypassed. To further mitigate the risk to its raw water supply, EBMUD developed a repair plan and approach that identifies how raw water service could be restored within 6 months, utilizing a bypass scheme of floating in-place and sinking to the river bottom six 32-inch diameter high density polyurethane bypass pipes, and by connecting these pipes to Mokelumne Aqueduct No. 3 using manifolds on both sides of the river.

The second case study involves treated water pipelines supplying water to Alameda, an island with no water storage facilities. Four underwater pipeline crossings currently supply water to the island including some 16- to 24-inch diameter cast iron pipes installed between 1918 and 1946, located in potentially liquefiable soil with a high likelihood of failure. Results of a Crossings Master Plan study determined that failure of any one of the crossings could lead to a reduction in the level of service to Alameda Island, and recommended three new 24-inch diameter pipeline crossings and in-street pipelines connecting the new crossings to existing transmission pipelines.

This paper summarizes the process used to assess the vulnerability of underwater crossings for these two case studies and identifies mitigation strategies to improve water supply reliability considering both the likelihood and consequence of failure. This includes process used to evaluate underwater crossing alternatives, considering various alignment options and construction methods including micro-tunneling, horizontal directional drilling, and float-and-sink, as well as other criteria including cost, constructability, survivability, speed of repair, and environmental factors. The process used to select an alignment and construction method for the first Alameda crossings replacement is discussed, including design details to reduce potential for differential settlement.

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INTRODUCTION

The East Bay Municipal Utility District (EBMUD) provides drinking water to over 1.4 million customers on the eastern side of the San Francisco Bay. The EBMUD water system is comprised of 167 reservoirs, 132 pumping plants, 29 embankment dams, 5 water treatment plants, 90 miles (145 kilometers) of raw water aqueducts, and approximately 4,200 miles (6,800 kilometers) of treated water distribution and transmission pipelines. Figure 1 presents EBMUD's water supply infrastructure and service area.

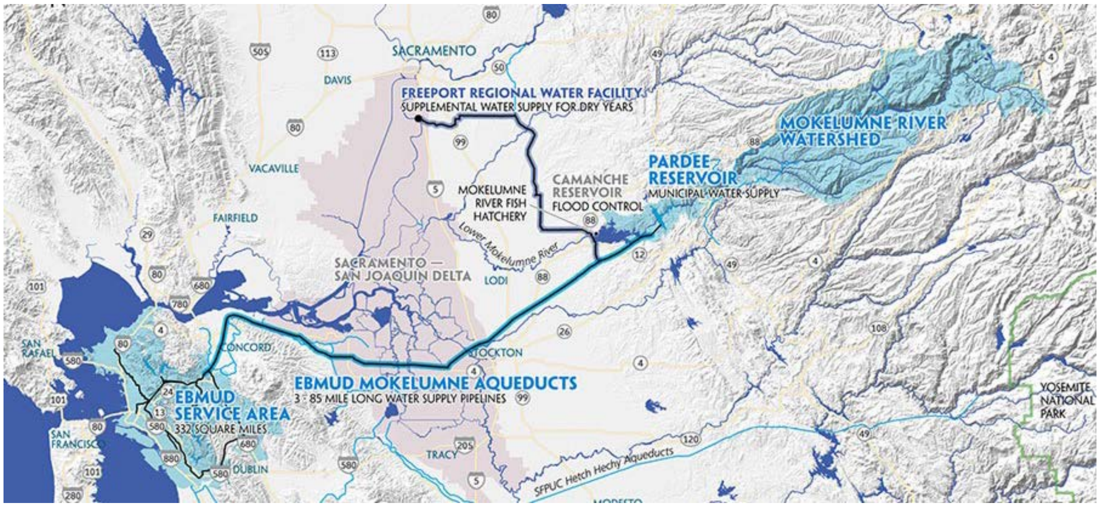

Figure 1: Map of EBMUD Water Supply and Service Area

Completed in 2007, EBMUD's $189 million Seismic Improvement Program (SIP) retrofitted 13 building structures, 70 storage reservoirs, 130 pumping plants, 5 water treatment plants, 56 pipeline fault crossings, 18 upgrades in areas of landslides and liquefaction, and 8 transmission system upgrades. These upgrades included $55 million for transmission system and $50 million in fault crossings improvements to meet various service level goals. The seismic improvement philosophy was to upgrade critical links for overall system performance, rather than fix every component of the system that could be damaged [1].

EBMUD's SIP, however, proved too costly to replace the nearly 2,400 miles of cast iron and asbestos cement pipes. Results of a recent study indicate that an earthquake sequence that begins with a Hayward Magnitude (M_w) 7.0 rupture of the Hayward Fault and 16 M_w 5.0+ aftershocks would cause on the order of 5,500 breaks and leaks that would take up to about 6 months to repair [2]. These estimates are consistent with results of EBMUD's 1994 SIP studies, which indicated that the extent of damage to distribution pipelines as a result of a M_w 7.0 earthquake would include more than 4,000 leaks and breaks, and that nearly 90% of the pipe damage would result from breaks in cast iron and asbestos cement pipe [3]. A majority of these breaks and leaks are expected to occur on smaller diameter (<300 mm) distribution pipes located in paved streets, which are relatively more accessible by emergency repair crews.

Of particular concern are breaks or leaks that could occur to underwater transmission pipeline (≥ 20-inch or 500mm in diameter) crossings that could take months to repair and could significantly impact EBMUD's water supply after an earthquake. This paper examines two such underwater crossings and discusses the approaches that EBMUD adopted to mitigate the risk of failure: the first is a "low risk, high consequence" example that considers potential levee failures in the Sacramento-San Joaquin Delta (Delta) from a low-probability seismic event that could cause structural damage to EBMUD's raw water aqueducts at river crossings; the second is a "high risk, high consequence" example that considers failure of transmission pipes that supply potable water to Alameda Island, a city of about 80,000 residents that depend solely on underwater pipeline crossings for its water supply.

SEISMIC SETTING

The highly active Hayward Fault dominates EBMUD's risk profile. This fault, capable of earthquakes of M_w 7.25, has produced major earthquakes on average every 140 years, with the last damaging earthquake occurring in 1868. According to the United States Geological Survey (USGS), the overall probability of a magnitude 6.7 or greater earthquake in the Bay Area in the next 30 years is 63%. The earthquake probability is highest for the Hayward Fault system, at 31%. As shown in Figure 2A, EBMUD's service area is bifurcated by the Hayward fault, and dozens of critical facilities are located within a few hundred meters of the Hayward Fault.

Beyond the Hayward Fault, several other faults threaten EBMUD's system, ranging from the larger San Andreas Fault in the west, the Calaveras and Concord Faults in the east, and the Central Valley fault in the Delta (see Figure 2B). The two case studies in this paper consider an earthquake event from the Central Valley Thrust Fault or the Midland Fault Zone, which could impact the Mokelumne Aqueducts at river crossings in the Delta, and an M_w 7.0 event on the Hayward fault, which could impact pipeline estuary crossings that provide water to the island of Alameda.

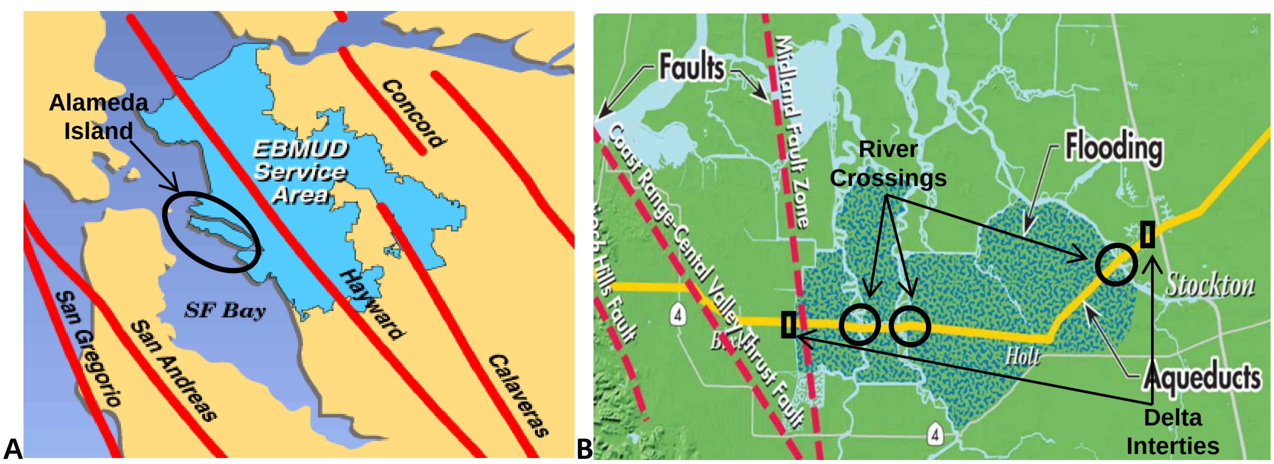

Figure 2: Fault Maps for EBMUD Service Area & Aqueducts in Delta Region

VULNERABILITY ASSESSMENT

Pipelines are susceptible to damage or failure as a result of seismic hazards like ground failure and ground motion. Ruptures or severe distortions of pipelines most often arise from fault movements, landslides, liquefaction, loss of support, or differential motion at interfaces [4]. The consequence of a pipeline failure, as a result of a seismic hazard, depends on a number of factors, including reparability (i.e. time to repair and restore service), level of service impacts, and customer

criticality, just to name a few. Failure of an underwater pipeline crossing presents a significant challenge in terms of damage assessment, accessibility, time to complete repairs, and cost.
The risk and consequence of a liquefaction-induced failure of underwater crossings located in the Delta and in Alameda vary significantly:

- **Low Risk, High Consequence Example -- Mokelumne Aqueduct No. 3 River Crossings:** While the risk of a liquefaction-induced failure of Aqueduct No. 3 is considered low, the consequence of such a failure is considered to be high if repairs cannot be completed within 6 months.
- **High Risk, High Consequence Example – Alameda Transmission Pipelines Estuary Crossings:** The risk of failure of three out of four in-service underwater estuary crossings to Alameda is considered to be high, and the consequence is considered relatively high as well.

These two case studies consider the seismic risk, consequence of failure, and the different strategies that EBMUD adopted to mitigate the risk and consequence of failure.

Case Study 1: Low Risk, High Consequence of Damage to a Raw Water Supply System

The Mokelumne Aqueducts consist of three large diameter pipelines of up to 87-inches (2,200 mm) in diameter that are the sole water supply to 1.4 million people in Northern California. EBMUD relies on these three aqueducts for its raw water supply, which are most vulnerable when they are above ground and cross the Delta. Natural Delta hazards include potential levee failures, flooding, land subsidence, and liquefaction. In 2017, EBMUD developed a strategy to determine how to protect its aqueducts in the Delta. This study evaluated hazards and risks to the aqueducts and alternative options to mitigate those hazards and risks [5].

As part of its SIP, EBMUD evaluated alternatives to seismically upgrade eight miles of elevated pipe, five miles of buried pipe, and three river crossings in the Delta region. The largest and newest of its three aqueducts, Mokelumne Aqueduct No.3, was upgraded to withstand a magnitude 6.7 earthquake. Upgrades included reinforcing levees and strengthening pipe joints at three river crossings. The two older and smaller of the three aqueducts, Aqueducts Nos. 1 and 2, were not seismically retrofitted and, therefore, have a much higher risk of failure in the Delta in the event of a large earthquake compared to Aqueduct No. 3.

Aqueduct No. 3 River Crossing Alternative Repair Study

Despite these seismic upgrades, which were completed in 2003 at a cost of $38 million, there remains a risk that Mokelumne Aqueduct No.3 could break or leak as result of liquefaction-induced levee failure at one of the river crossings, as a result of an earthquake with a return period greater than 500 years. While the probability of such an event is low, the consequence would be significant if repairs cannot be completed within 6 months, which is equivalent to EBMUD’s terminal raw water storage capacity.

To address that risk, EBMUD conducted a study that outlined the initial response and provided conceptual repair plans in the event of a major failure of Mokelumne Aqueduct No. 3 [6].

A major aqueduct and river crossing failure is defined as severe damage with all three aqueducts being severed and water flow interrupted. The study concludes that conventional repair methods for a major river crossing failure, using sheeting and trenching, would take approximately 8 months to complete. An 8-month return-to-service period was deemed unacceptable because the District’s current terminal storage cannot sustain customer demands for longer than 6 months. Additional conceptual design work was, therefore, undertaken to explore alternative repair methods that could result in a 6-month return-to-service. The resulting mitigation measures and conceptual plans that were developed are discussed in more detail in the next section of this paper under "Mitigation Strategies."

Delta Interconnections

Given the high probability of Aqueducts Nos. 1 and 2 suffering significant structural damage in the Delta from a catastrophic earthquake, EBMUD developed plans to interconnect all three of its aqueducts. In 2012, the District completed a $15 million project to interconnect its aqueducts on either side of the Delta. This will allow EBMUD to use surviving portions of Aqueducts Nos. 1 and 2 outside of the Delta to increase the raw water supply that can be delivered through Aqueduct No. 3 following an emergency. As shown in Table 1, these interconnections will allow EBMUD to significantly increase the flow of raw water that can be delivered to EBMUD's service area after an emergency.

TABLE I: Aqueduct Flow Capabilities With and Without Delta Interconnections

	Aqueducts In-Service			**Total Water Supply (MGD)**	
Condition	**No. 1**	**No. 2**	**No. 3**	**Pumped**	**Gravity**
Normal Operations	Yes	Yes	Yes	326	196
Delta Emergency (w/o Interties)	No	No	Yes	172	107
Delta Emergency (w/ Interties)	*Partial*	*Partial*	*Yes*	*256*	*166*

Case Study 2: High Risk, High Consequence of Damage to a Distribution System

Alameda is an island with no water storage facilities that relies on four underwater pipeline crossings for its water supply. Three of these crossings are cast iron pipes (installed between 1918 and 1946) located in potentially liquefiable soil, and have a high risk of failure that could result in a reduction in the level of service to Alameda. A Crossings Master Plan study evaluated failure of any one of the crossings and recommended three new 24-inch diameter pipeline crossings and in-street pipelines connecting the new crossings to existing transmission pipelines.

During an earthquake event, the risk to pipeline failure is the presence of young bay mud (YBM) and liquefiable soils. YMB is soft, unconsolidated silty clay, which is saturated with water. YBM has a low likelihood of liquefaction but remains a seismic hazard due to high seismic shaking amplification; the stresses associated with this amplification can rupture a pipeline that traverses through or above YBM. Liquefiable soils and artificial fill are present throughout the Oakland-Alameda estuary and are both susceptible to liquefaction. Lateral spreading during liquefaction can stretch the pipeline to the point of breakage.

Three of the four in-service crossings have severe risk of failure caused by a seismic event based on subsurface soil types, potential for liquefaction, shaking amplification, and the pipeline depth and alignment relative to these soil types. Two of these pipeline traverse through loose and liquefiable sandy layers in the submarine portion and through artificial fill at the approaches, putting these pipeline at high risk of later spreading and pipe failure. These pipes also traverse YBM at the approaches, which can undergo large amplifications of seismic-induced shaking and break pipe during a seismic event. Though information is limited for the third pipe, a sand layer appears to be in both approaches and can pose a risk to liquefaction and lateral spreading. In addition, liquefaction risk cannot be ruled out. The fourth crossing is at low risk of failure from a seismic event since it is embedded deep in relatively stable soil and traverses mostly through a silty clay layer, which does not pose a high risk to the pipeline.

MITIGATION STRATEGIES

Case Study 1: Low Risk, High Consequence of Damage to a Raw Water Supply System

As previously discussed in this paper, EBMUD completed a study and developed conceptual design work to explore alternative repair methods that would result in a 6-month return-to-service in the unlikely event of a major aqueduct failure. This study evaluated different alternatives and presented a conceptual design that focused on the use of non-conventional construction methods using High Density Polyethylene (HDPE) pipe for repair of a major river crossing failure at Old, Middle, and/or San Joaquin River.

Multiple joint-failures constitute a major failure of Mokelumne Aqueduct No. 3 at a river crossing. The Mokelumne Aqueduct No. 3 seismic upgrades completed in 2003 involved reinforcing the pipe joints at all three river crossings, which significantly reduced the potential for a major river crossing failure. Based on the seismic analyses performed during the upgrade evaluations, it is not expected that joints will fail during the 500-year design earthquake [6]. At worst, it was estimated that there would be no more than 3 failed joints, one for each river crossing, as a result of a 500-year event. This type of failure would be considered relatively *minor* and would likely involve repairs using conventional construction methods that could be completed within 6 months. The probability of a *major* failure at a river crossing is considered low and is not expected during the 500-year design earthquake.

A detailed plan was developed to address the low probability/high consequence event of having a *major* river crossing failure of Mokelumne Aqueduct No. 3. The goal was to determine if repairs could be completed within 6 months following a major event in order to restore raw water capacity to 174 MGD. As discussed below, it is estimated that a temporary repair could be accomplished within 6 months by floating in place and sinking to the river bottom a total of six 32-inch (800 mm) diameter HDPE pipes, and by connecting these HDPE pipes to the existing Aqueduct No. 3 using manifolds on both sides of the river. The HDPE pipe repair concepts and details are illustrated on Figure 3, and are discussed in more detail below.

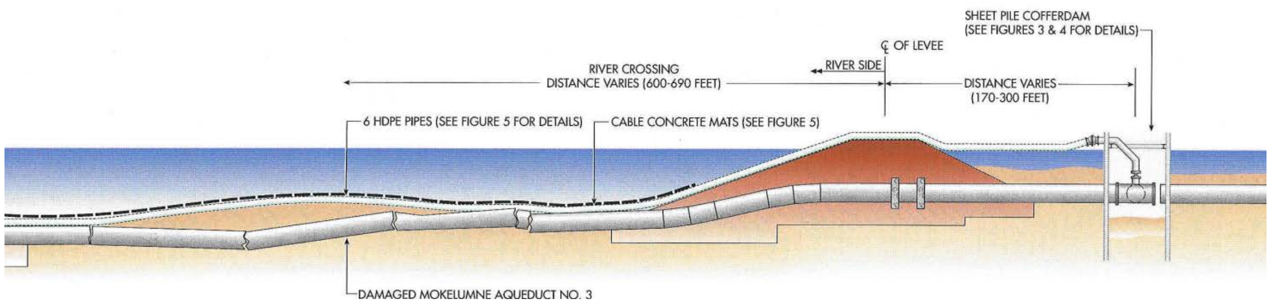

Figure 3: Aqueduct No.3: HDPE Temporary Float and Sink River Repair Concept

EBMUD developed a construction schedule for completing a river crossing repair using this method with input from contractors and the HDPE pipe distributor and manufacturer. Based on this detailed schedule analysis, EBMUD estimates that repair work could be completed and temporary service could be restored within 6 months (approximately 25.5 weeks).

This estimated repair timeline includes 1.5 months for damage assessment, preliminary design, and contract negotiations, 2.5 months for material acquisition, and 3 months for construction (some tasks have to be done concurrently, adding up to 6 months to return Aqueduct No. 3 to service). This timeline assumes use of two construction crews to install the cofferdam/manifold on both sides of the river at the same time, and includes installation of approximately 1,300 feet of HDPE pipe between connections. The schedule analysis also incorporates the estimated duration and interdependencies of various tasks required to complete an emergency river crossing repair.

<u>Conceptual Design Details and Construction Sequence</u>

The design concept for river crossing repair (illustrated in Figures 3 and 4) includes installing a manifold and connecting six 32-inch diameter HDPE pipes, with pipe diameter ratio (DR) of 9 (252 psi pressure rating), to the buried aqueduct at the levee. Manifolds would be connected to the existing buried portion of the aqueduct and installed as close as possible to the edge of the levees to reduce the lengths of HDPE pipes required for repair.

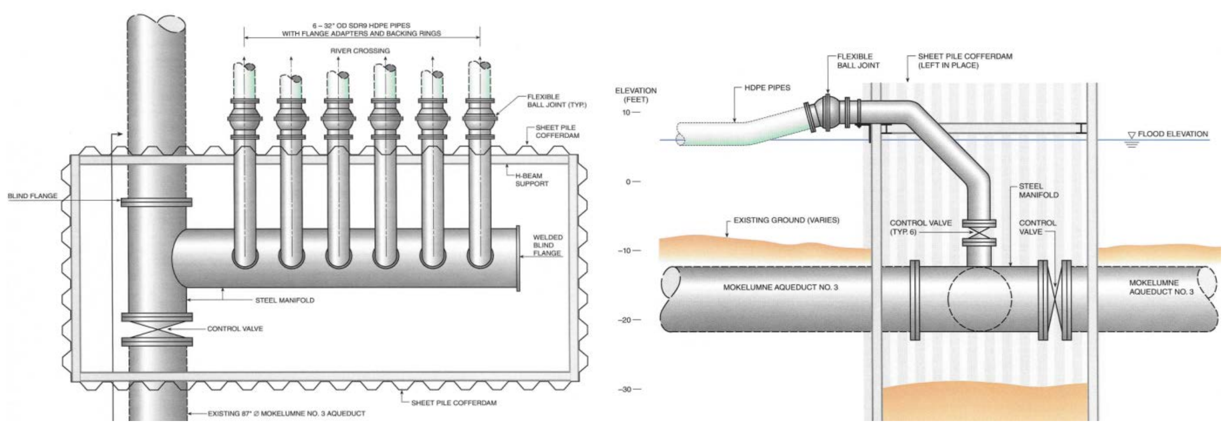

Figure 4: Aqueduct/HDPE Pipe Manifold, Levee Connection Detail: Plan & Section

The anticipated construction sequence for repairing river crossings with HDPE pipes using the "float and sink" method would be as follows.

1. Install a sheet pile cofferdam on each side of the river banks, as illustrated in Figures 3 and 4.

    a. Dewater and excavate to expose the existing aqueduct inside the cofferdam.

    b. Remove a section of the aqueduct and connect the pre-fabricated manifold and connection fittings.

    c. Deliver HDPE pipes to a designated staging area where fusion of the pipes, storage of materials, and other logistic will take place.

    The fusion of pipe joints is a process that could be done on barges, should the entire area near a river crossing failure be flooded.

2. Float the entire length of the assembled HDPE pipe into position.

3. Place pre-cast concrete ballast blocks at predetermined spacing and fill the entire length of HDPE pipe with water to sink the assembled pipe to the bottom of the river. The pipe could be arranged either in single, twin or triple line configurations. The ballast blocks may be installed on shore or on the water (on a low-profile barge), depending on the contractor's preference and any environmental restrictions in effect at the time of repair.

4. Perform the placement of the pipe in a controlled fashion, with marine surveyors directing the alignment and position of each pipe prior to sinking a segment of pipe, to ensure that it falls within the designated alignment/corridor.

5. Continue this process until all six HDPE pipe segments are placed in their proper location.

6. Place cable concrete mats on top of the HDPE pipe at the river bottom to protect the installed pipes from damage.

7. Install earth anchors, if needed, to keep the concrete mats in place.

8. Connect the 32" diameter HDPE pipes to the manifolds at aqueduct (see Figure 4).

9. Flush the HDPE pipes and restore service for Mokelumne Aqueduct No. 3.

Case Study 2: High Risk, High Consequence of Damage to a Distribution System

<u>Master Planning Efforts</u>

Water service to the City of Alameda (Alameda) is provided by four existing underwater pipeline crossings at three separate locations between the City of Oakland (Oakland), Alameda Island, and North Bay Farm Island (see Figure 5). Failure at any of the three crossing locations could lead to a reduction in the level of service for existing customers and potentially reduce the available water supply to Alameda Island and North Bay Farm Island.

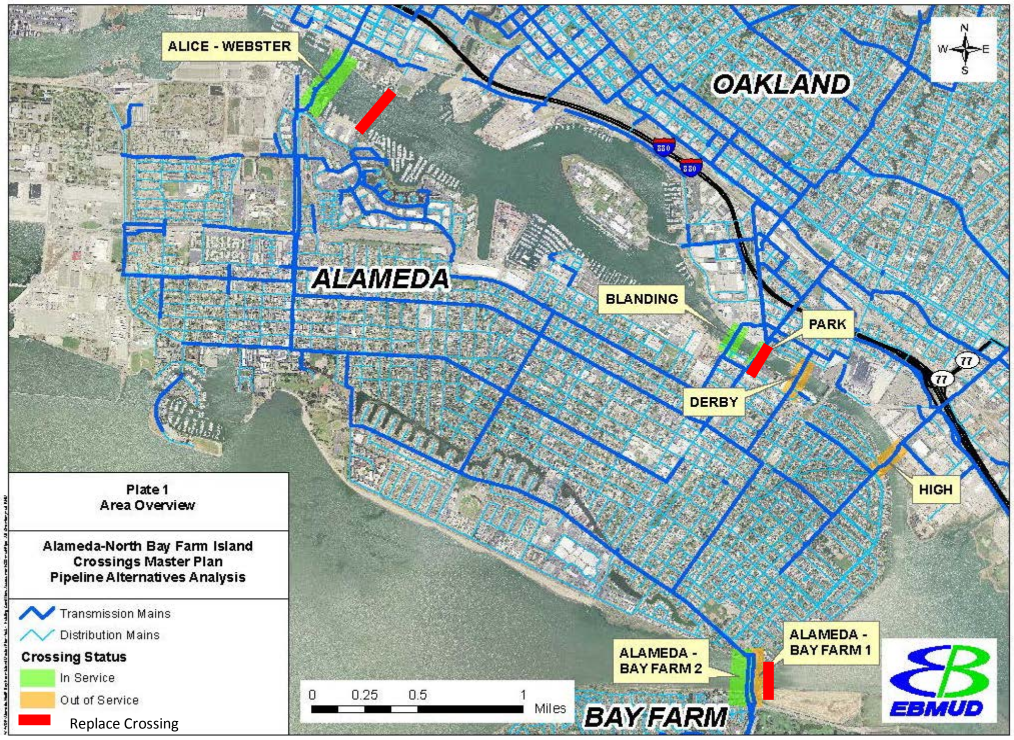

Figure 5: Alameda Crossings. Map Showing All Estuary Crossing Locations

In 2014, EBMUD completed the Alameda-North Bay Farm Island Crossings Master Plan, which recommended three new 24-inch (600 mm) diameter submarine pipeline crossings to be installed using horizontal directional drilling (HDD) and associated 24-inch, in-street pipelines connecting the crossings to existing transmission pipelines. EBMUD's goal is to replace three of the four existing pipeline crossings within the next 6 years to improve the long-term reliability and redundancy of the water distribution system, meet existing and future water needs, and facilitate future repair and maintenance [7].

The master planning effort, which was initiated in 2013, identified the need for three new crossings and replacement of in-street pipelines located in potentially liquefiable soil, to create a network of seismic-resilient pipes to improve the reliability of the water supply system to Alameda:

- **Crossing No. 1, Oakland Inner Harbor:** Approximately 10,500 feet of in-street pipeline in Oakland and on Alameda Island, and approximately 1,800 feet of underwater pipeline crossing.
- **Crossing No. 2, San Leandro Bay Channel:** Approximately 4,200 feet of in-street pipeline on Alameda Island and Bay Farm Island, and approximately 1,400 feet of underwater pipeline crossing.
- **Crossing No. 3, Tidal Canal:** Approximately 3,800 feet of in-street pipeline in Oakland and Alameda Island and approximately 1,400 feet of underwater pipeline crossing.

The approximate locations of these three replacement crossings are shown on Figure 5. The overall project scope will include abandoning existing crossings as these new crossings are constructed. EBMUD recently completed the planning effort, including an Environmental Impact Report (EIR) for all three crossings, and is currently proceeding with the design for the first crossing replacement, Crossing No. 1, which is shown in Figure 6A. Crossing No. 1 includes installation of 1,800 feet of

24-inch (600 mm) HDD pipeline under the Oakland Inner Harbor estuary, and 10,500 feet of connecting 24-inch (600 mm) pipeline on each side of the estuary, to replace in-street pipeline located in potentially liquefiable soil in Oakland and Alameda (see Figure 6B), for an estimated total cost $15 million. Crossing No.1 is scheduled for completion in 2020 and construction for Crossing Nos. 2 and 3 are currently scheduled for completion by 2023.

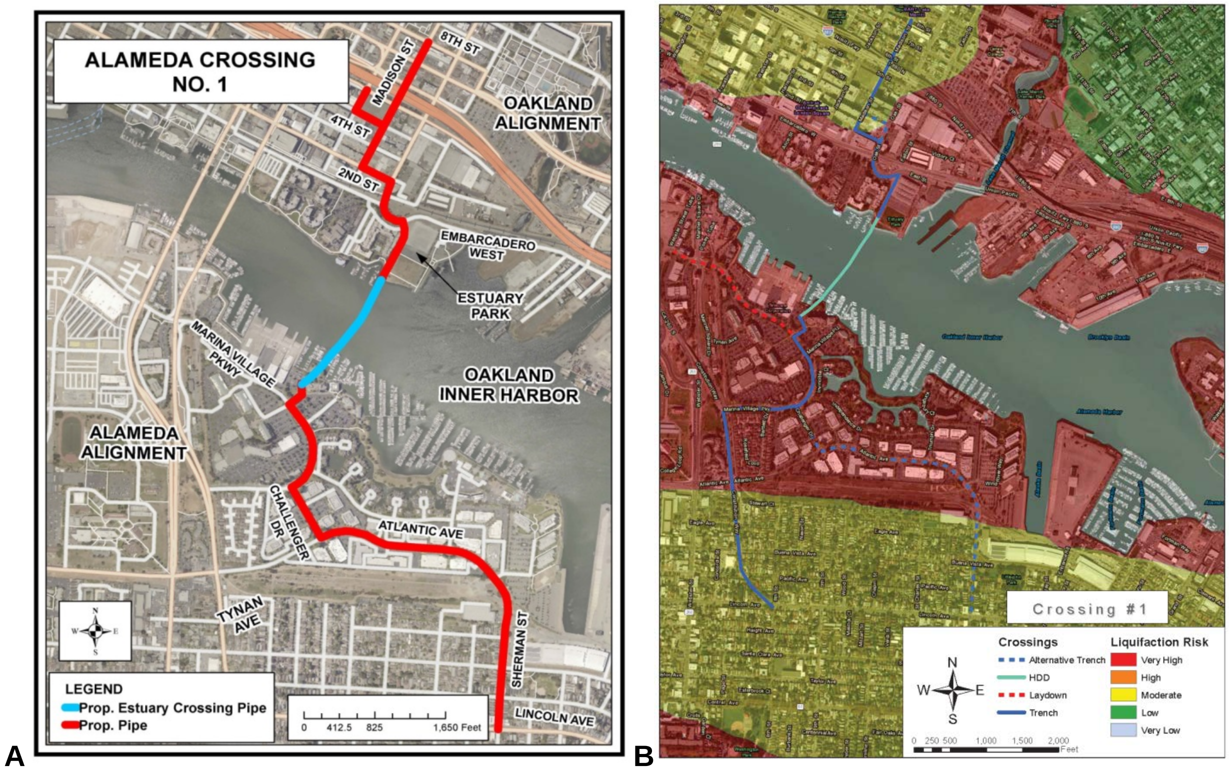

Figure 6: Alameda Crossing No. 1 New Crossing Location & Extent of Liquefaction

Alternatives Evaluation

Eleven alternative alignments were identified, as part of the Master Plan and EIR analyses, based on the need for adequate construction staging, length of the underwater crossing, and close proximity to the existing distribution grid and backbone piping on both sides of the crossing. These alignments were narrowed down to four preferred alignments based on construction accessibility on both sides, distance of additional piping needed to connect to a reliable transmission main, geology and geotechnical considerations, and construction costs.

Multiple design and construction approaches were developed for each of the four preferred alignments with the goal of maximizing survivability and minimizing repair-related water service outages attributable to a major seismic event. Microtunneling and HDD were identified as the two most feasible trenchless construction methods for the crossings. To avoid unstable ground conditions, deeper underwater pipeline crossings are needed, so both construction methods were developed to be in the deeper, more stable ground conditions.

Microtunneling consists of a jacking shaft from which the microtunneling boring machine (MTBM) and casing are advanced to a receiving shaft for retrieval of the MTBM. The shaft depths were selected to place the underwater tunnels below the fill and YBM and into the deep stable soils not prone to liquefaction. Three concepts for the water main riser pipe through the shaft to the surface connection were explored, including concrete encasements, structural backfill, and free-standing. These alternatives were evaluated based on protection against failure versus ease of access for future maintenance.

HDD is a three-stage construction method which originates from the surface. A U-shaped pilot hole is drilled, reamed and enlarged to the required size, and the carrier pipe is pulled into the hole. The depth of the crossing is dictated by the clearance requirements of the water body and to locate the crossing within a particular suitable soil horizon.

Design Details

The entry and exit angles will be 10-15 degrees. Oversized conductor casings are required at each end of the HDD to control fluid pressures to prevent hydraulic fracturing to the surface. The conductor casing is installed using pipe ramming up to 200 feet in length. Based on a 15-degree entry angle, the casing would reach a depth of 50 feet, which is the approximate boundary between liquefiable and non-liquefiable soils. The entry and exit pits will be located at least 200 feet onshore to allow installation of 200-foot conductor casings and associated ground improvements before the pipeline is under the estuary.

In order to ensure the HDD crossing is housed in non-liquefiable soils from surface to surface, ground improvements via jet-grouted columns will be incorporated as part of EBMUD's design to support the conductor casings in the liquefiable soils. These jet-grouted columns are 8 feet (2,400 mm) in diameter and spaced approximately 20-feet center-on-center. The conceptual design detail developed to reduce potential for differential settlement due to liquefaction, is shown in Figure 7.

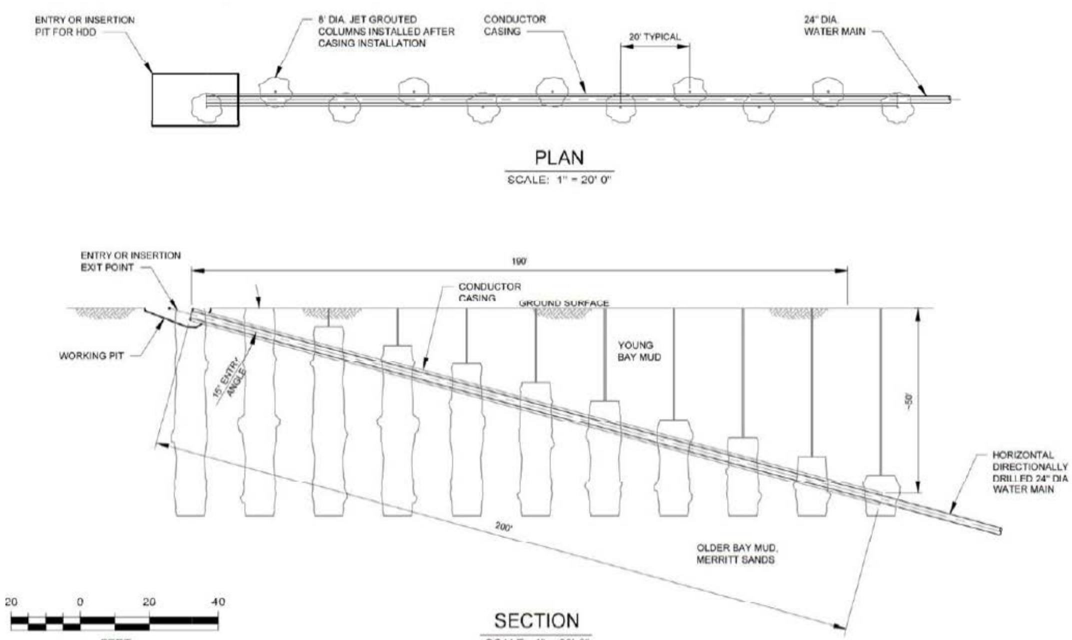

Figure 7: Jet-Grouting Support Concept for HDD Crossing No. 1

CONCLUSIONS

This paper summarizes the process EBMUD used to assess the risk and consequence of breaks to isolated segments of large diameter underwater pipeline crossings as a result of seismically-induced liquefaction, and the alternative approaches that can be used to mitigate the risk of failure.

In the first case study, a low-probability seismic event that would result in the failure of all three raw water aqueducts is considered. For this scenario, EBMUD adopted a two-pronged mitigation strategy that relied on the use of (1) interconnections at both ends of the Delta to allow damaged sections to be bypassed in the event of a failure of one or both of EBMUD's oldest and most vulnerable aqueducts, and (2) six HDPE bypass pipes installed using a "float and sink" method, and connected by manifolds on both sides of the river, which could be installed in the event that EBMUD's newest and most robust aqueduct suffers significant damage at a Delta river crossing.

The second case study considers a high-probability seismic event that could result in the failure of three of the four in-service estuary crossings that the Island of Alameda solely depends on for its potable water supply. Given the relatively high risk and consequence of such an event, which could reduce service to about 80,000 residents, EBMUD completed a Master Plan assessing the reliability and redundancy of the water supply and distribution system for Alameda and initiated the design to replace the first of three new crossings. A detailed analysis and evaluation of alternatives was used to select the location, installation method, and design details for the first crossing and connecting pipelines. The use of an HDPE pipeline, installed using HDD with conductor casings and jet-grouted columns to reduce potential for differential settlement in liquefiable soils, was ultimately selected as the preferred option. Crossing No.1 is currently in design and scheduled for completion in 2020 and construction for Crossing Nos. 2 and 3 are currently scheduled for completion by 2023.

This paper demonstrates the different approaches that can be considered and the advantages of adopting significantly different mitigation strategies that take into account the likelihood and consequence of failure of underwater pipeline crossings. In a "low risk, high consequence" scenario, water agencies should consider the use of alternative construction methods, such as "floating and sinking" HDPE pipelines in place, to restore temporary service while permanent repairs or replacement of a failed crossing can be completed. In a "high risk, high consequence" scenario, water agencies should consider underwater crossing alignment options and construction methods, such as micro-tunneling and HDD, given cost, constructability, survivability, speed of repair, and environmental factors.

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Verification and evaluation method for the seismic performance of potable water mains lined with cured-in-place pipe (CIPP)

Hiromasa Ishizeki and Masakatsu Miyajima

ABSTRACT

This paper presents earthquake damage surveys, experiments on seismic behavior, and a performance evaluation method using seismic calculation, for potable water mains lined with cured-in-place pipe (CIPP). CIPP is a trenchless technology that forms a new pipe within an existing pipeline for the purpose of renewal or corrosion prevention of aging pipes, and is used mostly in pipes with non-anti-seismic joints.

Japan has suffered significant damage to potable water pipelines caused by frequent seismic activities. It is reported that most of the resulting damage was water leakage caused by pullout of those joints that didn't have a separation preventing function, generally called non-anti-seismic joints.

For this research, an earthquake damage survey was first conducted on potable water mains in which PALTEM HL liners had been installed in the past. The survey showed that there were no damage reports for these pipelines. CIPPs were, therefore, judged to potentially contribute to the seismic improvement of pipelines with non-anti-seismic joints.

Next, physical experiments were conducted on pipe specimens lined with a fully-structural CIPP to verify seismic behavior. Even under loading conditions that reflected the past earthquakes with seismic intensities of 4 or above on the Japan Metrological Agency's (JMA) scaling, the CIPP protected host pipes from joint pullout, and the jointed pipelines exhibited behavior similar to a single, continuous pipe. The CIPP itself did not show any damage or leaks.

In addition, to establish a methodology to evaluate the seismic performance of CIPP that is installed inside existing pipes, a calculation model and its parameters were selected based on the seismic behavior observed and data obtained in the previous experiments. After that, the performance criteria required for CIPP were selected and material tests were conducted to determine the allowable stress using the fully structural CIPP.

This study has confirmed that CIPP improves seismic performance of old potable water pipelines and has enabled evaluation of seismic performance by seismic calculation in accordance with different site conditions.

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INTRODUCTION

CIPP is one of the trenchless technologies that create a new pipe within a deteriorated pipe buried underground. A CIPP liner is a composite material of liner tube with impregnated curable resin. A liner generally consists of non-woven fabric and often glass fiber. Figure 1 illustrates a typical structure of CIPP.

A resin-impregnated liner is inserted by a technique called inversion that uses air pressure to turn the liner inside out within an existing pipe. After insertion, the air pressure is maintained for the liner to closely fit to the host pipe until the resin cures and a CIPP is formed. The mechanism of inversion is illustrated in Figure 2.

Because the lining material is installed by inversion, it does not create loads such as friction force during insertion. Therefore, CIPP can be easily installed for a long distance in a pipeline even with curves and bends. In addition, installation of CIPP is not constrained by ground facilities, traffic circumstance or other buried obstacles because it requires no excavation except for a working pit at each end of a pipeline to be rehabilitated.

The length of deteriorated pipes that are reaching their design life is significantly increasing in Japan, and renewal and seismic strengthening of those pipes are becoming urgent issues. The conventional open-cut replacement method is still the primary countermeasure, however, there are many sites where pipes are buried under arterial streets, railroads, and rivers that make it difficult to excavate.

CIPP, a trenchless technology, is therefore employed for a broad range of infrastructure such as gas mains, potable water mains, sewers and irrigation lines. CIPP has become a common methodology especially in the Japanese gas and sewer industry because those industries have already instituted public guidelines [1], [2] for use of CIPP. These guidelines also define seismic performance of CIPP in term of leak prevention.

On the other hand, in the potable water field, CIPP is not yet publicly classified as an industrial standard for renewing and seismically strengthening deteriorated mains. Despite the fact that CIPP is not yet commonly accepted in the Japanese water works industry, it is believed that it is capable of a certain degree of seismic resistance performance. A verification study on the seismic performance of CIPP for potable water is reported in this paper.

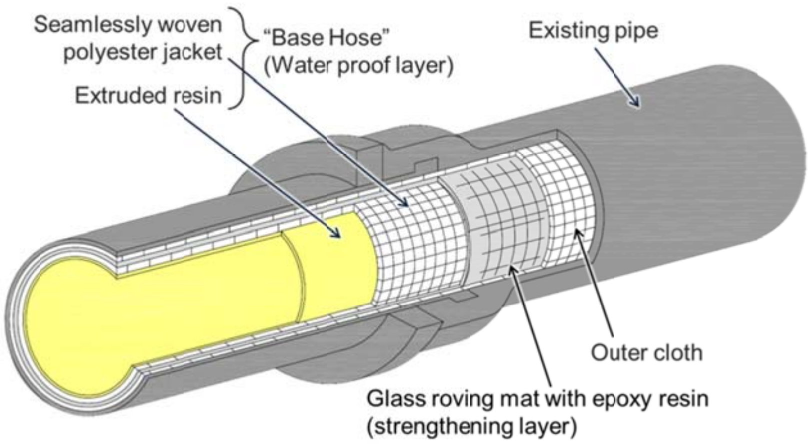

Figure 1. A typical structure of a CIPP (PALTEM Super-HL Liner as an example)

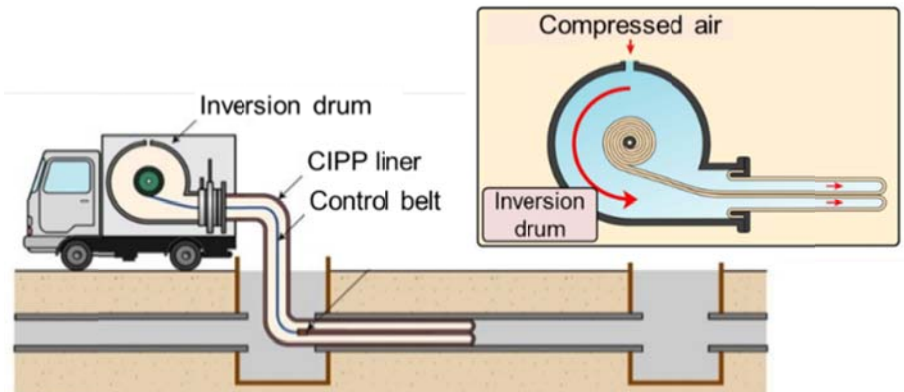

Figure 2. Inversion mechanism

RESEARCH ON CIPP INSTALLED IN QUAKE-STRICKEN AREAS

Ashimori Industry Co., Ltd., Osaka, Japan, has been providing and installing CIPP since 1980 under its technique brand name "PALTEM" and more than 90% of their works by length were performed in Japan including areas stricken by major earthquakes. In the 35+ years of PALTEM history, its products have experienced at least 6 major earthquakes with a seismic intensity of more than 6-upper on the rating system of the Japanese Meteorological Agency, not including aftershocks. However, there has been no report of leak or failure (at least not as a post-quake damage report) from stricken cities in which PALTEM HL (hose lining) liners were used. It should be noted that portions of PALTEM's early stage liners are semi-structural and non-structural.

Before this study project, we had already conducted post-quake research [3] on PALTEM CIPP installations after "The Great Hanshin Earthquake" which hit cities such as Osaka and Kobe in the mid-west portion of Japan in 1995. In one of the major cities in the region, the municipal water authority found no leak in water mains retrofitted with PALTEM CIPP, while about 1,000 defects were reported in the entire 4,000 km distribution network. In the same city, a gas distributor reported no leakage from their gas mains that were lined with PALTEM liners, and our own sewer inspection also confirmed no leaks. Similar results were confirmed in our research and inspection after "the 2011 Tohoku Earthquake".

Our research was extended for this study project and was focused on potable water mains. Cities, towns, boroughs and villages were selected in municipal areas that had been stricken by major earthquakes with the threshold of seismic intensity equal to 6-upper as it is the specified class for seismic resistance assessment of new water main installation in Japan. Some locations were further narrowed down to "district levels" if, in a municipal level, ground liquefaction was reported during earthquakes.

Table 1 shows the result of crosschecking between official quake damage reports and Ashimori's past installation records in the selected areas. About 6.7 km of PALTEM CIPP were installed in municipalities stricken by earthquakes of seismic intensity 6-upper or above. 30 km were installed in areas in which ground liquefaction was reported. No leak or failure was reported from these municipalities or areas.

TABLE 1. CROSSCHECKING BETWEEN QUAKE REPORTS AND INSTALLATION RECORDS

Dates	Earthquakes	Locations (Prefectures)	Installation records (meter)			Damage Status
			Seismic intensity ≥ 6-upper	Ground liquefaction Reported		
			Municipal level		"District" level	
Jan/17/1995	Great Hanshin	Hyogo	1,143	1,143	88	No damage report
Oct/06/2000	West Tottori	Tottori	-	161	TBC	
Oct/23/2004	Chuetsu	Niigata	132	2,332	1,423	
Mar/25/2007	Noto	Ishikawa	40	-	-	
Jul/16/2007	Chuetsu Offshore	Niigata	132	-	-	
Mar/11/2011	Tohoku	Miyagi	571	538	83	
		Fukushima	125	152	TBC	
		Ibaraki	4,547	4,678	TBC	
		Chiba	-	1,357	TBC	
		Saitama	-	2,465	TBC	
		Tokyo	-	4,278	TBC	
		Kanagawa	-	12,949	1,310	
		Total	6,690	30,053	2,904	

TBC = to be confirmed

Figure 3. Joint pullout in a ductile iron pipe, [5]

Our research has also found that PALTEM CIPP survived in existing ductile iron pipes with conventional non-seismic-resistant joints. A research of Investigative Commission 2013 for Seismic Strengthening of Pipelines [4] over existing pipes has found that failure ratios of existing water pipelines were significantly higher for steel pipes with screwed joints, cast iron pipes (CIP) and ductile iron pipes (DIP) than for other types. The majority of failures were from joint pullout in ferrous pipes. An example of joint pullout in a DIP is shown in Figure 3.

These iron pipes without seismic-resistant joints are usually old and likely to be scheduled for rehabilitation or replacement. In fact, among 380 km of water main rehabilitations with PALTEM CIPP, approximately 65% were installed in old ductile iron and cast iron pipes. Even though the CIPPs have been used mainly on those types of pipe that are relatively weak in earthquake resistance, our research has revealed the fact that there were no failure reports after severe earthquakes. Hence, it can be deduced that the CIPP installations have seismically strengthened those existing pipelines with non-anti-seismic joints.

VERIFICATION OF SEISMIC BEHAVIOR

When verifying seismic behavior of a pipeline that is retrofitted with CIPP, it should not be ignored that CIPP always exists inside a host pipe. CIPP is not directly buried underground, and it rather forms a multi-layer structure by closely fitting to the interior wall of an existing pipe. Therefore, the host pipe's seismic behavior, i.e. joint displacement behavior, influences the CIPP's seismic behavior.

In the past, an experimental study [3] had been conducted using a non-structural "hose liner" to verify if water tightness was maintained in an event of joint pullout. The result was favorable and it was also found, after gathering long-term experience in lining works and continuing fundamental studies, that joint displacement is less likely to occur if a CIPP was inside a host pipe.

CIPP's three characteristics related to pull-out resistance: close-fitting by inversion pressure, circumferential expansion by internal water pressure and bonding strength of epoxy resin are assumed to be the main causes for the non-displacement phenomena. Figure 4 illustrates a structure of a host pipe retrofitted with a CIPP and the reinforcing characteristics of CIPP.

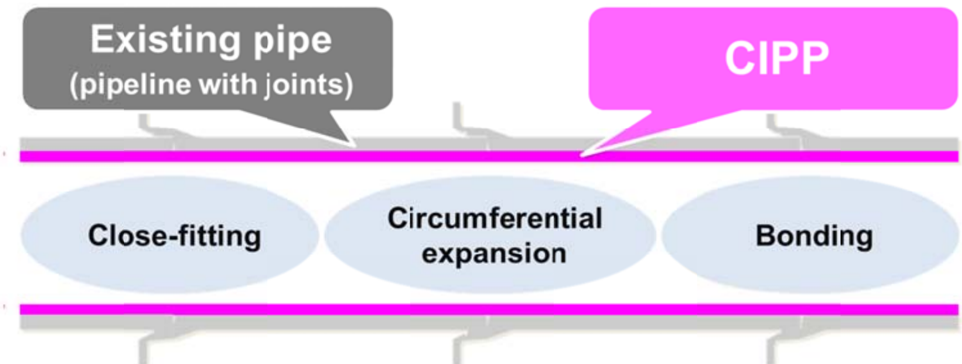

Figure 4. Three reinforcing effects of CIPP

TESTS FOR FRICTION FORCE MEASUREMENT

Joint pullout occurs in an earthquake when a force that displaces a joint, namely pullout force, is greater than the pullout resistance force, according to Kumaki and MIyajima [6]. The joint pullout force develops from the friction force between the ground and an existing pipe and it is assumed to be 0.0098 N/mm^2 according to a seismic design standard in Japan [7]. On the other hand, the pullout resistance force in a pipe retrofitted with a CIPP is presumed to develop from the friction force between the host pipe and the CIPP.

In order to confirm "non-slidability" between a host pipe and a CIPP, a test for friction force capability was conducted. For this test, PALTEM Super-HL, a fully structural CIPP liner was installed in a short section of steel pipe, then an axial load was applied from the top end of the vertically placed steel pipe, and the load was measured at the point that interface slip started between the CIPP and the steel pipe. The friction stress is calculated by dividing the load measured by the contact area between the host pipe and the CIPP. Three specimens were prepared for this test. In two of them (No.2 and 3), a thin nylon tube sheet was installed to intervene between the CIPP and the steel pipe to eliminate the bonding strength at the interfaces. Figure 5 illustrates the test setup and the results are shown in Table 2.

In specimen No.1, for which both the close-fitting effect by inversion pressure and bonding strength of resin are acting, the frictional resistance between the CIPP and the steel pipe was 40 times greater than assumed to act between the ground and an existing pipe. In specimens No.2 and No.3 with only the close-fitting effect, the frictional resistance was 2.5 times greater. Also, in another reference test, close-fitting and circumferential expansion by internal water pressure generated a friction resistance that was about 10 times greater than the standard assumption for friction resistance between ground and a steel pipe. In a real lining situation, all the three effects act simultaneously. The tests proved that the friction resistance between a CIPP and a host pipe was far greater than the maximum force assumed to be developed between a host pipe and the ground that is used in the Japanese seismic design standard [7]. Therefore, it can be anticipated that joint displacement hardly ever occurs even under an earthquake motion if a CIPP is installed inside a jointed pipeline.

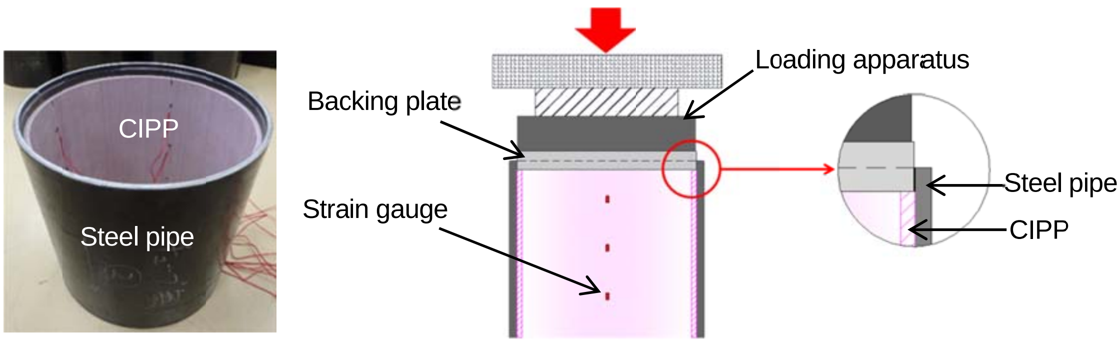

Figure 5. Test setup

TABLE 2. RESULTS OF FRICTION FORCE TEST

CIPP		"Super-HL" Φ300, t=4.0 mm			Reference test
Host pipe		Steel pipe, Φ300, L=300 mm			
Specimen		No.1	No.2	No.3	
Intervening sheet		-	Material A	Material B	Material A
CIPP's Properties	Close-fitting	✓	✓	✓	✓
	Circumferential expansion	-	-	-	✓(0.75MPa)
	Bonding	✓	-	-	-
Friction force (N/mm^2)		0.411	0.025	0.025	0.096

PHYSICAL TESTING FOR VERIFYING SEISMIC BEHAVIOR

Physical simulation tests were performed with jointed specimen pipes with CIPP installed to observe seismic behavior. The main purposes of these tests are as follows;

1) To observe joint displacement behavior under a load that simulates an earthquake.
2) To measure the load that causes joint displacement.
3) To measure the load that causes a defect in CIPP.

For these purposes, a test specimen was prepared as follows;

1) A pair of ID 300 mm, L=6 m, mortar-lined ductile iron pipes were connected via non-anti-seismic joints.
2) A t=0.2 mm nylon tube was inserted. This nylon tube was used in order to create the most severe condition by eliminate the bonding strength between the host pipe and the CIPP which, in an actual installation, depends on interior surface status such as quality of cleaning or roughness due to deterioration.
3) A DN 300 mm, t=4 mm CIPP was installed through the two connected ductile iron pipes.

The stages of specimen preparation are shown in Figure 6 and the structure of the joint is illustrated in Figure 7.

The test specimen of ductile iron pipes with installed CIPP was then subjected to the following test procedure;

1) Hydraulic jacks were installed on both the horizontal sides of the test specimen and longitudinal load was applied.
2) 0.75 MPa internal water pressure was maintained during the longitudinal loading so the test specimen simulated a pipe under internal service pressure.
3) Joint displacement was measured by gauges that were installed around the joint.

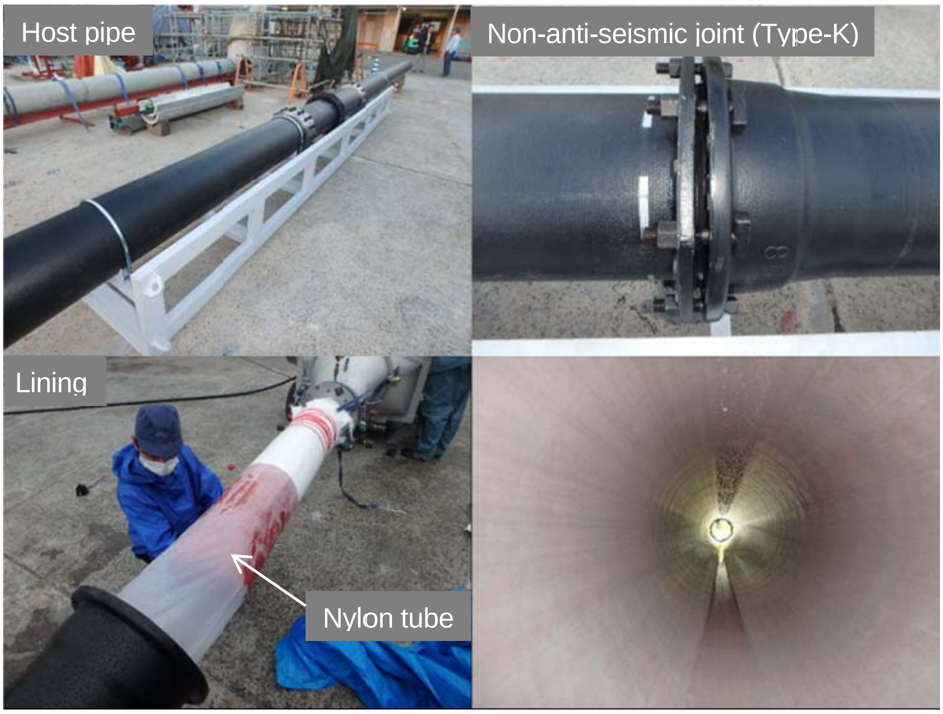

Figure 6. Stages of specimen preparation

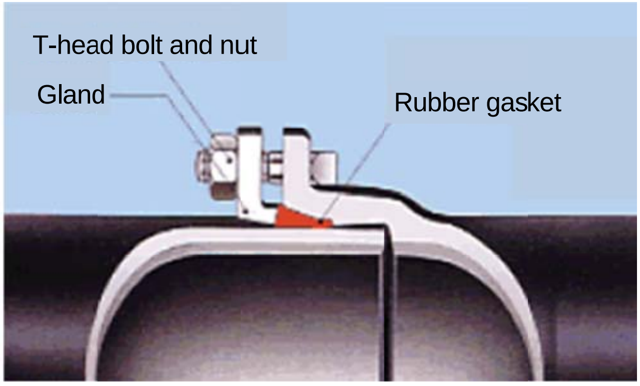

Figure 7. Structure of joint, [8]

The level of longitudinal load applied to the pipe specimen in this experiment was determined as follows;

1) The loading level must be high enough that joint pullout would occur in an existing pipe (without CIPP). Joint pullout force is generated by stress that acts on a ductile iron pipeline due to an earthquake, according to Kumaki and Miyajima [6].
2) Equation 1, referred to in Japan Water Works Association's guideline [7], is employed to calculate a necessary seismic load. This is one of standard formulas in Japan that was obtained based on past earthquake experiences and is used to calculate axial stress for a seismic intensity of 4 or above.
3) The equation gives an axial load of 27.69 kN where joint pullout force starts exceeding pullout resistance strength. For this experiment, 60 kN is used to provide a safety factor of approximately 2.

$$R = \sigma_{2L} \times A = \frac{\pi \cdot D \cdot \tau \cdot L}{2A} \times A \qquad (1)$$

Where,

R : Joint pullout force
σ_{2L} : Axial stress in Level-2 seismic motion
A : Cross-sectional area of pipe
D : Outside diameter of pipe (300 mm)
τ : Friction force between pipe and ground (=0.0098 N/mm^2)
L : Length of pipe (6,000 mm)

The experimental setup is shown in Figure 8.
The results of the experiment are summarized as follows;

1) Joint displacement (pullout) was not observed even under the 60-kN load.
2) The load was then increased until joint displacement occurred, and approximately 400 kN was needed to cause joint displacement.
3) The CIPP inside the ductile iron pipeline did not suffer any damage nor showed any leakage through the entire experiment.

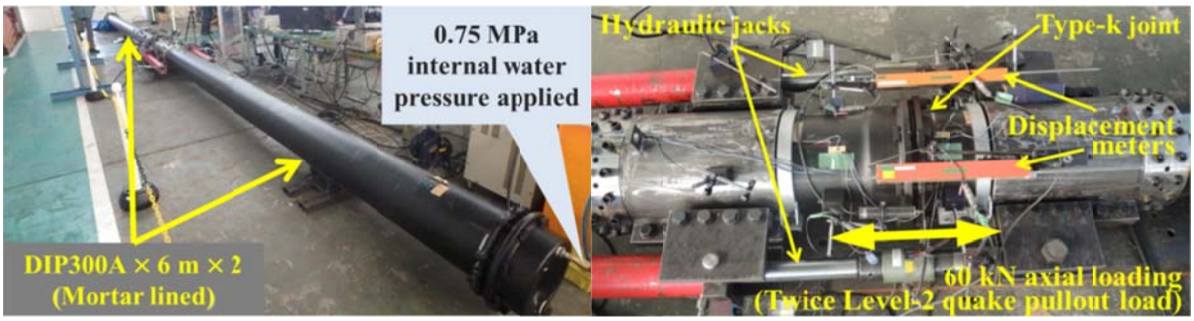

Figure 8. Experimental setup

The joint in the pipeline specimen with CIPP installed did not show a displacement under an axial load that is twice the calculated earthquake load. The load that finally caused joint displacement was 400 kN which is 15 times greater than the calculated earthquake load. The bonding strength of the curable resin was eliminated by the intervening nylon tube between the CIPP and the host pipes. In an actual CIPP watermain installation, a CIPP is typically strongly secured by bonding of epoxy resin inside the host pipe.

The two tests showed that, under the conditions simulated, a jointed pipeline with CIPP installed behaves like a single, continuous pipe including the joint. From the observation that the joint pullout behavior under seismic motion was suppressed by CIPP, it can be said that the seismic performance has improved in comparison to a pipeline with a non-anti-seismic joint. In addition, the CIPP showed no structural defect even though it was exposed to a load that is 15 times greater than the calculated seismic load. Moreover, it maintained the design burst pressure of 5.0 MPa under a burst test that was performed after the loading test. Hence, the structural CIPP is assumed to satisfy the required seismic strength both during and after seismic loading.

EVALUATION METHOD BASED ON SEISMIC CALCULATION

The previous sections have shown CIPP's capability of suppressing joint pull-out behavior and seismic strength performance, however, it is not enough to provide only a generalized seismic performance evaluation of CIPP. Site conditions need be reflected in a seismic calculation method to verify if a CIPP's strength is fully satisfied under an earthquake. To evaluate the seismic strength of a CIPP installation, a method is presented below to compare the seismic strain acting on the CIPP and the CIPP's allowable strain.

Calculation of Strain Acting on CIPP

The "Seismic Design and Construction Guidelines for Water Supply Facilities" of Japan Water Works Association (JWWA) [7] specifies a seismic design calculation method based on the response displacement method for welded steel pipes as a continuous pipeline. However, two issues need to be addressed before immediately using the specified equation.

The first one is that CIPP is not directly buried underground and it lies within a jointed pipeline. When calculating strain that is generated on a CIPP, the joint displacement behavior under seismic motion needs to be reflected. To address this issue, the previously explained loading test proved that the jointed ductile iron pipeline with the CIPP installed behaved similarly to a single, continuous pipe. In other words, a ferrous pipeline jointed with old, non-anti-seismic joints but retrofitted with a CIPP can be considered as a continuous pipe with ferrous outer material. Hence, it is concluded that the above equation for seismic strength calculation of welded steel pipe is applicable in the case of a pipeline retrofitted with a fully structural CIPP.

The second issue is lack of validity to apply the seismic strain that is calculated based on material characteristics of steel pipe for evaluation of CIPP, a plastic pipe. There is a great difference in the tensile elastic modulus of the two different pipe materials. To address this issue, the tensile elastic modulus of CIPP is employed so that seismic strain acting on the model pipeline is greater than that for the ferrous pipe to provide a conservative calculation.

With these assumptions, JWWA's seismic calculation method for welded steel pipe can be applied to CIPP in a jointed ferrous pipe with the characteristics of the plastic material being considered.

Setting CIPP's Allowable Strain

Because a fully structural CIPP does not rely on the strength of the existing pipe, its allowable strain must be determined based only on the CIPP's physical properties. To determine the allowable strain for seismic design calculations, earthquakes are classified into two levels, a Level-1 earthquake and a Level-2 earthquake, in accordance with the Japanese seismic design practice for water facilities [7].

A Level-1 earthquake is defined as an earthquake that likely occurs over the service period of a pipe, and it is generally estimated to be of a seismic intensity of 6-lower or less. A Level-2 earthquake is defined as an earthquake that barely occurs over the service period but could be catastrophic, and it is generally estimated to be of a seismic intensity of 6-upper or above.

For Level-1 earthquakes, it is defined in the guideline that a requirement for seismic performance of CIPP is to satisfy "the limit state in which the dynamic property of CIPP material falls within the elastic range" [7]. Although ferrous materials generally have a clear yield point as a boundary between the elastic range and plastic

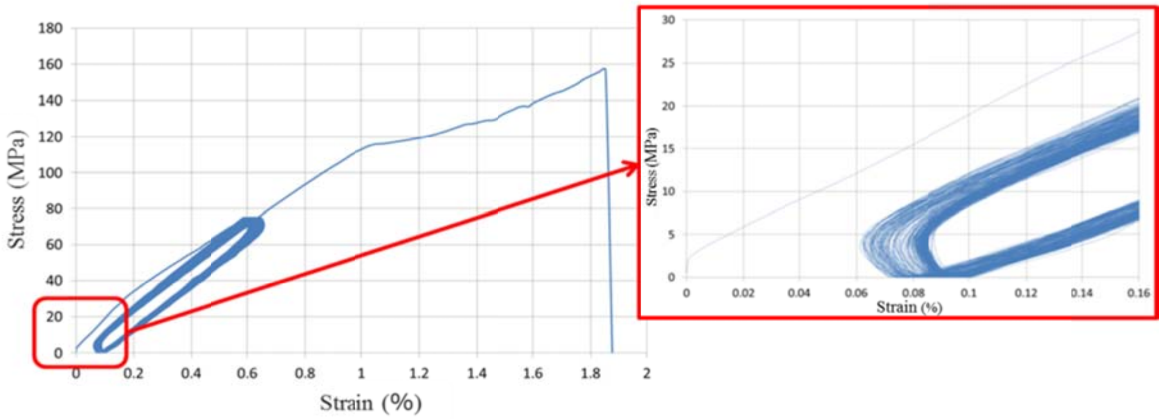

Figure 9. Record of cyclic strain test

range, the stress-strain relation of CIPP material has no clear yield point. Therefore, as an alternative method to judge the elastic range of the CIPP used in the seismic experiments, cyclic strain tests were performed and residual strain was measured.

A 0.6% strain was cyclically applied on a flat test piece of the CIPP at the rate of 5 mm/min for 300 repetitions, as shown in Figure 9. It was confirmed that the residual strain is 0.1% or less after the cyclic strain tests.

In general, a stress level that leaves 0.2% strain is assumed as the yield stress for materials such as glass, concrete, plastic, and rubber. Hence, we decided that the result of the cyclic test showed a satisfactory margin of safety. In addition, the test pieces didn't show any reduction in strength after the cyclic test. The 0.6% strain maintains safety factor of 3 to the breaking stress of this CIPP material, which is approximately 2.0%. The test setup is shown in Figure 10 and Table 3 shows the results.

Figure 10. Setup of Level-1 cyclic strain test

TABLE 3. RESULT OF LEVEL-1 CYCLIC TEST

Strain applied (%)	Test Specimen	Residual strain after cyclic test (%)	Tensile strength after cyclic test (MPa)
0.60	1	0.07	160.6
	2	0.09	157.4
	3	0.07	163.2
-	Initial value	-	159

Figure 11. Setup of Level-2 cyclic strain test

TABLE 4. RESULT OF LEVEL-2 CYCLIC TEST

Strain applied (%)	Test specimen	Physical status after cyclic test (%)	Tensile strength after cyclic test (MPa)
1.20	1	No damage	137 (average)
	2		
	3		
-	Initial value	-	140

For Level-2 earthquakes, the seismic resistance of CIPP is defined to satisfy “the limit state in which no water leak occurs even under partially plasticized status” [7]. Cyclic strain simulating a Level-2 seismic motion was applied to check the integrity of CIPP and determine allowable strain under Level-2 seismic motion.

1.2 % strain was applied on flat test pieces at the frequency of 5 Hz for 500 repetitions. No damage such as rupture was found and, again, no reduction in strength was confirmed by a tensile test after the cyclic strain tests. The 1.2% strain maintains a safety factor of 1.5 to the breaking stress of this CIPP material. Figure 11 shows the test setup and the results are shown in Table 4.

An Example of a Seismic Design Calculation

In this paper, a seismic design calculation method for CIPP has been theorized as follows.

1) The equation used is the same as one for welded steel pipe since the presence of the CIPP integrates the host pipe’s jointed structure and the entire pipeline becomes as if a single-layer, continuous pipe. However, only the CIPP’s material properties are to plugged into calculation.
2) The calculated strain is compared only to the allowable strain of the CIPP because, when the seismic performance of a full-structural CIPP is to be verified, material properties of host pipe should be ignored.

The equation used employs the response displacement method which well reflects the response properties of the ground and enables the consideration of dynamic ground motion based on a static analysis of ground displacement and strain. A model calculation is presented below with ground conditions and other calculation variables chosen from JWWA’s Guideline [9] as shown in Figure 12.

The tensile elastic modulus and the linear expansion coefficient of PALTEM’s fully structural CIPP are employed as the physical properties of CIPP. Figure 12 illustrates the model conditions and the calculation results are presented in Table 5.

As the result of the model calculation, seismic strains are within the allowable strain of CIPP for both Level-1 and Level-2 earthquake simulations. Under this condition setting, the CIPP satisfies the required seismic strength performance.

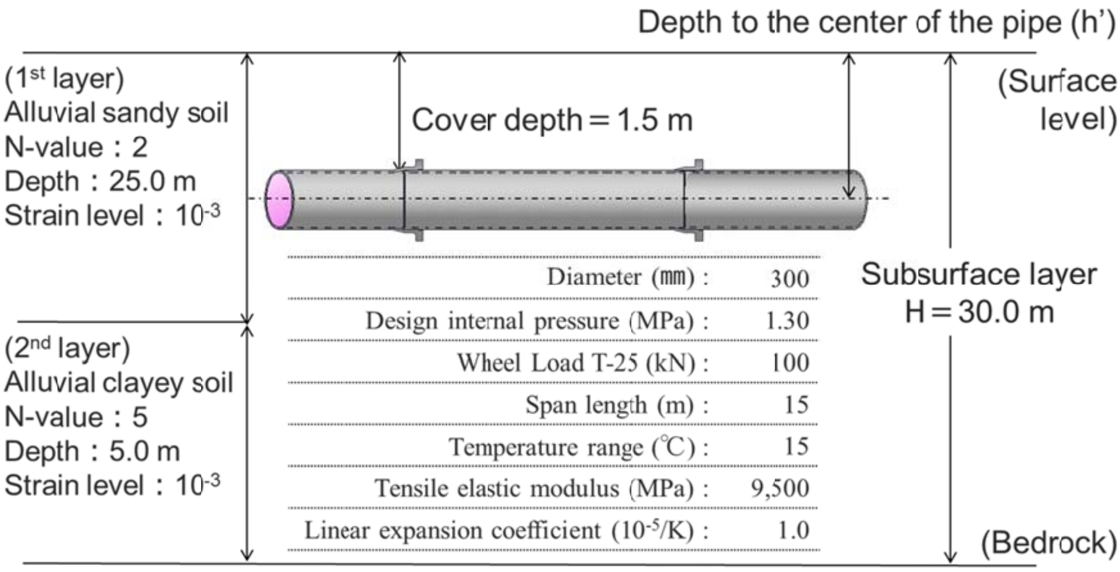

Figure 12. A model ground condition for verification, [9]

TABLE 5. VERIFICATION RESULT OF SEISMIC PERFORMANCE

		Level-1	Level-2
Normal load	Design internal pressure	0.152%	
	Vehicle load	0.046%	
	Temperature change	0.015%	
	Unbalanced subsidence	0.010%	
Seismic load		0.060%	0.502%
Total Strain in axial direction		0.283%	0.725%
Allowable strain		0.600%	1.200%
Result of verification		**Within allowable strain**	**Within allowable strain**

CONCLUSION

This study has included a survey of past CIPP installations in quake-stricken areas, physical tests on seismic behavior of simulated pipes with CIPP installed, and verification of seismic strength of CIPP by calculation under model ground conditions. The study concludes as follows.

1) There was no failure report of CIPP from areas that suffered seismic intensity of more than 6-upper and/or liquefaction.
2) A fully structural CIPP rehabilitation suppresses joint pull-out behavior of the host pipe through the friction force that develops between the CIPP and host pipe.
3) It required a more than 15 times greater load than the calculated seismic load to generate joint displacement in a pipeline that was retrofitted with the fully structural CIPP.
4) The fully structural CIPP didn't show any leak or damage even under the load that was 15 times greater than the seismic load.
5) A method has been developed to calculate the stress that acts on the CIPP-installed pipe in an earthquake using the response displacement method already in use for welded steel pipe.
6) A way to determine the allowable strain of a CIPP for Level-1 and Level-2 earthquakes has been proposed. (In the case of PALTEM Super-HL CIPP, this is 0.6% and 1.2%, respectively.)

As the result of verification and evaluation conducted during this study, it can be stated that CIPP does strengthen old potable water mains against seismic damage. A seismic design calculation reflecting different site conditions is now possible and represents a way to evaluate the seismic performance of CIPP with clearer criteria.

Future research is expected to include ground deformation status such as subsidence by broader verifications using both theoretical data to be obtained from experiments/analysis and actual data from past installation records.

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The Preliminary Study of the Impact of Liquefaction on Water Pipes

Jerry J. Chen and Y.C. Chou

ABSTRACT

Damages to the existing tap-water pipes have been found after earthquake. Some of these damages are derived from the soil liquefaction. Excess pore water pressure generated due to shear wave has been studied by way of the well-known numerical software PLAXIS in this article. The dissipation of pore pressure after soil liquefaction will cause ground subsidence. The loose sand can easier generate pore water pressure and cause a larger settlement. A greater liquefaction thickness will cause a larger ground settlement and will result in a more severe damage to DIP tap-water pipes. The numerical calculations reveal that the damage of tap-water pipe occurs mainly at the border between soil with and without liquefaction. Elongation and bending are the most common damage type happened in the existing tap-water pipes during earthquake. The installation of flexible joints has also mentioned to reduce the damage to the tap-water pipes. It is expected that the concept and calculation described in this paper would be helpful for the engineer in gaining the ability of analysis so that the more effective design can be developed for such problem in the future.

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Introduction

The dissipation of excess pore water pressure after soil liquefaction will cause ground subsidence. The uneven ground subsidence may cause damage to the existing tap-water pipe. The magnitude of ground subsidence is mainly related to the depth of soil liquefaction, thickness of soil liquefaction and inclination distribution of soil liquefaction layer. The impact of the above factors on existing tap-water pipes is studied in this article. The preliminary numerical calculation shows that the damage to tap-water pipes occurs mainly at the border between soil with and without liquefaction. In general, the uneven thickness of soil liquefaction layer and the inclined distribution of soil liquefaction layer will have a greater damage to the tap-water pipes. In addition, the numerical results reveal that the greater thickness of the soil liquefaction layer, the greater subsidence of tap-water pipe after the dissipation of excess pore water pressure caused by the soil liquefaction. To reduce the damage to the tap-water pipes, flexible joints are also introduced in this article.

Excess pore water generation due to SH shear wave

PLAXIS has options to deal with undrained behaviour in an effective stress analysis. In PLAXIS, it is possible to specify undrained behaviour in an effective stress analysis using effective model parameters. The presence of pore pressures in a soil body, usually caused by water, contributes to the total stress level. According to Terzaghi's principle, total stresses σ can be divided into effective stress σ′, and pore water pressures σ_w. However, water is supposed not to sustain any shear stress, and therefore the effective shear stresses are equal to the total shear stresses. Accordingly, the excess pore water pressure is related to isotropic stress.[1]

$$\Delta\sigma = \frac{1}{3}(\Delta\sigma_1 + \Delta\sigma_2 + \Delta\sigma_3)$$

Total stress $\sigma = K_u \varepsilon_u$

Excess pore water pressure $\sigma_{excess} = B\sigma = \frac{\alpha\varepsilon_v}{nC_w + (\alpha - n)C_s}$ $C_w = 1/K_w$ $C_s = 1/K_s$

Effective $\sigma' = (1 - \alpha B)\sigma = K'\varepsilon_v$

In which K_W is the bulk modulus of water; K_S is the bulk modulus of soil material; n is the soil porosity; B is the Skempton parameter.

In PLAXIS it is possible to simulate pore pressure generation derived from SH wave excited at ground bottom, as shown in Figure-1a. The finite element mesh in calculation is shown in Figure.-2a. The pore pressure generation at different depth of ground is given in Figure.-2a, which reveals that the pore pressure generated during the course of earthquake seems not much difference.

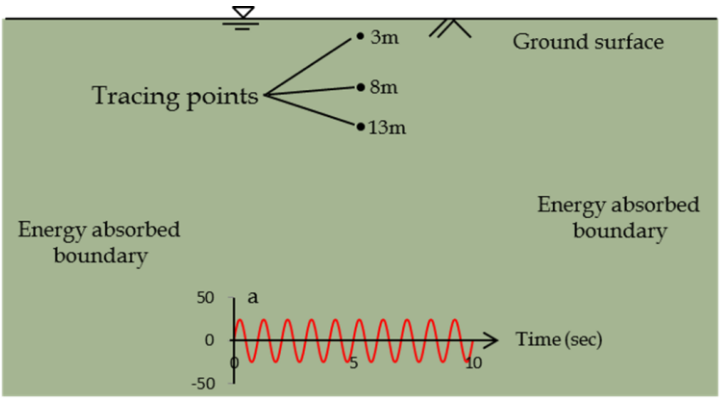

Figure-1a Layout and tracing points of pore pressure

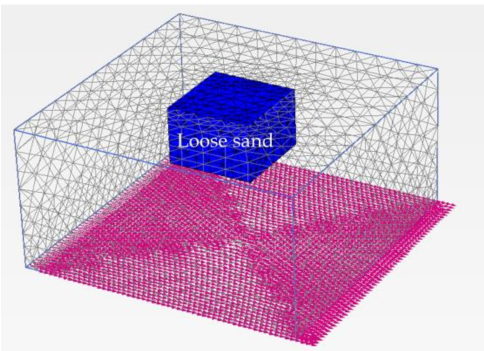

Figure-1b Finite element mesh in calculation

However, the excess pore pressure stress ratio r_u is obviously difference, where the stress ratio r_u is defined as the pore water pressure (u_w) divided by its effective overburden pressure (σ'_v), i.e. $r_u = u_w/\sigma'_v$, as shown Figure-2b. In the liquefied zone, $(u_w)_{max}$ would always equal to the effective overburden pressure (σ'_v), i,e. r_u=1.0

$$\text{Excess pore pressure ratio } \mathrm{r_u} = \frac{\text{excess pore water pressure } (u_w)}{\text{effective overburden pressure}(\sigma'_v)}$$

Figure 3 is the typical time history of excess pore pressure generated by the shock wave at various depths below the ground surface. The pore pressure ratio $r_u = u_w/\sigma'_v$ was used to estimate the liquefaction during earthquake.

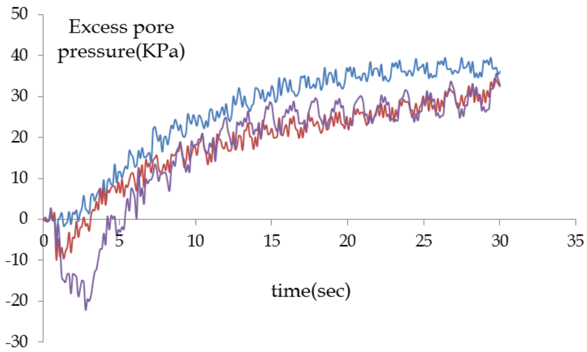

Fig-2a Excess pore pressure at various depth

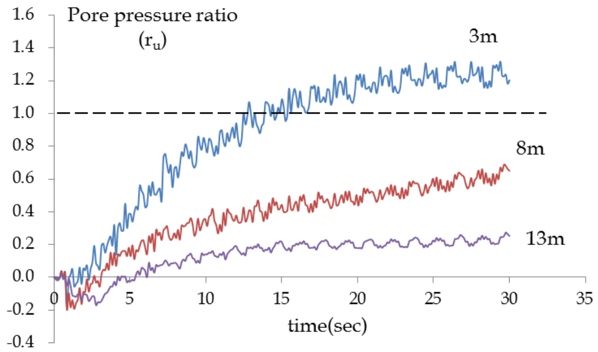

Fig-2b Excess pore pressure ratio at various depth

Excess pore water generation in various underground water tables

The location of ground water table below the ground surface will dramatically affect the liquefaction potential of soil. The lower ground water will not easy to generate excess pore pressure during earthquake. Figure-3 indicates the pore pressure generation at various ground water tables below the ground surface. It can be seen that the pore pressure generation is quite sensitive to the ground water table. The numerical calculations show that it is difficult to bring about liquefaction if the underground water located at more than 5m below the ground surface.

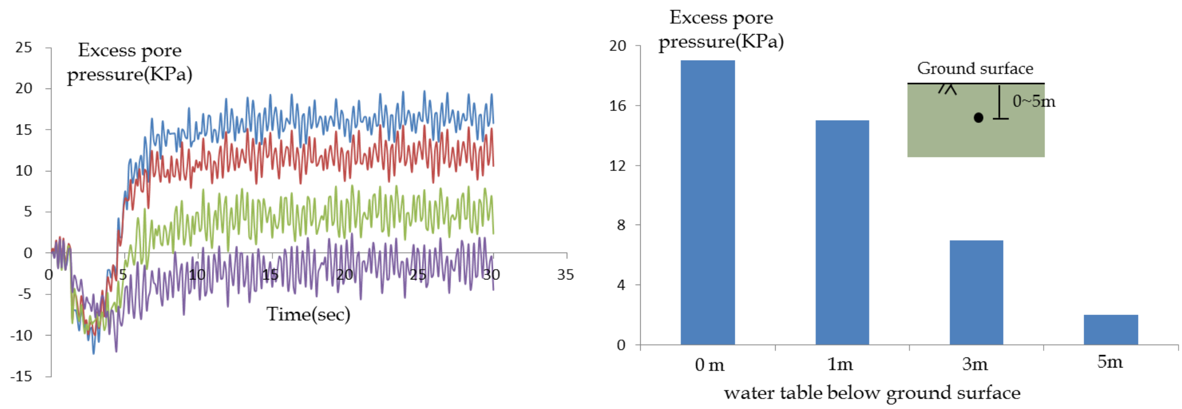

Figure-3 Pore pressure generated with various water table

Ground settlement due to liquefaction

The pore pressure generated during earthquake has to be dissipated to equilibrium the pore water pressure in the surrounding liquefaction area. According to the theory of consolidation, the ground located at liquefaction area will be settlement after the dissipation of the excess pore water pressure. The dissipation of excess pore pressure will result in the consolidation of the ground. In the liquefied zone, the excess pore pressure would always equal to the effective overburden pressure (σ'_v) so that it will induce a liquefaction. Accordingly, the settlement derived from the liquefaction means that the liquefaction layer below the ground subjected to another the effective overburden pressure, which is only limited to at the range of liquefaction. A higher excess pore pressure generated corresponds to a larger settlement. In general, the loose sand can easier generate pore water pressure and cause a larger settlement, as shown in Figure.-4. Also, a greater liquefaction thickness will cause a larger ground settlement.

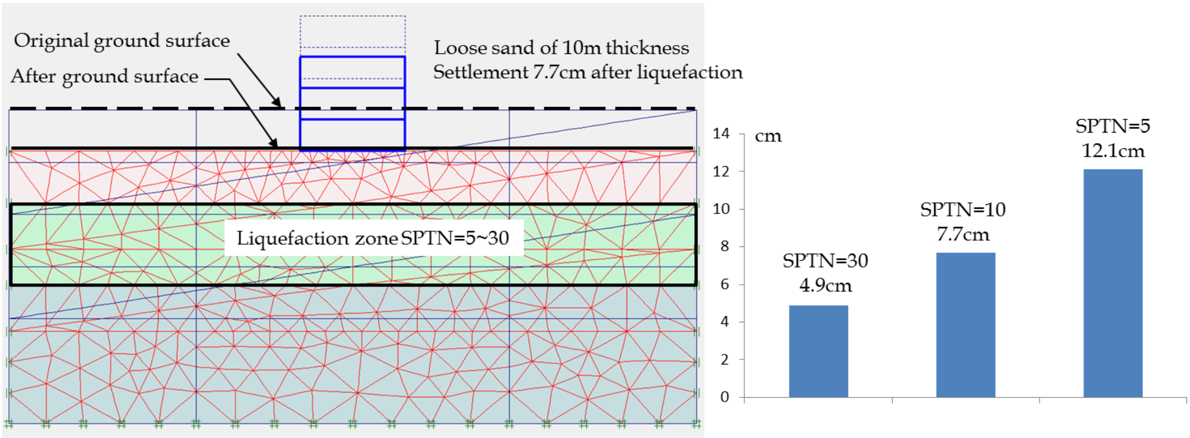

Figure-4 Settlement in different sand properties after liquefaction.

In addition, the distribution of liquefaction zone will affect the distribution of ground settlement. Figure-5 shows the incline liquefaction zone will lead to the building tile after earthquake if liquefaction happened.

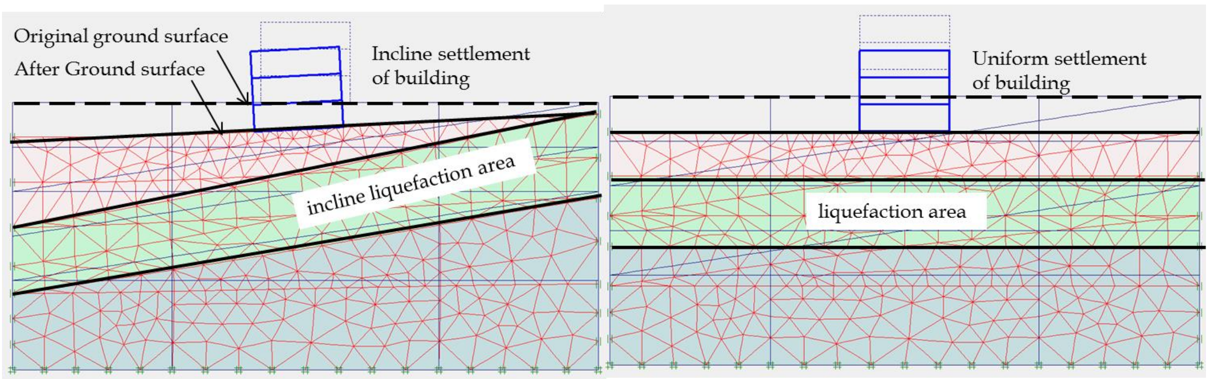

Figure-5 Ground settlement due to incline liquefaction area

The allowable elongation and rotation angle of ductile cast-iron pipe (DIP)

The DIP tap-water pipe buried in the ground is not a one-piece molding. In general, the DIP tap-water pipe is made up of multiple ductile cast iron pipes (DIP). The connection of each cast iron pipe possesses a certain allowable rotation angle and expansion or compression. Accordingly, the ductile cast iron pipes (DIP) is allowed to be constructed in the road turn or climb up and down.

The K-type DIP of 6m in length is widely used in the underground tape-water pipe. The allowable amount of expansion/compression and rotation angle is 3.4cm and 1.5°, respectively, which corresponds to the rate of change in the vertical and horizontal is 0.0262, H/V=0.0262, as shown in Figure-6. The deformation and rotation angle of cast iron pipes (DIP) due to the liquefaction settlement shall be less than the allowable value. [2][3]

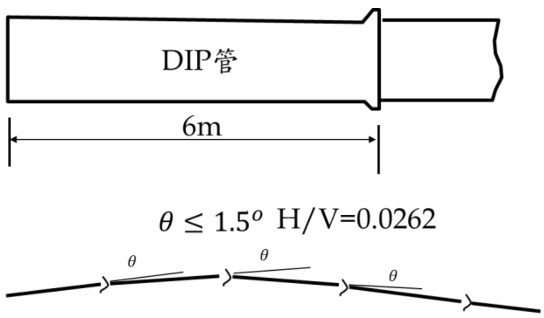

Figure.-6 Allowable rotation angle of ductile cast-iron pipe (DIP)

The engineering properties of ground and DIP tap-water pipe

By way of numerical calculation, the impact of liquefaction settlement on the DIP tap-water pipe will be studied in this article. The engineering properties of ground and DIP tap-water pipe have to be included in the FEM analysis. In accordance with the geological investigation, the ground in this analysis consists of saturated loose sand and dense sand. The engineering parameters adopted in the numerical calculation are given in Table-1.

Table-1 Engineering properties adopted in numerical analysis

	SPT-N	E (KPa)	υ	c (KPa)	φ (degree)	Remark
Sand_1	5	10000	0.35	5	29	Loose sand
Sand_2	35	70000	0.32	5	38	Dense sand
DIP	-	1.67E8	0.33	-	-	

Configuration and finite element mesh in numerical calculation

In accordance with the preliminary evaluation, the saturated loose sand is prone to liquefaction. The whole area includes soil with different natures, such as clay, loose sand and dense sand. Accordingly, the DIP tap-water pipe may pass through possible liquefaction area and non-liquefaction area. The liquefaction zone will cause settlement after the earthquake, whilst the non-liquefied zone will remain unchanged. Thus, the area located at boundary of liquefaction zone and non-liquefaction zone will undertake an uneven settlement, which will damage to the DIP tap-water pipe. The uneven settlement due to liquefaction will stretch and twist the DIP tap-water pipe. The numerical analysis in this paper aims to study the elongation and rotation angle in DIP tap-water pipe when liquefaction happened. Therefore, whether the designed DIP can meet the requirement will be examined.

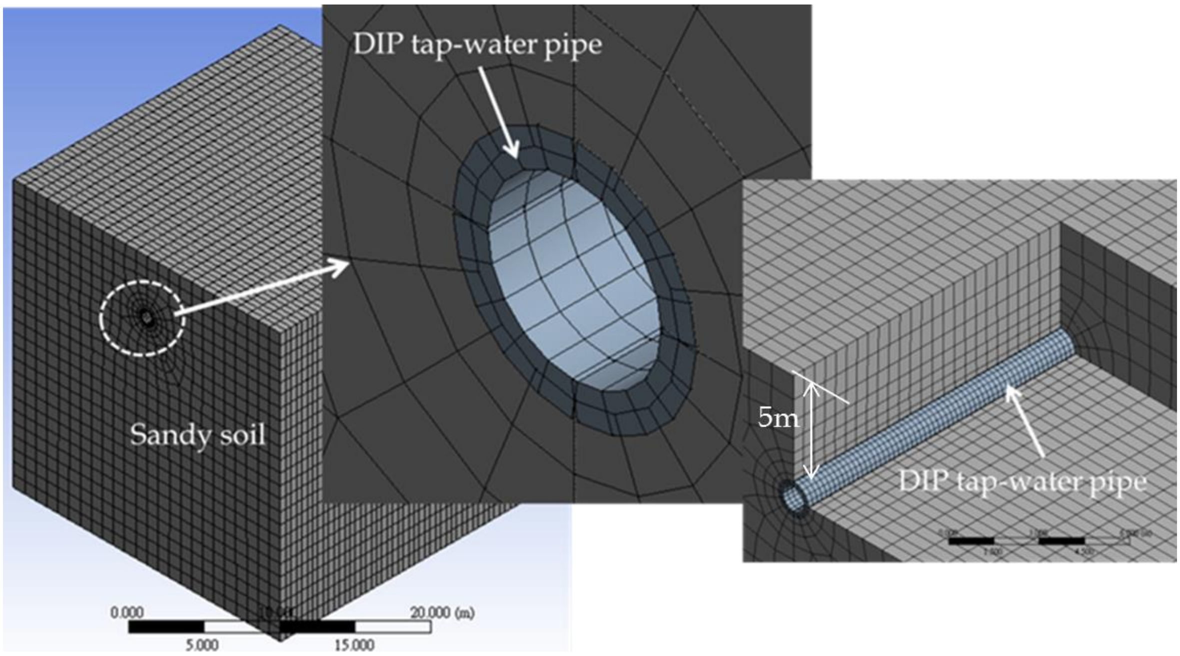

Figure.-7 Configuration and finite element mesh in numerical calculation

To avoid the difficult selection of soil spring parameters in the calculation of soil-structure interaction, it has been suggested that soil and DIP tap-water pipe shall be simultaneously considered in the three-dimensional numerical calculations. In the finite element calculation, block elements are used to simulate the ground settlement in the whole area. The block element can only provide stress tensor $\sigma_x, \sigma_y, \ldots \tau_x, \tau_y, \ldots$, which is not available for the design so that shell elements will be adopted to simulate ductile cast-iron pipes to obtain the axial force, shear force and bending moment in the DIP tap-water pipe. The block element and shell element are different attributes. Therefore, the contact behaviour has to be experienced to bond these two different types of elements. [4]

Results of finite element calculation

The DIP tap-water pipe is buried at 5m beneath ground surface. The configuration and finite element mesh in numerical calculation is given in Figure.-7. Based on the engineering parameter given in Table-1, the FEM numerical approach reveals that the soil liquefaction results in around 8cm ground settlements. The results of numerical calculation are depicted as follows

Except for the DIP tap-water pipe located at boundary between liquefied and the non-liquefied zone, the displacement of tap-water pipe presents uniform since the thickness of the liquefaction layer is uniform as well. The ground settlement and DIP's deformation due to liquefaction are given in Figure-8, which shows that large settlements will occur in the range of liquefaction area. Moreover, the liquefaction settlement will affect a nearby range where the DIP tap-water pipe will be subjected to an extra elongation and will lead to an extra axial force and bending moment.

In this study case, the thickness of loose sand is 8m. The DIP tap-water pipe is buried at 5m below ground surface. The numerical analysis shows that the liquefaction settlement is around 0.8cm.. The DIP subsidence derived from liquefaction will stretch and twist the DIP tap-water pipe rested on the border of liquefied and non-liquefied zone.

Examination of rotation angle and elongation in ductile cast iron pipe (DIP)

Earthquake shaking will generate excess pore water pressure and even cause soil liquefaction. After earthquake, the dissipation of excess pore water pressure will lead to a ground subsidence.

The DIP tap-water pipe located not at the liquefaction zone would not be damaged. However, the DIP tap-water pipe may be damaged if the pipes are rested on the liquefaction area. The larger ground settlement will result in a more severe damage to DIP tap-water pipes, in particular, when the DIP tap-water pipes are located at the boundary between liquefied and non-liquefied areas. The numerical calculation shows that the DIP tap-water pipe located inside the liquefaction zone presents an uniform deformation. Nevertheless, the DIP tap-water pipes will undertake a serious distortion if the pile is located at border of liquefied and non-liquefied areas.

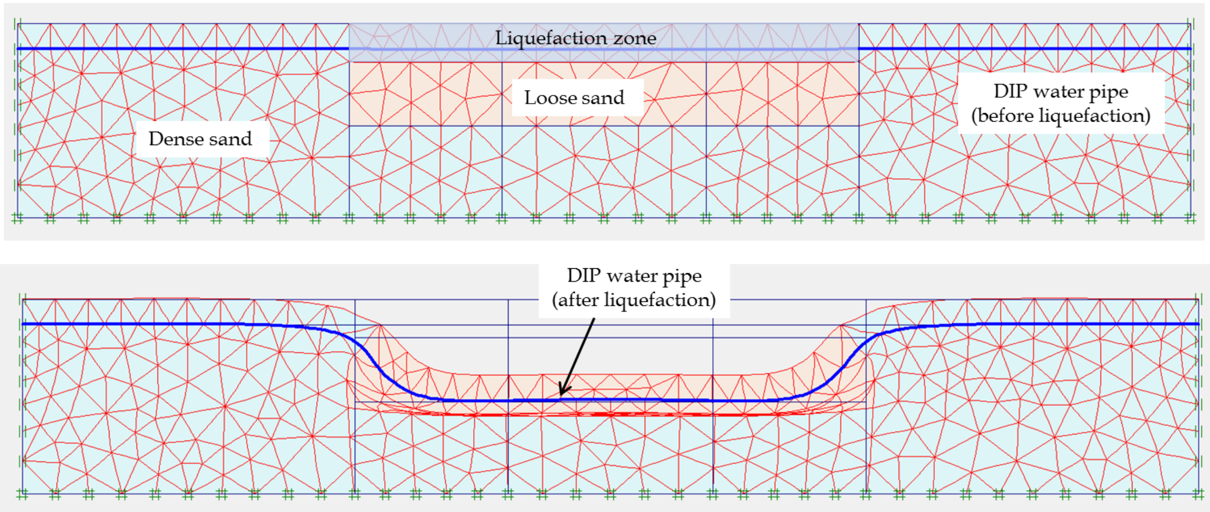

Figure.-8 Deformation of DIP tap-water pipe before and after earthquake

The ground settlement will draw the tap-water pipes. The shape of pipe elongation due to pulling out presents a similar to that of hyperbolic secant curve, as shown in Figure.-9. The rate change of elongation indicates the bending angle of DIP tap-water pipe and it looks like a similar to Gauss curve, as shown in Figure.-10. The overall shape of the stretched tap-water pipe looks like a hyperbolic secant curve. The largest deformation and bending angle of the tap-water are all at in the middle of the stretched curve. In general, a larger liquefaction settlement will cause a more severe elongation and bending angle in DIP tap-water pipes. Accordingly, the axial elongation and bending angle due to the large settlement derived from liquefaction have to be calculated to examine whether the liquefaction will cause the damage to the DIP tap-water pipe.

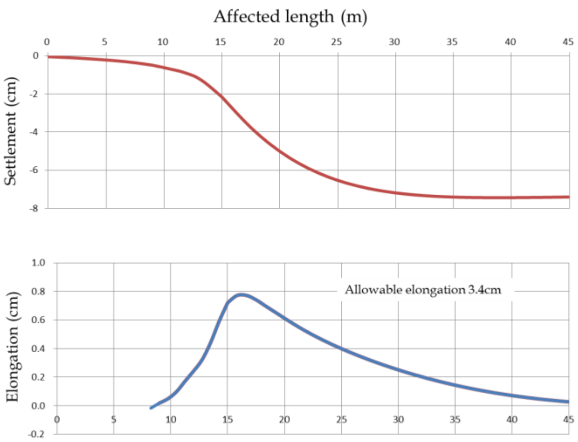

Figure.-9 Elongation of DIP tap-water pipe

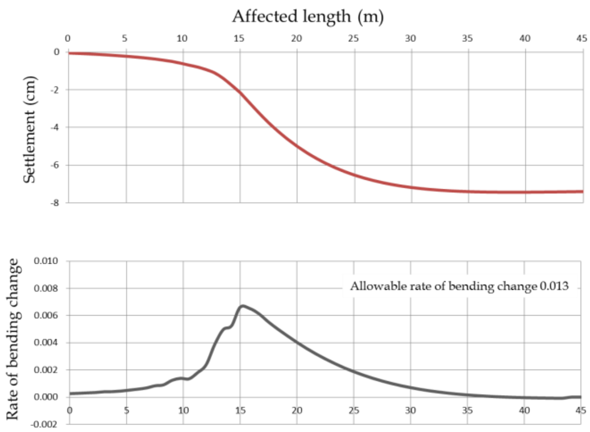

Figure.-10 Bending angle of DIP tap-water pipe

In accordance with the engineering properties of DIP tap-water pipe, the allowable amount of expansion/compression is 1.7cm if the safety factor 2 is taken into account. The numerical calculation shows that the elongation of DIP tap-water pipe resulted in liquefaction settlement is only 0.8cm, which has no exceeding the allowable limit, as shown in Figure.-9. Similarly, the rate change of bending is about 0.0075, which is much less the allowable limit of 0.013. Consequently, the liquefaction settlement is not large enough in the above calculation so that it needs not to install the flexible joint to absorb the large deformation. [5]

Installation of flexible joints if necessary

In this study the liquefaction thickness is 8m below the ground surface and the settlement after earthquake is only about 8cm. It displays no harm to the existing tap-water pipes. However, the liquefaction settlement may result in damage to the tap-water pipe if the liquefaction thickness is large enough. Usually, a larger liquefaction thickness corresponds to a greater ground settlement and the DIP water-pipe will be subjected to a stretch displacement, which will lead to an extra axial force and bending moment on tap-water pipe. To reduce the extra force on tap-water pipes, flexible joints are suggested to be installed to absorb the stretch displacement of water-pipe. In general, the stretch displacement takes place amid the border between the liquefied and the non-liquefied zone and the shape of the stretch displacement presents a similar to the Gaussian curve, as shown in Figure.-9&10. The most elongation of water-pipe is at the middle of the stretch range so that the function of the flexible joint can be fully developed if the flexible joint is installed in the middle of the stretching range.

Conclusions

- The location of ground water below the ground surface will dramatically affect the liquefaction potential of soil.
- The loose sand can easier generate pore water pressure and cause a larger settlement. Also, a greater liquefaction thickness will cause a larger ground settlement.
- To avoid the difficult selection of soil spring parameters in the calculation of soil-structure interaction, it has been suggested that soil and water-pipe shall be simultaneously considered in the three-dimensional numerical calculations.
- The larger ground settlement will result in a more severe damage to DIP tap-water pipes, in particular, when the DIP tap-water pipes are located at the boundary between liquefied and non-liquefied areas.
- Except for the bending of DIP, it also needs to examine the amount of DIP elongation. The flexible joint can absorb the DIP elongation and reduce the bending of DIP.
- The most elongation of water-pipe is at the middle of the stretch range so that the function of the flexible joint can be fully developed if the flexible joint is installed in the middle of the stretching range.

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[4] ANSYS on-line manual 2013
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Developing Business Continuity Management in Kobe City Waterworks Bureau

Akinori Sakata, Masahiro Wada, Tsutomu Mitsuishi and Nagahisa Hirayama

ABSTRACT

It is expected to keep supplying water even in an emergency, because water is indispensable for daily life and urban activities. Recently risks of natural disasters including earthquake, climate change, and terrorism and so on are increasing. Kobe City decided to develop Business Continuity Plan (BCP). Furthermore we found that it would be important to raise BCP and to establish management process, named as Business Continuity Management (BCM).

Generally most of Emergency Manuals based on individual “causes” of disasters. It would be difficult to deal with complex causes and an unexpected event if we think only one cause. Therefore we should aim to make the manual which is focused on the “result”.

Furthermore we think capacity development is very necessary. So the staffs should participate in developing BCP, which contains increasing awareness of impending crisis and developing ability for emergency response. We revised the existing manual through workshops in order to take advantage of the staffs’ know-how.

In addition we investigated all the contents thoroughly and integrate them into the BCP. The components of Kobe’s BCP is as follows, 1) Duty Table – Duties at the time of disaster. 2) Duty List – check list of duties listed in Duty Table. 3) Work Flow – flowchart of chronological order

We have developed our BCP with focusing on “the result” instead of “the cause”, to deal all kinds of disasters. From now we will keep revising BCP through table top exercises and will complete BCM, then we will be able to continue to supply water in emergency time.

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INTRODUCTION

Waterworks must be robust enough to supply water even under an emergency to support the citizen life. There are many kinds of risk which may adversely affect the safe and secure water supply, such as natural disasters like earthquakes and water shortage, water quality problems due to abnormal raw water quality, facility problems like water pipeline burst or equipment failure, a new type flu epidemic, and a terror. In the event of an emergency, the number of staff or facilities may not be sufficient due to additional works to cope with disasters, which are normally not required. Staff will be required to act by their judgement when necessary. It is important to decide "who will do what, when, how, and for what reason" in advance.

BUSINESS CONTINUITY PLAN (BCP)
AND BUSINESS CONTINUITY MANAGEMENT (BCM)

Business Continuity Plan (hereafter called BCP) is a plan which enables the continuity or quick recovery of important businesses. BCP prioritizes businesses to determine the operation system and operation procedures in advance. Those preparations allow the business not only to recover quickly but also to reduce impacts to its operations.

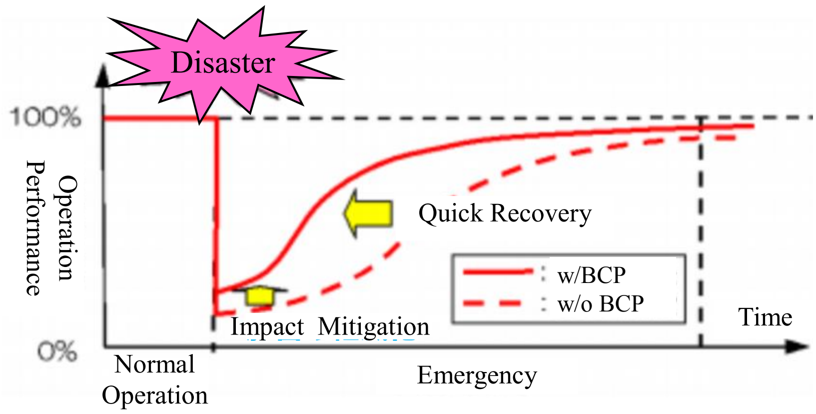


Figure 1. Concept of the BCP

Business Continuity Management (hereafter called BCM) is the management activity under a normal operation which continuously improves the BCP so that effective and reasonable business continuity will be ensured under an emergency.

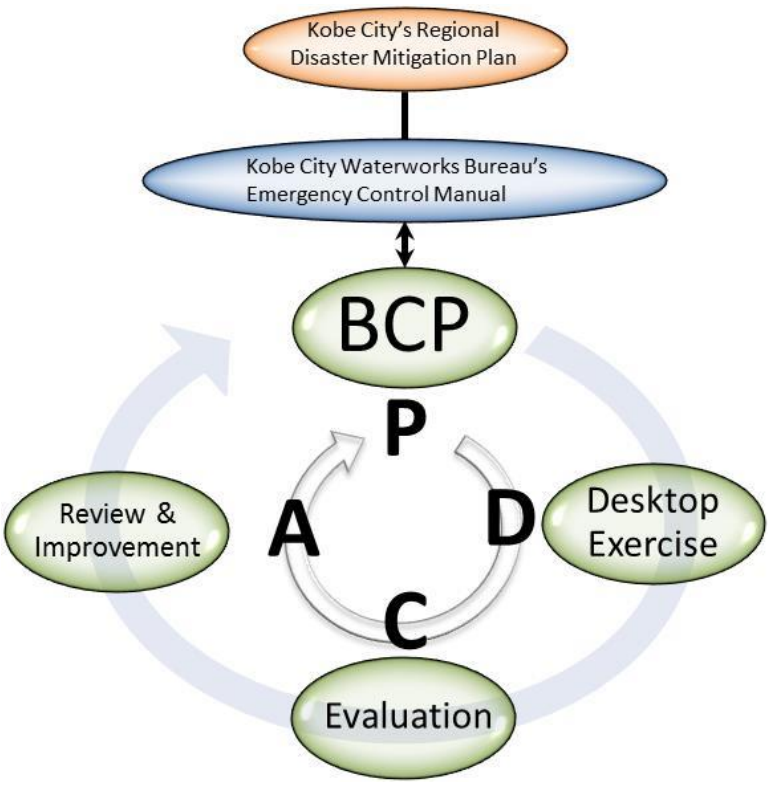


Figure-2. Concept of the BCM

ESTABLISHING THE BCP

Assumed Emergency

Many of BCPs are prepared focusing on the "root causes of an emergency", in other words, "cause events". This approach results in setting disaster by disaster countermeasures, which makes it difficult to apply the solution to complex cases. Another issue of this approach is that it cannot react to an unexpected case.

To continue important operations no matter what an emergency occurs, Kobe City Waterworks Bureau decided to focus on the "results from an emergency", in other words, "result events" when it sets up the BCP manual, rather than the "cause events".

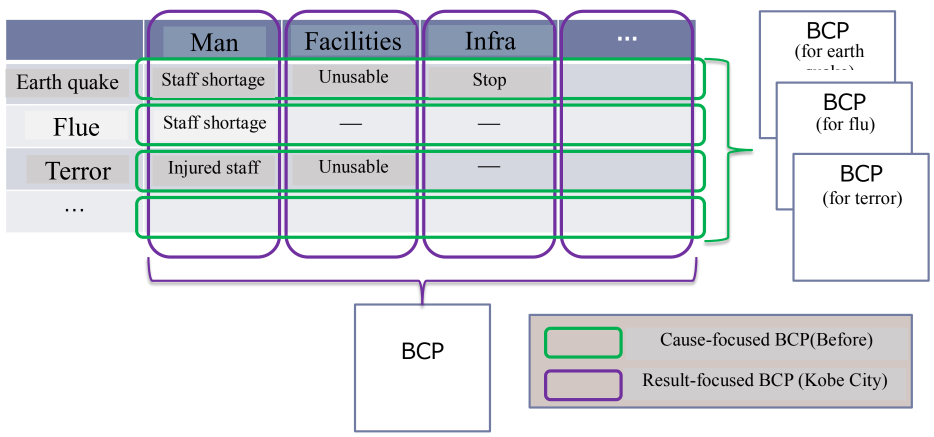


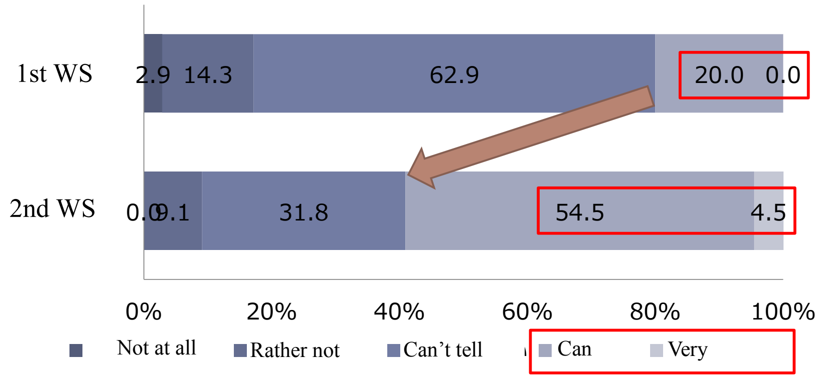
Figure-3. Damage assumptions of Kobe City Waterworks Bureau's BCP

Procedure for Establishing the BCP

The purpose of crisis management activities in Kobe City Waterworks Bureau is sharing common understandings about an emergency and enhancing the ownership feeling among staff. Workshop style lecture was adopted since the staff participative plan setting will penetrate the BCM more effectively in the organization as countermeasures for an emergency.

Two workshops were held in 2014, selecting 39 staff, which account for 5 % of total number of staff, both from office workers and from technical workers. The first workshop specified emergencies that the waterworks bureau may encounter and discussed the issues and countermeasures for businesses, organizations, and individuals. The second workshop selectively focused on a water leakage case and analyzed what needed to be done in chronological order. Surveys were carried out on those participants and effectiveness of the workshop was measured. After the first workshop, positive responses ("Strongly can" or "can") to a question of "How much can you image an emergency concretely which applies to Kobe City Waterworks Bureau?" accounted for 20 %, while after the second workshop, the positive responses to the same question reached up to 59 %.This result implies that the staff participative workshop improved the awareness against emergency among staff.

Figure-4. Workshop at Kobe City Waterworks Bureau



[Summary of Answer]
Q. How much can you image an emergency concretely which applies to Kobe City Waterworks Bureau?

Fig-5. Survey result comparison between the first and the second workshops

In 2015, based on the outcome from the workshop, operation flow was clarified. Survey on priority of operations was carried out to each department and a proposal of the BCP was prepared.

In 2016, a desktop exercise was performed to confirm that the proposed BCP is sufficient and to find out if there is anything to add to it. Staff from each department gathered in an online conference room. The assumption was that a suspect was captured at a distributing reservoir facility. Public relations and the manual format were pinpointed as improving areas after the exercise.

The new BCP of Kobe City Waterworks Bureau has just been prepared in January 2017 incorporating the feedbacks from the desktop exercise.

STRUCTURE OF THE BCP

Kobe City Waterworks Bureau prepared a crisis management operation manual in 2012, integrating separately prepared manuals for natural disasters, abnormal water quality problems, terrors, etc. after reviewing each content. While it enabled to find any countermeasures in one manual, the large volume brought a difficulty for a staff to find out an appropriate section quickly.

To solve that issue, Kobe City Waterworks Bureau's BCP consists of three parts, which makes it easier to use as a manual: 1. "Operation list" which analyzes operations under disaster, 2. "Operation flow chart" which clarifies the operation flow in chronological order, 3. " Operation card" which is a checklist of the operations listed in the "Operation list".

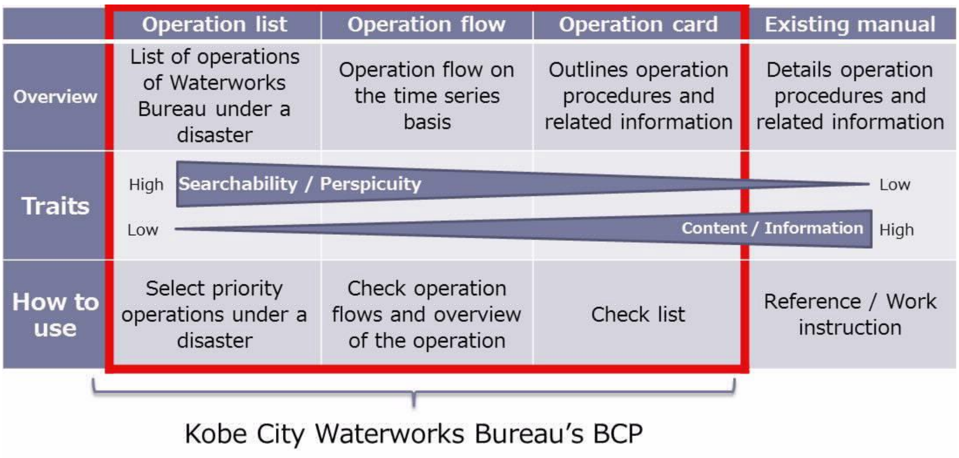


Figure-6. Structure of Kobe City Waterworks Bureau's BCP

Operation List

A operation list was prepared. This will help to understand the overview of Waterworks Bureau's operations (normal and emergency operations) and will benefit to make operations more effective. The operation list includes information about each operation regarding the department in charge, existence of manuals, and the inputs / outputs for that operation.

The operation list also includes priorities at each timing after the occurrence of a disaster with a range of "in a few hours", "in a few days", and "in a few weeks". Those priorities were set based on the survey of each department. The range will allow the staffs to cope with unexpected events such as when the assumption did not match the actual disaster.

Category 1=Temporal 2=Normal	Dept.	Operation	Input	Output	Priority			Assumptions			
					Within a few hours	Within a few days	Within a few weeks	Staff shortage	Fund and material shortage	Facility and equipment shortage	Water pollution ,etc
1	All	Safety Check		Form A	High	Low	Low			○	
1	General affair Section	Collect safety information	Form A		High	Middle	Low			○	
…	…	…	…	…	…	…	…				

Figure-7. Operation list

Operation Flow

The operation flow analyzes the operations listed on the operation list in chronological order basis from the occurrence of a disaster and to the completion of the recovery. It will accommodate a smooth communication between the central office and the branch offices. The operation flow explicitly shows "What process a department is working on in the entire process" and "What will be delivered to the department (INPUT) and what should be done by the department and who is to receive the results (OUTPUT)".

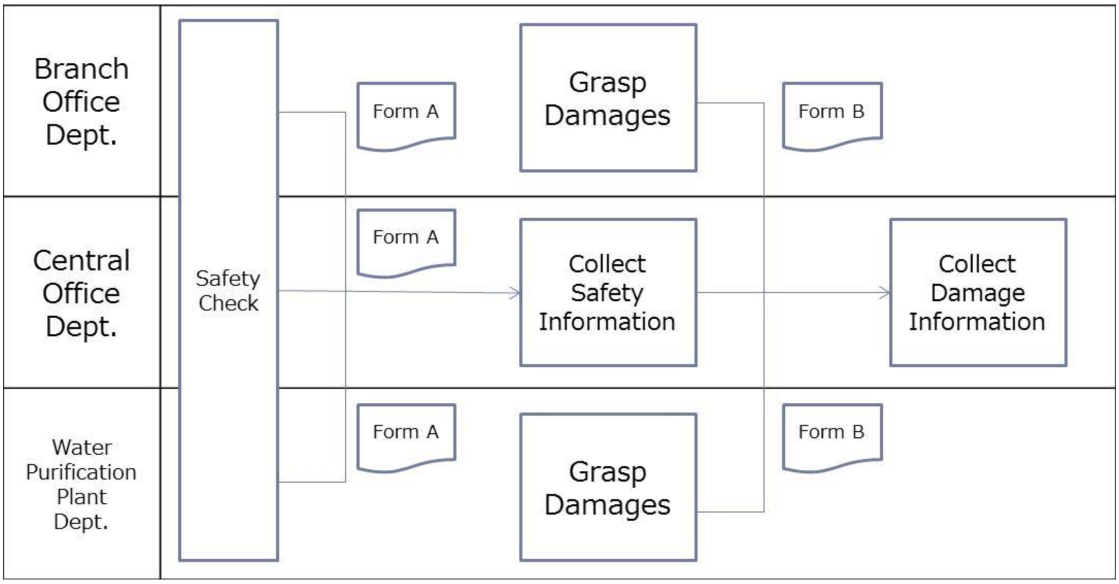


Figure-8. Operation flow

Operation Card

The operation card will enable each staff to complete an allocated operation no matter who it is. It includes a check list of operations listed in the operation list. The card consists of basic information (department of a staff in charge, name of the staff, when to perform the operation), operation procedure, related information (existence of manuals or contacts), and other special information. The related information section includes , so that a staff can quickly open a correct page of the existing manual, when needed.

◆Operation Card (Check sheet)

	■Emergency Operation □Normal Operation	ID No.	0-1
Operation	Check a source of ignition or gas leakage / Initial fire fighting / Restore the office		
Input	—		
Output	—		

Basic Information
・Operation name
・Input / Output, etc.

1. Basic Information

Department	
Position / Name	
Operation period	yyyy/mm/dd hh:mm - yyyy/mm/dd hh:mm

Input Information
・Name of the staff
・Operation period

2. Operation Procedure

	Operations detail
□	(When the magnitude of the quake is large) Hide and set the body as low as possible and wait the shaking subsides.
□	The fire-warden to take preventive actions. (Cut the gas and the electricity)
□	(When fire occurred)Perform the initial fire fighting using a close-hand fire extinguisher, etc.
□	(When fire expanded despite the initial fire fighting)Ask the fire fighters for support.
□	Conduct emergency measures, prevent a source of ignition from catching fire, and stop gas leakages.
□	Conduct life saving activities such as rescue of people and first-aid treatments.
□	
□	

Operation Procedure (Check list)

3. Related Information

Category	Yes / No	Detail
Manual	■Yes □No	Kobe City Waterworks Bureau's Crisis Management Manual（Ⅰ-8～15、Ⅲ-1～2）
Map / Documents	□Yes ■No	
Contact	□Yes ■No	
Related regulation	□Yes ■No	
Other materials/equipment	□Yes ■No	

Related Information
・A page number of the manual to refer to
・Form, etc.

Fig-9. Operation card

FUTURE ACTIVITIES

Kobe City Waterworks Bureau has been working on preparing the BCP focusing on the “result events”, not “cause events”, so that we can cope with variety of disasters.

The BCP-based desktop exercise was held and it enhanced ownership feeling against emergency among staff. Our plan is to make the BCP more complete and to set up the BCM so that we can effectively continue business even under an emergency environment.

Cross-sector Infrastructure Planning for Water Purveyors and Critical Care Facilities

Anna T. Lau, Jose L. Rios, and Xavier J. Irias

ABSTRACT

Water supply interruptions from a major catastrophic event can severely compromise the operations of a medical facility during a time when the facility's services are most needed by society. For example, in a magnitude 7 earthquake, the East Bay Municipal Utility District (EBMUD) is expected to experience 4,000 to 6,000 main breaks, which could impact one or more of the sixteen hospitals in EBMUD's service area. To better assess and support emergency water supply planning for these critical customers, EBMUD launched a hospital outreach program to discuss its water system capabilities, limitations, and emergency preparedness measures. The twofold purpose of this program is to survey and better understand hospitals' emergency water supply readiness and expectations, and to facilitate coordinated planning efforts to enhance water supply resilience.

This paper summarizes findings from recent outreach efforts to six of the sixteen hospitals in EBMUD's service area that have recently completed seismic retrofits and upgrades to their facilities. While most hospitals have a general awareness of water supply disruptions resulting from emergencies, few were prepared for the severity and lengths of possible water service impacts, and some were overly optimistic about the quantity of water required to sustain operations. During recent seismic retrofits and hospital upgrades, the hospitals addressed critical infrastructure needs, but some did not incorporate adequate on-site storage for a 72-hour water outage or build sufficient redundancy to strengthen emergency water supply reliability. In fact, only two out of the six hospitals is currently in compliance with the California Office of Statewide Health Planning and Development (OSHPD) 2030 requirements for on-site storage.

EBMUD's outreach experience suggests that improvements in four areas – awareness of water infrastructure vulnerabilities, understanding of emergency water supply needs, implementation of on-site water storage or alternative water supply, and coordinated planning – could greatly enhance emergency planning for water purveyors and medical facilities, leading to better performance across both infrastructure sectors.

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INTRODUCTION

The East Bay Municipal Utility District (EBMUD) is a water/wastewater utility located in the San Francisco East Bay Area of California, USA providing water service to approximately 1.4 million customers in a seismically active area. As the owner and operator of important lifelines, EBMUD is continuously concerned with providing reliability, security and resilience in the face of various hazards.

Following the 1989 earthquake that damaged the water system, EBMUD initiated a major seismic upgrade program to its system after studying and evaluating the vulnerability and reliability of its critical facilities. The first step in the upgrade was a seismic evaluation which indicated that in a magnitude 7 earthquake, EBMUD could experience 4,000 to 6,000 main breaks in its over 4,200 miles of pipelines, plus damage to many of its storage, pumping, transmission lines and treatment facilities. As a result, EBMUD developed and implemented a retrofit program that invested more than US$350 million to strengthen its water and wastewater facilities for seismic safety. EBMUD continues to enhance seismic reliability with ongoing facility improvements.

In addition, EBMUD continues to enhance its emergency preparedness with its robust emergency plans to protect lives and ensure an orderly approach to disaster recovery. EBMUD prepares for emergencies by proactively monitoring and improving its facilities, conducting emergency training exercises, maintaining business continuity plans to recover critical functions quickly, and coordinating emergency preparedness efforts with other agencies. EBMUD has mutual aid response agreements with a water agency in southern California and a water agency in Nevada, both chosen to be outside the likely impact zone for most hazards that could strike EBMUD, but near enough to offer prompt aid. EBMUD has also worked with other water agencies to establish emergency intertie connections that could be utilized to transfer water supplies between EBMUD and the San Francisco Public Utilities Commission via the City of Hayward to the south, the Contra Costa Water District to the east, and the Dublin San Ramon Services District to the southeast.

In spite of EBMUD's efforts to strengthen its facilities and continually prepare for emergencies, EBMUD recognizes that a major seismic event will likely result in substantial water supply impacts to its customers. A 2015 study[i] of cross-sector interdependencies identified that an area of particular concern is other critical infrastructure sectors, i.e., those EBMUD relies upon to provide water service and those that rely upon water to perform their essential functions. In particular, that study determined that planning-level assumptions across critical infrastructure sectors were not consistent, and suggested that better information sharing across sectors might substantially improve overall societal resilience. In response to that finding, EBMUD undertook increased dialogue and outreach with the hospitals served by EBMUD. This paper describes the outreach process and key lessons learned, which might be helpful to other utilities seeking to reduce cross-sector impacts and increase societal resilience.

BACKGROUND

In EBMUD's service area, there are currently sixteen general acute care hospitals varying in size and characteristics (number of beds, building heights, age of building construction, etc.). These hospitals are located in different parts of the EBMUD water distribution system with different pressure zones and varying water pressure, storage and pumping supplies, and related infrastructure. Figure 1 presents the EBMUD water service area and the locations of the sixteen hospitals.

In 2001, a major new law known as SB 1953 was passed which called for hospitals in California to improve seismic performance. The law called for a suite of measures, including structural retrofits, non-structural retrofits, and provisions, to withstand up to three days' outage of lifeline services, including electrical power and potable water. The law set out various compliance dates for the measures. A complicating factor in compliance is that oftentimes a seismic structural upgrade to a hospital triggers a host of other regulations. For example, disabled access provisions may be required, which could make retrofits fairly complex or even lead to reconstruction in lieu of retrofit. Accordingly, the compliance dates for the law have been adjusted over the years.

To help hospitals chart a course toward compliance with SB 1953, EBMUD in 2002 embarked on a study to assess water service issues and evaluate water service reliability improvements to the hospitals in its service area. After two years of study and outreach efforts with the hospitals, EBMUD completed a final report[ii] that focused on each hospital's existing water service, water needs, and evaluation of potential alternatives, if any, to improve water service reliability. Some of the key findings and benefits of this initial outreach include:

- Hospitals' primary focus was on meeting regulatory requirements for seismic upgrades by 2013.
- All of the hospitals had some on-site emergency water supplies and the hospitals planned to augment these supplies to meet 2030 regulatory requirements (storage supply of 189 liters (50 gallons) per day per bed for 72 hours).
- Hospitals and EBMUD gained a better understanding of the hospitals' existing water service, water use, and emergency water needs and expectations.
- Hospitals were made aware of potential alternatives to improve water service reliability at their expense.
- The hospitals and EBMUD obtained up-to-date contact information.

The report was provided to the hospitals in 2004 and also recommended that EBMUD continue to maintain contact with all the hospitals to ensure contact lists and water supply information were updated. Accordingly, EBMUD has completed periodic updates by reaching out to the hospitals over the years. In 2015, EBMUD conducted a phone survey of the sixteen hospitals to obtain updated contact information and to assess the hospitals' emergency water preparedness. The survey highlighted a range of knowledge and level of emergency preparedness among the hospitals. The 2015 survey also revealed that there are frequently gaps between the water supplier's projections about possible water service interruptions and likely impacts, and the perceptions of its key customers as to their exposure to service interruptions. This gap was discussed in a 2015 paper[i] that examined cross-sector knowledge gaps.

As a follow up to the 2015 findings, EBMUD has conducted a concerted effort to reach out and meet with several hospitals that completed hospital retrofits or new construction. This paper will examine what EBMUD learned in regard to those hospitals' emergency preparedness improvements, particularly water supply improvements for emergency purposes.

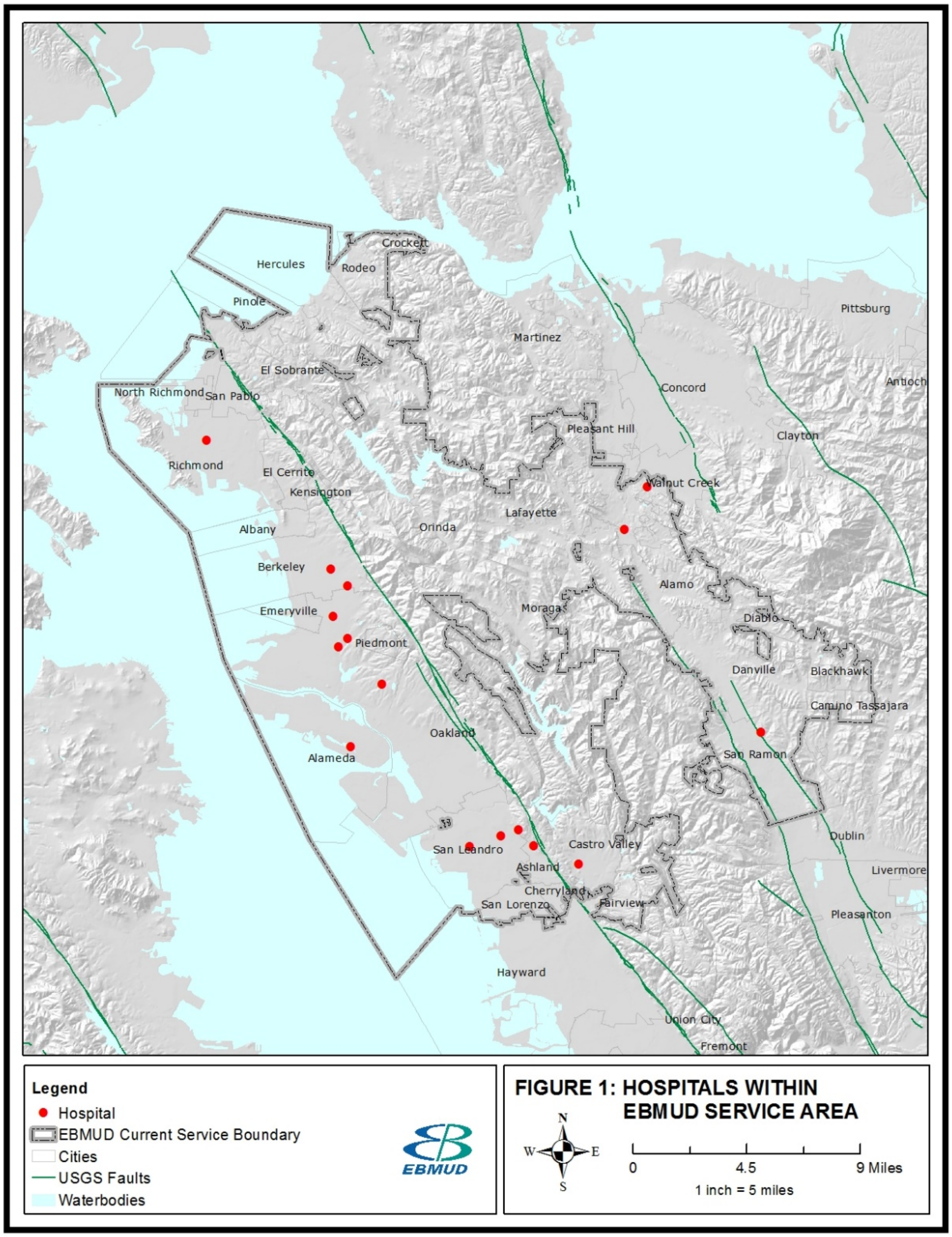


FIGURE 1: HOSPITALS WITHIN EBMUD SERVICE AREA

HOSPITAL OUTREACH (2016 – 2017)

Description

In response to California's hospital seismic safety law, SB 1953[iii], mandating hospitals to meet updated seismic safety standards, six out of sixteen hospitals within the EBMUD service area recently underwent multi-million dollar seismic retrofits and improvements. To ensure ongoing communication with its most critical customers, EBMUD launched a hospital outreach program in 2016 targeting these six hospitals. The twofold purpose of this program is to survey and better understand the hospitals' current emergency water preparedness and to facilitate coordinated planning efforts to enhance water supply resilience.

The outreach largely consisted of meetings between EBMUD management and engineers and key hospital chief engineers, facility managers and/or emergency management staff. During these sessions, EBMUD shared the current state of its water system and emergency response, and interviewed hospitals about their emergency readiness and expectations. The hospitals provided updated information about their facilities and water service connections, which allowed EBMUD to identify strategies for hospitals to improve water supply reliability. Finally, EBMUD shared water distribution maps and fact sheets, distributed copies of industry guidance on emergency water needs for medical providers i.e., specifically, the Center for Disease Control's Emergency Water Supply Planning Guidelines for Hospital and Health Care Facilities[iv], and exchanged key contact information with the hospitals. In some instances, follow up meetings were conducted to initiate communications between hospital facility staff and EBMUD's first responders. Information collected during the outreach was used to update EBMUD's customer records, its emergency response system (known as Marconi), and its geographic information system (GIS).

Outreach Benefits

The outreach yielded a number of benefits for all parties as listed below:

- Hospitals gained a better understanding of EBMUD's water distribution system, including its strengths and vulnerabilities.
- Hospitals gained awareness of EBMUD's emergency preparedness initiatives as well as emergency response priorities and protocols.
- From tabletop discussions to field investigations with hospital staff, EBMUD confirmed water service connections and corrected discrepancies in its customer and mapping databases.
- EBMUD verified key hospital information such as the number of beds, acute care facilities, critical water service connections, and current and future improvement plans.
- EBMUD obtained updated information on new hospital facilities and emergency water supply.
- Hospitals were offered ideas to enhance their water supply reliability (at their expense).

The subsequent sections will focus on key outreach findings and opportunities for enhancing water supply resiliency from a water purveyor's perspective.

Hospital Emergency Preparedness

Most of the newly renovated hospitals have incorporated state-of-the-art building design, cutting-edge medical technology and equipment, innovative features and amenities, and some form of backup water and power supply. Having addressed critical infrastructure needs, the hospitals are no longer at a major risk of collapse during an emergency. However, it is unclear whether they can remain fully operational for the crucial 72 hours following a disaster without adequate emergency planning for basic resources such as water and fuel.

Generally, responses from the outreach indicate that hospitals are aware of potential water supply disruptions that can result from natural disasters or isolated incidents and have taken some steps to address water supply reliability. In this regard, survey responses indicate the following:

- Three of six hospitals have added some type of on-site potable water storage tank as part of their recent retrofits.
- Two hospitals have engaged a team of water consultants to conduct water use audits, evaluate emergency water preparedness, and identify opportunities to strengthen water dependent operations.
- All but one hospital have a sufficient drinking water supply in place to meet hydration needs for at least 24 hours.
- More than half of the hospitals cited internal emergency operation plans, water disruption plans, and/or code-dry policies that guide the management of water supply during an emergency.
- One hospital established a Memorandum of Understanding with a local water vendor to deliver water in the event of an emergency.

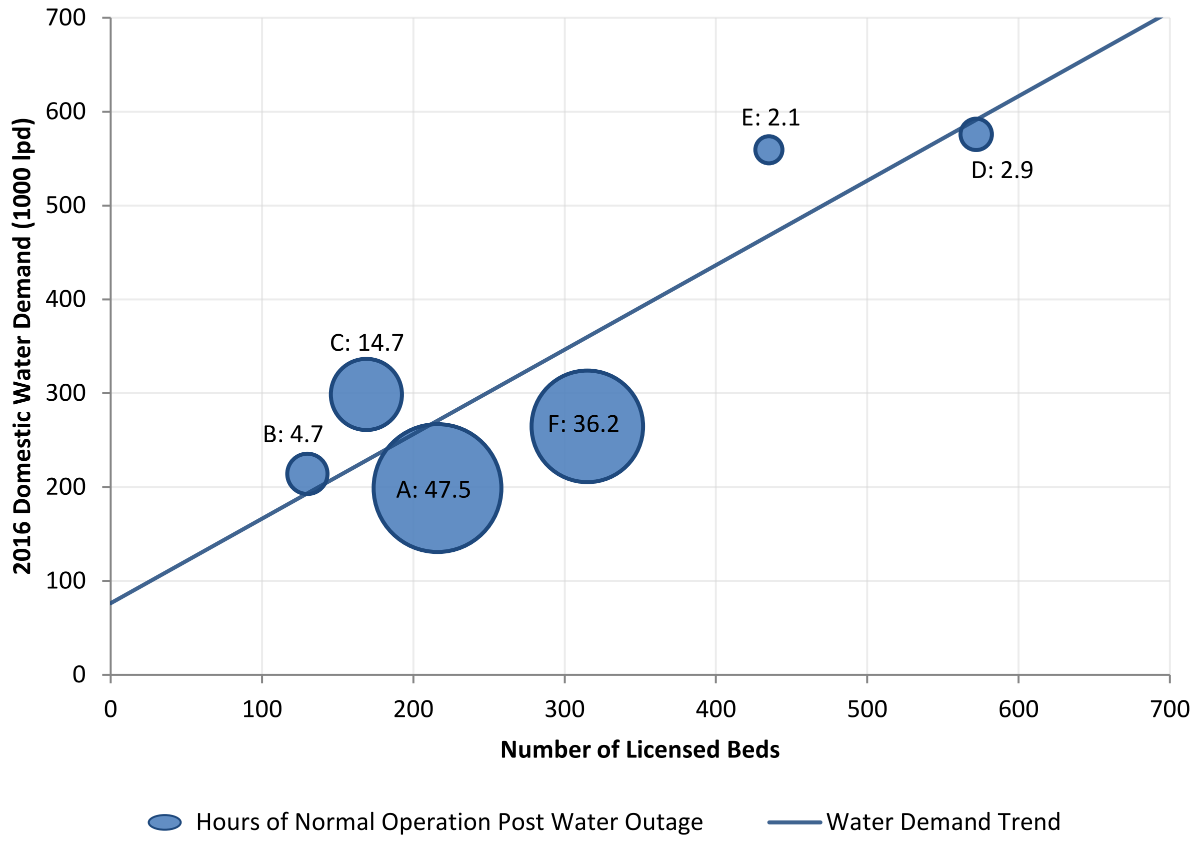
While most hospitals have made progress towards emergency water supply planning, few appeared to be adequately prepared to face the severity and length of possible water service impacts. The statistics indicate the following:

- All hospitals were surprised to learn that EBMUD may encounter 4,000 to 6,000 main breaks in a magnitude 7 earthquake and that the restoration period for full service recovery could range from a period of days to well over a year.
- Three of six hospitals were not aware of their baseline water usage.
- During recent retrofits, two hospitals removed existing plumbing interconnections, eliminating an important redundant water feed to the EBMUD distribution system.

Three of six hospitals have no current on-site potable water storage tanks. Despite the lack of on-site storage, some hospitals appeared to be optimistic about the quantity of water required to sustain operations, citing a belief that they can function for more than 48 to 96 hours following a water service failure. However, data on hospital baseline water use and available water supply shows that three out of the six hospitals can sustain fewer than five hours of normal demand during an outage. To examine this projection in greater detail, hospitals’ average water demands are plotted against hospital size measured by the number of beds in Figure 2.

In 2016, average water demand at the six hospitals ranged from approximately 200,000 to 576,000 liters per day (lpd) (53,000 to 152,000 gallons per day (gpd)). As expected, the demand typically rose with increasing number of beds, and this trend can be modeled by linear regression as shown in Figure 2. Hospitals that fall above the regression line consumed more water per bed than the ones below the trend line. More importantly, Figure 2 displays the estimated hours a hospital can tolerate without water through the magnitude of the bubble plots. The estimates assume normal hospital operation and are based on the 2016 average daily water consumption and the total amount of emergency water supply available or planned at each hospital. Without any curtailment in water use, hospitals in this sample can sustain normal operations ranging from 2.1 to 47.5 hours. Specifically, hospitals without dedicated on-site potable water storage tanks (Hospitals D and E) can sustain no more than a couple hours of normal demand during an outage.

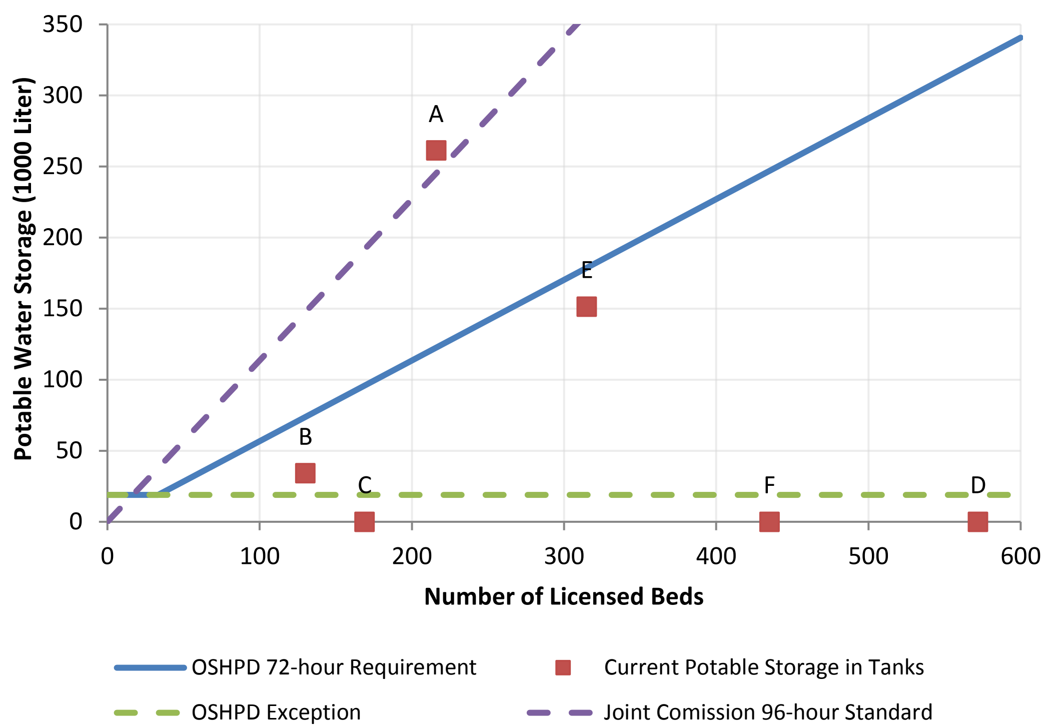
Figure 2: Water Demand and Hour of Normal Operation Post Water Service Disruption for Different Hospital Size



The California Office of Statewide Health Planning and Development (OSHPD) generally requires acute care hospital buildings to maintain sufficient on-site water supply to support 72 hours of continuous operation in the event of an emergency. Exceptions can be made with the installation of hook-ups that allow for the use of transportable sources and an approved Water Conservation/Water Rationing plan that provides onsite supply of potable and industrial water sufficient to support a minimum of 24 hours of operation. However, in no event shall the on-site water storage capacity be less than one tank with at least 18,927 liters (5,000 gallons) capacity. This requirement, which is implemented in the California Plumbing Code (CPC), affects new acute care hospital buildings and will go into effect for all existing acute care hospital facilities in the state of California by the year 2030.[v] At the federal level, the Joint Commission calls for hospitals to have in place a plan to respond to a 96-hour loss of service for all utilities, including water. Through past experiences and disaster forecasts and projections, various governmental and non-profit groups such as Red Cross, Center for Disease Control (CDC) and FEMA advises all sectors, including medical, to be prepared for water outages of 3 to 14 days.[i]

Despite regulations and guidelines, only two out of the six hospitals indicated that they are in compliance with OSPHD's 2030 requirement. A third hospital plans to achieve compliance with the construction of an 88,389 liter (23,350 gallon) underground water storage tank in the next two years. Figure 3 illustrates the relationship between OSHPD's 72-hour storage requirement and hospital size measured by the number of licensed beds. The two parameters generally constitute a linear relationship because the regulation baseline calls for 189 liters (50 gallons) of potable water per licensed bed per day for 72 hours. Assuming OSHPD's 189 liters (50 gallons) per bed per day benchmark, the Joint Commission's 96-hour standard is also plotted for reference. The six data points on the chart represent the number of beds versus volume of potable water storage of individual hospitals. The area underneath the solid line denotes one of two conditions: 1) hospital does not have adequate potable water storage given its size; or 2) hospital may be able to achieve compliance through seeking OSHPD's approval of a Water Conservation/Water Rationing plan provided that a minimum storage tank of 18,927 liters (5,000 gallons) and an emergency hook-up connection are available.

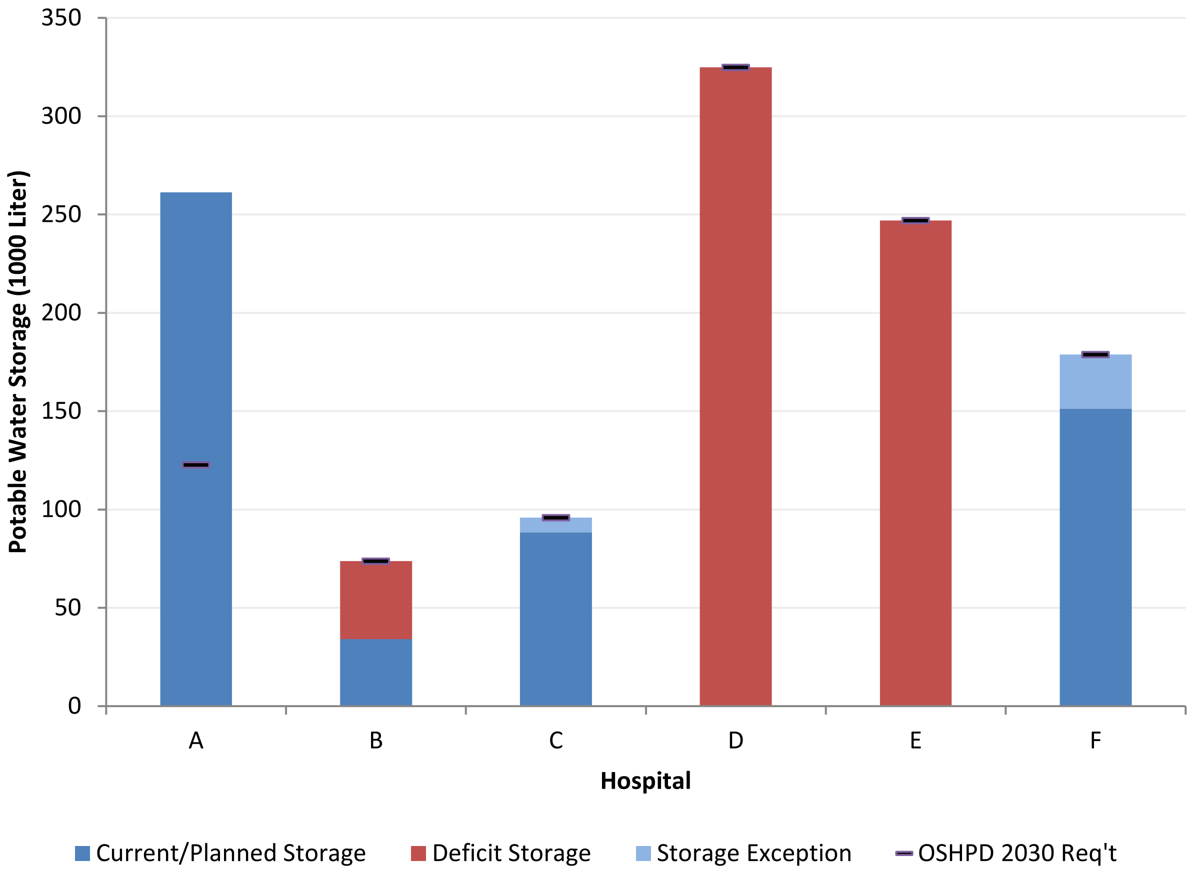
Figure 3: OSHPD 2030 Storage Requirement and Hospital Size



As Figure 3 suggests, Hospital A's emergency water supply is well over OSHPD's baseline requirement and has even exceeded the Joint Commission's 96-hour guideline. In contrast, Hospitals C, D and E have zero potable water storage at this point.

Figure 4 provides a separate view of the percentage of storage met for each of the six hospitals in the survey. For each hospital, the black marker indicates the baseline potable water volume required by OSPHD by the year 2030. The blue area denotes the portion of the requirement that is currently met or planned, the light blue area represents the portion of the requirement met through exceptions, and the red area shows the portion of the requirement that is not yet met.

Figure 4: 72-hour Potable Water Supply Compliance



The figure indicates that there are three hospitals that do not meet the 2030 OSHPD requirement. When questioned, these hospitals indicated that there are no immediate plans to increase on-site water supply or improve water supply reliability.

Table 1: Hospital Emergency Water Supply

ID	No. of Licensed Beds	Emergency Water Supply (liter)			Interconnected System
		Potable Water Tank	Non-potable Water Tank[b]	Bottled / Canned Water	
A	216	261,193	132,489		yes
B	130	34,069	7,949	MOU[c]	no
C	169	*88,389*[a]	94,635		no
D	572		37,854	30,904	no
E	435		37,854	11,924	yes
F	315	151,416	246,052	1,537	yes

a. Hospital C plans to construct an 88,389 liter (23,360 gallon) tank by 2019.
b. Non-potable tank includes hot water tanks, fire water storage tank, etc.
c. Hospital B has a Memorandum of Understanding (MOU) with a local vendor to deliver supplies of bottled water in the event of an emergency.

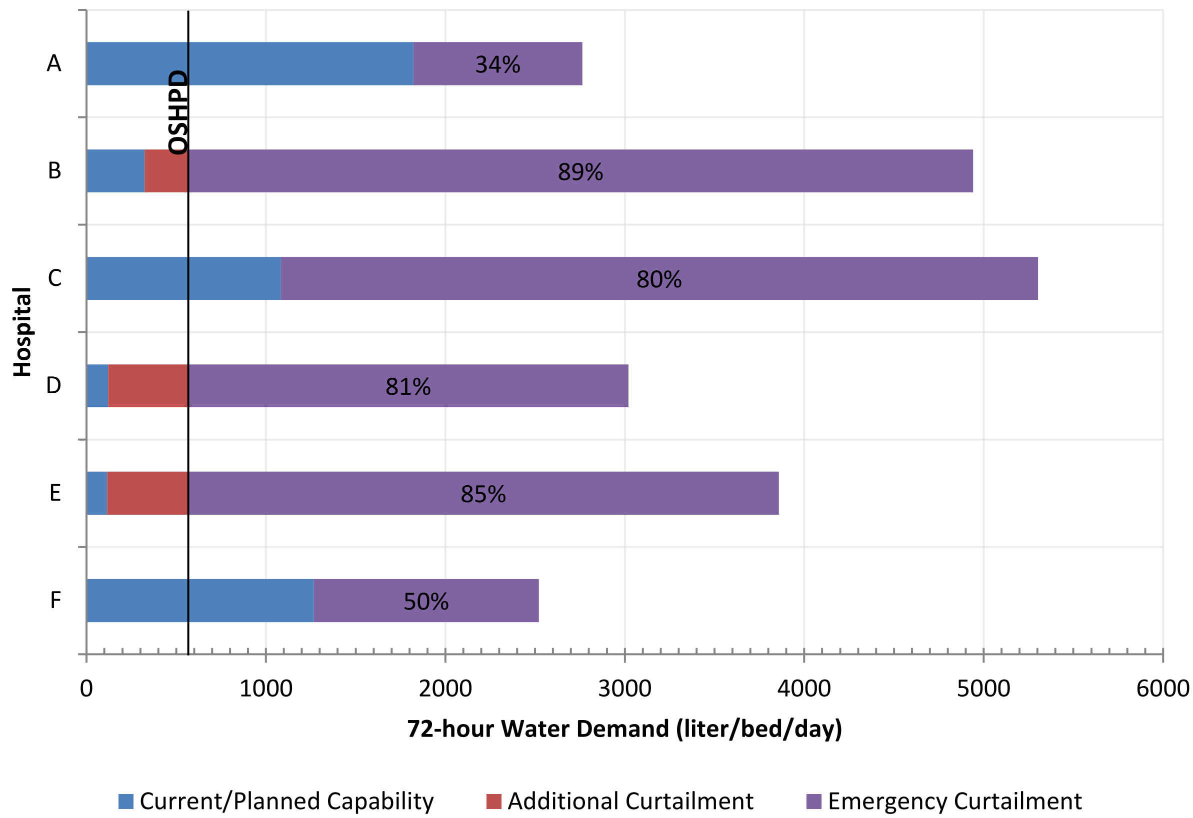
Table 1 summarizes the types of emergency water supply available at each hospital. In general, the hospitals' inventory of on-site water supply can be separated into three key categories: potable water tank, non-potable water tank, and bottled/canned water stockpile. Surprisingly, two of the largest hospitals in the sample did not integrate any on-site potable storage tanks in recent facility upgrades. At the same time, they also have the lowest non-potable water storage to licensed bed ratio. On the other hand, these two hospitals carry the largest inventory of bottled/canned water. One of the two hospitals cited that their inventory of bottled/canned water can provide up to 168 hours of drinking water supply. Yet, it is not apparent how the hospital will meet industrial (e.g. cooling towers, chillers, boilers), medical (e.g., dialysis, sterilization, magnetic resonance imaging units), and domestic (e.g. toilet flushing, hand washing, bathing, food services) water needs, which constitute the majority of the water usage in a hospital and are essential for a hospital to stay in operation. This finding is consistent with that of earlier research of different hospitals and suggests that this planning gap may be widespread.[vi]

Figure 5 shows the estimated amount of curtailment required to achieve OSHPD's guideline of 568 liters (150 gallons) per bed for 72 hours given the current average water consumption. It is assumed that hospitals can utilize their potable and non-potable supply sources to meet demands. On average, the hospitals need to curtail 70% of their water supply to either meet OSHPD's benchmark or their current supply reserves. In the case of Hospital A, only 34% curtailment would be needed due to the relatively higher amount of emergency water supply available. For Hospitals B, D, and E, additional curtailment beyond the OSHPD standard would likely be required if the hospitals intend to remain operational for 72 hours. Since Hospitals D and E have no on-site potable storage tanks in place, they will likely face severe challenges in addressing patient care beyond basic hydration needs. Based on Figure 5, it appears that most hospitals will need to make significant curtailments to function for the full 72 hours following an outage even with the required OSHPD water supply on site.

To help bridge the gap between emergency supply and demand, the American Water Works Association (AWWA) and CDC recommend that each hospital develop an Emergency Water

Supply Plan (EWSP) as part of its Emergency Operations Plan (EOP) to identify water use and water restriction protocols that will allow it to meet regulatory standards and codes.[iv]

Figure 5: Emergency Water Use Curtailment



Overall, there appears to be a wide variation in the knowledge and preparedness of emergency water supply planning across the six hospitals.

Water Reliability Alternatives

Beyond achieving the OSHPD 72-hour on-site storage requirement and developing EWSP, EBMUD has identified additional options that hospitals can pursue to enhance water supply reliability. Some of the improvement opportunities are detailed below.

- Interconnect/loop campus plumbing system with a second meter to improve water supply redundancy.
- Replace aging mains and mains with questionable seismic performance, such as asbestos cement.
- Install a stub out connection to allow water to be supplied via a hydrant or transportable source in an emergency.
- Establish contracts with water truck vendors to deliver water in the event of an emergency.

- Install an additional water service connection from an adjacent pressure zone for added redundancy.
- Apply for redundant water service from an adjacent water supplier as an alternative water source.

These options were presented to the six hospitals during multiple outreach sessions. Hospitals may wish to pursue them at their own expense.

EBMUD EMERGENCY PREPAREDNESS INITIATIVES

In addition to the Hospital Outreach Program, EBMUD has recently embarked on several other initiatives to improve water supply resiliency and emergency preparedness. The following section describes a few initiatives that are currently underway.

Critical Customer Identification and Communication

EBMUD is developing a Critical Customer Identification and Communication Pilot Project to establish a uniform process for managing critical customer information and communication for all stakeholders. The project outlines roles and responsibilities to enhance communication during interruptions in service or water quality impacts to critical customers. Additionally, it defines the process for identifying critical customers, obtaining and updating key customer information, notifying customers, and updating mapping database to include critical customer data. The project also involves the development of a tool to spatially allocate critical customer information onto online water distribution maps and GIS. This new feature will enable EBMUD first responders to readily identify and access critical customer information to ensure that priority is given to maintain and restore water to their services.

Pipeline Rebuild and Pipeline Replacement Program

The average age of pipelines in EBMUD's service area is 68 years (ranging up to 120 years) and some are beginning to fail. In response, EBMUD initiated the Pipeline Rebuild Program to ramp up the rate of pipeline replacement from 10 miles per year to 40 miles per year by 2030. To support this program, a new Pipeline Replacement Program (PRP) was implemented to prioritize pipeline replacements using a comprehensive risk analysis. The program evaluates pipeline risk based upon user defined likelihood and consequence of failure rankings for EBMUD's entire pipeline inventory. Risk scores are computed in ArcGIS using pipeline attributes and performance data such as pipeline age, leak history, ground slope, criticality of connected customers, whether a creek is being crossed, etc.

Using these parameters, the likelihood of failure (LOF) and consequence of failure (COF) of each pipeline are computed with a 1 through 5 ranking system, with 1 representing negligible LOF or no COF and 5 representing very likely LOF or very high COF. Under this system, pipelines with high LOF and COF scores are prioritized for replacement. As mentioned, criticality of specific customers is considered in EBMUD's Pipeline Risk Model as one of the several criteria used to calculate the COF scores for distribution pipelines. Critical customer designation is currently assigned to hospitals, health services, schools, airports, sanitary collection and disposal facilities, electronic communication facilities, and electric, steam and natural gas facilities. Pipelines that serve water to these critical facilities are given a higher consequence of failure score. When replacing high risk mains, EBMUD also applies optimization techniques such as clustering the replacement of nearby pipelines to minimize overall cost, time, and resources. As a result of the PRP Risk Model and clustering, two major hospitals have benefitted by having multiple pipelines replaced near their campuses.

Pipeline Improvement Program

In addition to its PRP, EBMUD undertook a study to review aging, undersized mains serving critical customers and large fire services. This study was launched in 2013, after an old 4-inch diameter (100 mm) water main installed in the 1940s broke in a downtown area, causing a major disruption in water service to several high rise office buildings. This incident prompted a study that examined where such aging mains are concentrated, how many customers they serve, and which types of water customers they serve. This study determined that in some instances, these mains serve critical customers where an outage could result in significant impacts, and recommended how to sequence and prioritize their replacement.

The program resulted in a plan to replace 12 miles of aging 4-inch pipelines, including one mile of mains serving hospitals and health services. This program will initially focus on the replacement of approximately 6 miles (10 km) of mains that serve EBMUD's most critical facilities such as hospitals, health services facilities, laboratories, as well as office buildings and apartment buildings which have a fire service. In a second future phase, EBMUD plans to replace an additional 6 miles of mains that supply other facilities with fire services. A large majority of these mains (80%) provide service to critical facilities located in Oakland and Berkeley with a total of 197 fire services. Of these 197 services, which are connected to the mains that will be replaced in the first phase of this program, 71 (36%) serve wholesale and resale establishments, 66 (34%) serve multi-unit buildings, 31 (16%) serve schools or hospitals, and the remaining 29 (14%) serve other business types.

CONCLUSION

Cross-sector interdependencies will likely play a significant role in the aftermath of future major disasters. Left unaddressed, those interdependencies have the potential to increase overall societal impacts caused by damage to critical infrastructures.

A primary way of addressing interdependencies is to close knowledge gaps, so that experts within each distinct infrastructure sector understand what to expect from other sectors upon which they depend, and understand what is expected of them by other infrastructures. The hospital outreach described in this paper was done with that goal in mind. EBMUD gained an increased understanding of how critical care providers rely upon water supply, and those care providers gained important information on ways to improve resilience to water supply disruption.

In short, emergency preparedness is a joint effort and an effective emergency response will require ongoing support and commitment from both parties. The Hospital Outreach Program is a first step in paving the way for a variety of opportunities for both sectors to learn, grow, and solve problems together. In the future, EBMUD will continue to reach out to critical customers, especially the remaining hospitals pursuing seismic retrofits, and the community to educate and raise awareness on emergency water planning, update critical customer information, and explore opportunities for coordinated planning and support. In addition, EBMUD will continue to look for opportunities to replace aging pipelines serving hospitals and health services facilities as part of its pipeline replacement and improvement programs.

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U.S. Approach to Share Seismic Awareness, Hazard Assessment and Mitigation Practices with a Larger Universe of Water and Wastewater Utilities

David Goldbloom-Helzner and Craig A. Davis

ABSTRACT

More than 143 million Americans, almost half the population of the United States, live in areas that are vulnerable to earthquakes. The West Coast is particularly susceptible, but earthquakes can happen almost anywhere. For example, in the Central United States, the New Madrid Seismic Zone is a significant threat to eight states. For a community, water and wastewater utilities are critical lifelines and with tens of thousands of utilities located across the country, many are in earthquake hazard areas.

The U.S. Environmental Protection Agency (EPA) wants vulnerable utilities to be aware of this earthquake hazard and the potentially devastating impacts to public health and the environment. A number of large and some medium-sized water utilities have been at the forefront of research efforts and have already implemented earthquake mitigation measures. However, awareness of the threat is much more sporadic at most other utilities. Also, because of the catastrophic nature of earthquakes and the sometimes substantial costs for resilience, utilities may be discouraged to conduct hazard assessments and implement mitigation measures. So how can less informed small, medium, or even large water and wastewater utilities build resilience to earthquake hazards?

The EPA's Office of Water has a mission to help water and wastewater utilities prepare for, mitigate, respond to and recover from various hazards, including earthquakes. With the assistance of an Advisory Review Team composed of utilities, water associations, federal agencies and state mitigation officers, the EPA developed a suite of earthquake resilience products to share lessons learned to a larger universe of utilities. This suite of products includes:

- Earthquake Resilience Video.
- Earthquake Resilience Guide.
- Earthquake Interactive Maps.

The products were based on the latest research by water and earthquake experts. Additionally, the products were designed for water utilities that are located in earthquake-prone areas, but have not yet taken steps to understand their seismic hazards or taken steps to address them. The products also were designed to be easy-to-use and formatted so that best practices can be accessed with only a few clicks. The EPA has also developed an outreach strategy for communicating and sharing these products with utilities prone to earthquake hazards. The earthquake resilience products are available through the EPA's water utility resilience website [https://www.epa.gov/waterutilityresponse].

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NATIONAL APPROACH FOR EARTHQUAKE RESILIENCE FOR THE WATER SECTOR

More than 143 million Americans, almost half the population of the United States, live in areas that are vulnerable to earthquakes. The West Coast is particularly susceptible, but earthquakes can happen almost anywhere. For example, in the Central United States, the New Madrid Seismic Zone is a significant threat to eight states. For a community, water and wastewater utilities are critical lifelines and with tens of thousands of them located across the country, many are in earthquake hazard areas. Water and wastewater utilities are particularly vulnerable to earthquakes due to their extensive networks of above and below ground pipelines, as well as other facility assets like pumps, tanks, administrative and laboratory buildings and reservoirs (Figure 1).

Figure 1: Damaged Clarifier

A number of large and some medium-sized water utilities have been at the forefront of research efforts and have already implemented earthquake mitigation measures. However, awareness of the threat is much more sporadic at most other utilities. Also, because of the catastrophic nature of earthquakes and the sometimes substantial costs for resilience, utilities may be discouraged to conduct hazard assessments and implement mitigation measures. So how can less informed small, medium, or even large water and wastewater utilities build resilience to earthquake hazards?

The U.S. Environmental Protection Agency (EPA) wants vulnerable utilities to be aware of this earthquake hazard and the potentially devastating impacts to public health and the environment. EPA's Office of Water has a mission to help water and wastewater utilities prepare for, mitigate, respond to and recover from various hazards, including earthquakes. If water and wastewater utilities understand the threat of earthquakes and the potential impacts to both their infrastructure and the community, utility owners and operators can make more informed decisions regarding earthquake mitigation options (Figure 2). While requiring financial investment, earthquake resilience and mitigation projects can significantly reduce or even prevent much costlier damages and economic impacts from future earthquakes. Also, the faster a water or wastewater utility recovers from an earthquake, the faster the community it serves can recover. Because of the factors above, the EPA began to consider developing a national approach to share seismic awareness, hazard assessment and mitigation practices with a larger universe of water and wastewater utilities.

Figure 2: Mitigation for Basin

In addition, the timing seemed right for developing such an approach. The EPA spoke with and obtained support from government stakeholders in earthquake resilience, including our federal partners including the U.S. Geological Survey (USGS) as well as state partners representing water primacy agencies, state geological agencies and state hazard mitigation officers. The EPA's efforts were consistent with other associated federal activities, notably the Federal Earthquake Risk Management Standard that governs federal facilities. Also, over the last several years, certain water and wastewater utilities have established best practices for earthquake resilience, although the dissemination of this information was somewhat limited. When the EPA reached out to small utilities located in earthquake vulnerable areas (Figure 3), there was generally an enthusiastic response for the EPA to provide technical assistance and tools for earthquake resilience. This sentiment was best represented by a small water utility in western Tennessee that said that the EPA's earthquake resilience guidance

Figure 3: Partnership Approach

"is long overdue and I am happy EPA recognizes this very real threat." Overall, there seemed to be a strong interest in a national approach to address earthquake resilience for water and wastewater utilities.

After consideration, the EPA decided to develop a national approach that includes:

- A series of earthquake resilience products.
- Targeted outreach efforts to the water sector.

EARTHQUAKE RESILIENCE PRODUCTS

To help develop earthquake resilience products, the EPA established an Advisory Review Team composed of utilities, water associations (e.g., Association of State Drinking Water Agencies and American Water Works Association), federal agencies (e.g., USGS) and state hazard mitigation officers. The Review Team included water utilities that are leaders on earthquake resilience (e.g., Los Angeles Department of Water and Power and East Bay Municipal Utilities District, California) as well as small utilities (e.g., Mount Pleasant Waterworks, South Carolina) that might be users of the products. The EPA developed several products to share lessons learned to a larger universe of water utilities. These include:

- Earthquake Resilience Video.
- Earthquake Resilience Guide.
- Earthquake Interactive Maps.

The target user group was comprised of small and medium utilities that are located in earthquake-prone areas, but have not yet taken steps to understand the hazard or taken steps to address them.

The products were based on the latest research and efforts by water and earthquake experts. Additionally, the products were designed with easy-to-use and accessible formats; for example, the video is animated and the guide is clickable to quickly access the needed information. The EPA is currently in the process of communicating and sharing these products to utilities that are vulnerable to earthquake hazards. Below is a description of each product.

Earthquake Resilience Video

This animated video, *Surviving the Quake* (Figure 4), is an awareness video targeted to utilities, but can also be useful for city or town managers and funding agencies. The video shows the types of damage that earthquakes can cause to water and wastewater utilities (Figure 5), as well as the greater community. The video also discusses the concept of earthquake resilience and the way that utilities can evaluate the hazard, assess vulnerable assets and implement and fund mitigation measures. Additionally, the video points to the other EPA tools including the Earthquake Resilience Guide and Earthquake Interactive Maps.

Figure 4: Awareness Video

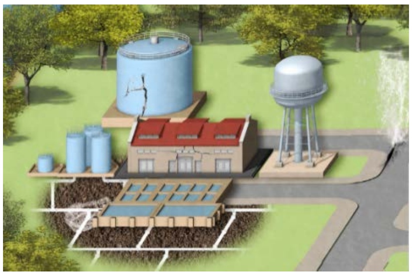

Figure 5: Animated Utility

Earthquake Resilience Guide

This Guide (Figure 6) helps water and wastewater utilities to be more resilient to earthquakes. The Guide outlines steps to evaluate the earthquake hazard and mitigate impacts. The three steps include:

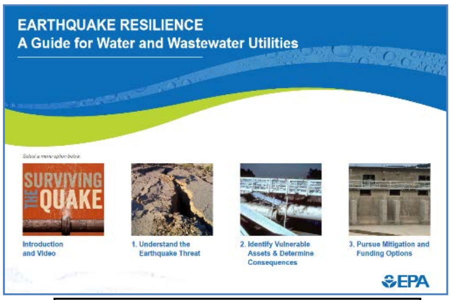

Figure 6: Homepage of Guide

- Step 1 - Understand the Earthquake Threat.
  This step informs the user about different types of earthquakes (e.g., natural, induced) and ground movements (e.g., shaking, liquefaction, subsistence). It also links the user to the Earthquake Interactive Maps tool which will be discussed later.
- Step 2 - Identify Vulnerable Assets and Determine Consequences.
  This step discusses the vulnerability of specific water utility assets to earthquakes, including a characterization of potential earthquake impacts to building structures, pipelines, tanks, reservoirs, pumps, lift stations, wells, treatment facilities and power assets (Figure 7). It also covers how an asset's construction material, design or age can affect its vulnerability. For example, one table shows anticipated earthquake damage to different building structures, while another table assesses earthquake vulnerability of pipeline materials and joint types.

Figure 7: Manhole Floats from Liquefaction

- Step 3 - Pursue Mitigation and Funding Options.
  This step contains best practices from water utilities that have used mitigation measures to address the earthquake threat. The user can simply click on photographs to identify mitigation measures and strategies. Here, the Guide includes numerous tables that list mitigation measures and the relative costs of implementing these measures. Some tables identify mitigation measures for life safety (Figure 8), while others do so for specific utility assets, such as pipes and tanks. Finally, the step summarizes how to implement and fund mitigation through government funds, capital improvement planning and asset management.

Small and medium utilities, especially those in lesser known earthquake hazard areas like the New Madrid Seismic Zone, will benefit from the information in this Guide. However, the Guide cautions water utilities about proposing major seismic upgrades based solely on this information - a more detailed on-site analysis is recommended.

✓	Mitigation Options for Immediate Life Safety	Cost
1. Protect your employees		
	a. Make sure employees know your emergency response plans and practice emergency action drills.	$
	b. Maintain emergency generators (seismically certified) at employee locations to help mitigate widespread power outages.	$$
	c. Retrofit buildings to prevent collapse of occupied buildings. For seismic protection, follow the ASCE 7 Standard Minimum Design Loads for Buildings and Other Structures (2016) for new buildings and ASCE 41-06 for retrofit buildings. This could be accomplished by adding new seismic bracing or shear walls.	$$$
	d. Anchor equipment (e.g., computers, bookshelves) as well as laboratory equipment and chemical/fuel tanks.	$
	e. Identify people who can perform post-earthquake building inspections for safety.	$
2. Protect the public from catastrophic failures of vulnerable storage tanks or reservoirs		
	a. Seismically retrofit water tanks (e.g., anchoring to foundations).	$$$
	b. Strengthen concrete tank walls, replace non-flexible connections, and improve roof structures over large reservoirs.	$$$
	c. For new tank installations in high risk seismic zones, determine if liquefaction or other permanent ground movements are possible. If so, stabilize the foundation to minimize movement. Design the tank height to safely account for sloshing forces during an earthquake.	$$$
3. Plan for emergency public health and firefighting		
	a. Work with community and state officials to develop a plan to provide emergency drinking water.	$
	b. Develop a plan for emergency sewage capability, including portable or improvised chemical toilets.	$
	c. Plan for use of temporary bypasses to move wastewater flow away from the public following ground movement.	$$
	d. Address high consequence sewers like those that are difficult to repair (e.g., under rivers, highways, or buildings).	$$$
	e. Coordinate with firefighting agencies on a plan for obtaining alternate water supplies if the water system is disrupted. For example, consider swimming pools, reclaimed water, and pressurized seawater.	$

Figure 8: Mitigation Options for Immediate Life Safety

Earthquake Interactive Maps

The Earthquake Interactive Maps are a series of maps showing natural earthquake hazard, liquefaction, faults, induced earthquakes and earthquake history. Water utilities can zoom into their own location within each of the maps. Examples of the Earthquake Hazard and Liquefaction Maps are shown in Figures 9 and 10, respectively. The Earthquake Interactive Maps help water utilities better understand their seismic hazard, and are based on the latest data from the U.S. Geological Survey and state agencies. Also, the maps present the experiences and stories of

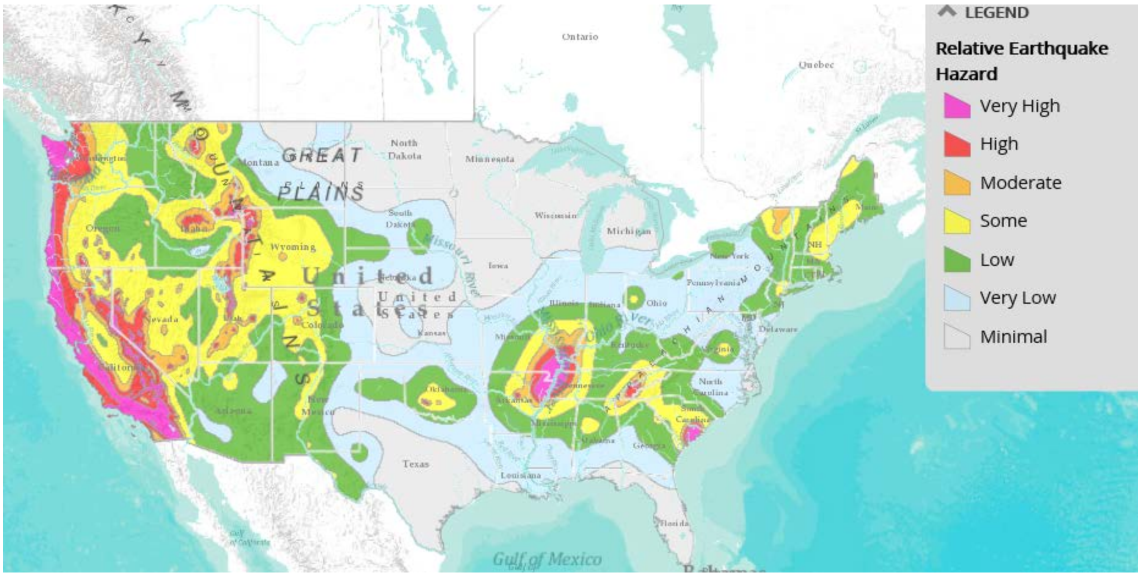

Figure 9: Earthquake Hazard Map from U.S. Geological Survey

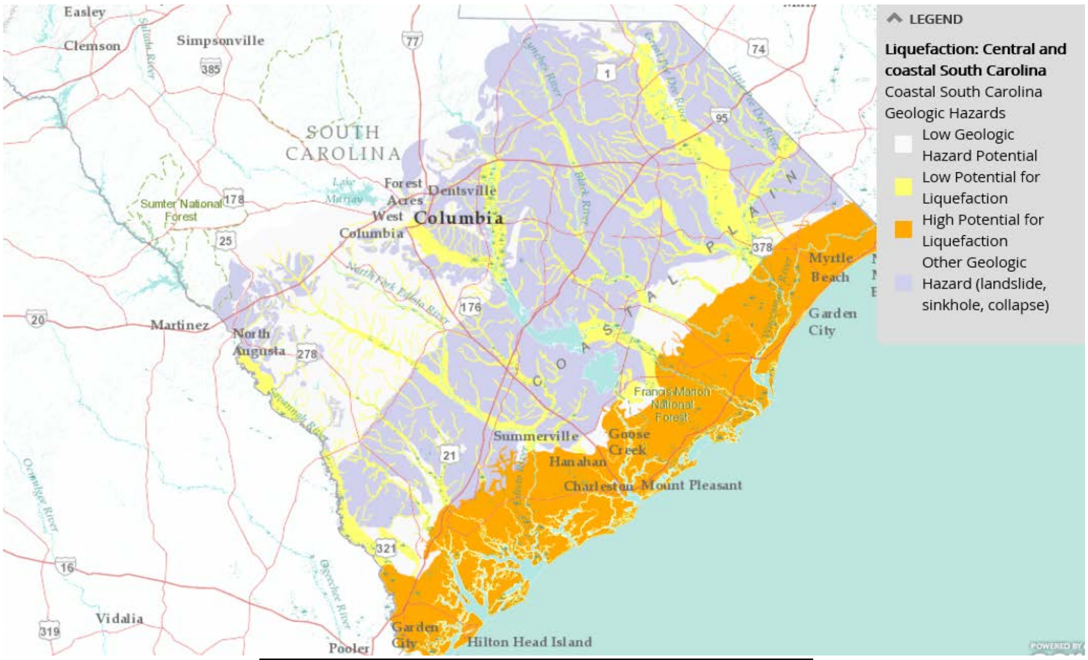

Figure 10: Liquefaction Map of South Carolina

several water utilities that have implemented measures to become more resilient to earthquakes (Figure 11).

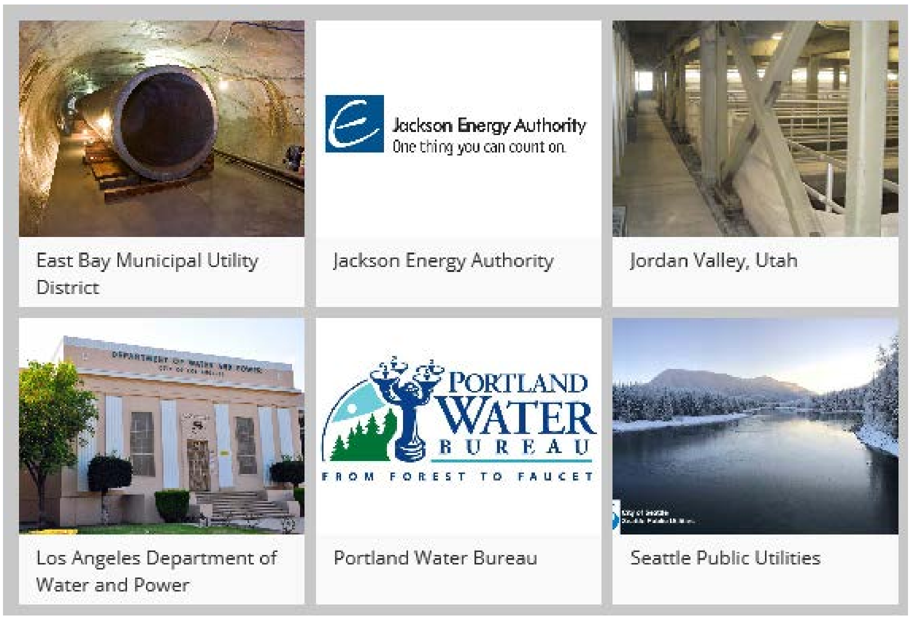

Figure 11: Utilities Examples - shared experiences in mitigating impacts to earthquakes

OUTREACH FOR EARTHQUAKE RESILIENCE PRODUCTS AND EFFORTS

EPA has also developed an outreach strategy for communicating and sharing these products with utilities that are vulnerable to earthquake hazards. The strategy includes the following activities:

- Post products on the EPA website.
  The earthquake resilience products will be available in late fall 2017 on the EPA's water utility resilience website at https://www.epa.gov/waterutilityresponse.
- Conduct expert panel webinar.
  The EPA plans to hold a webinar on earthquake resilience for water and wastewater utilities. The Video, Guide and Maps will be introduced, and earthquake resilience experts will present and be available to answer questions from water utility participants.
- Present at conferences.
  EPA will actively promote the products at water and wastewater sector conferences, as well as selected earthquake and mitigation conferences.
- Demonstrate liquefaction.
  EPA has developed a small scale model to demonstrate the effects of liquefaction on water and wastewater system assets. To be used at conferences and poster sessions, this model demonstration can help communicate the importance of considering liquefaction in mitigation planning.
- Author journal articles.
  For water and mitigation trade publications, the EPA plans to write several journal articles on earthquake resilience for the water sector.
- Promote earthquake resilience during visits to selected communities.
  The EPA proposes to visit a number of communities in earthquake prone areas like the New Madrid Seismic Zone to promote the earthquake resilience tools and perhaps conduct workshops and site visits to assess the hazard and propose mitigation strategies. The EPA

would facilitate such visits with EPA and FEMA regional staff, state primacy agencies, state mitigation agencies, local political officials and local mitigation and emergency managers, as well as the water and wastewater utility representatives.

- Participate in New Madrid Recovery Exercise in 2018.
  The EPA plans to participate and involve the water sector in the Department of Homeland Security New Madrid Recovery Exercise in 2018.

CONCLUSION

The EPA is supporting a national strategy to help small and medium water and wastewater utilities build resilience to earthquakes. Such efforts are key for communities nationwide to prepare for and recover from such disasters. In concert with other water stakeholders, the EPA has developed a suite of easy-to-use products to help water utilities become aware of the earthquake hazard, identify vulnerable assets, and mitigate potential damage and service disruptions. The products include an Earthquake Resilience Video, Earthquake Resilience Guide, and Earthquake Interactive Maps. The EPA also has a robust outreach strategy to promote the use of these products by water utilities and their communities.

‘Disaster-resistant Waterworks Model, Connecting all to the Water of Life’ and the countermeasures against natural disasters examples
Sharing the specific measures of cooperation with major cities and mutual help to community groups

Takuya NAKAGAWA[1], Yuki WATANABE[2], Keisuke SAWADA[3], Wataru HOSODA[4], Yoshiaki KONNO[5], Kunihiko ONUMA[6]

ABSTRACT

On March 11, 2011, the Great East Japan Earthquake, the most powerful earthquake (Mw 9.0) ever recorded in the country struck.

Four years after the Great East Japan Earthquake, The Third United Nation World Conference on Disaster Risk Reduction (hereafter referred to as WCDRR) was held in Sendai City from March 14th to March 18th in 2015. Based on this knowledge, the Sendai City Waterworks Bureau held a Symposium for the WCDRR: Connecting all to the Water of Life with participants from the industry, government, academics and citizens. In light of the discussion, we proposed and sent out the message of the ‘Disaster-Resilient Waterworks Model, Connecting all to the Water of Life’ (hereafter referred to as “The Model”), which combines ①Self-Help by individual citizens, ②Mutual Help together with local communities, schools and businesses, ③Public Support from water suppliers, and ④Cooperation with entire stakeholders including plumbing constructors and the National Water Supply Utilities Network.

In this paper, we explain the correspondence between The Model which we proposed at the 3rd WCDRR and our current countermeasures against disasters. In addition, we will explain two of our measures, ‘Mutual Help’ and ‘Cooperation’ that are focused on emergency water supply. An example of the first measure, ‘Mutual Help’ is ‘Emergency Water Taps’ that enable citizens to set up a water supply station on their own after an event such as disaster. Based on the experiences of the Great East Japan Earthquake, we constructed an ‘Emergency Water Tap’ at each elementary school that is a designated refuge area since FY 2013. We explain that an outline of an ‘Emergency Water Tap’, educational campaign of an explanatory meeting for a local community residents and that progress. The second measure is ‘Cooperation’ with plumbing constructors and the National Water Supply Utilities Network. We have signed a memorandum of mutual support in a disaster with the Sapporo City Waterworks Bureau and the Tokyo Metropolitan Waterworks Bureau. We share information and hold joint disaster training with those cities. In addition, we also hold joint disaster training with other cities and The Japan Water Works Association and through this we have established various relationships.

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1. INTRODUCTION

At the Sendai City Waterworks Bureau, we have taken various steps to create a disaster-resilient water supply, for example, reinforcing water pipes against earthquakes and enhancing cooperation with other cities and associations based on our experiences in the Miyagi Oki Earthquake (1978) and the lessons learned from the Kobe Earthquake (1995). By implementing these measures, our total water management system has steadily developed, so that all water facilities can be used flexibly and efficiently on a day-to-day basis as well as in times of disaster in order to provide customers with a stable water supply.

On March 11, 2011, the Great East Japan Earthquake, the most powerful earthquake (Mw 9.0) ever recorded in the country struck. There was no major damage to Sendai City's purification plants or distribution reservoirs, but the transmission main pipe of Miyagi Prefectural Wide-area Water Supply broke. The water supply to Sendai City was cut off, resulting in suspension of service to a maximum of 230,000 households, or about 50% of water service users in the city. At the time, the Sendai City Waterworks Bureau did not have enough human resources and we were not able to provide customers with an emergency water supply, despite of the support of many other cities.

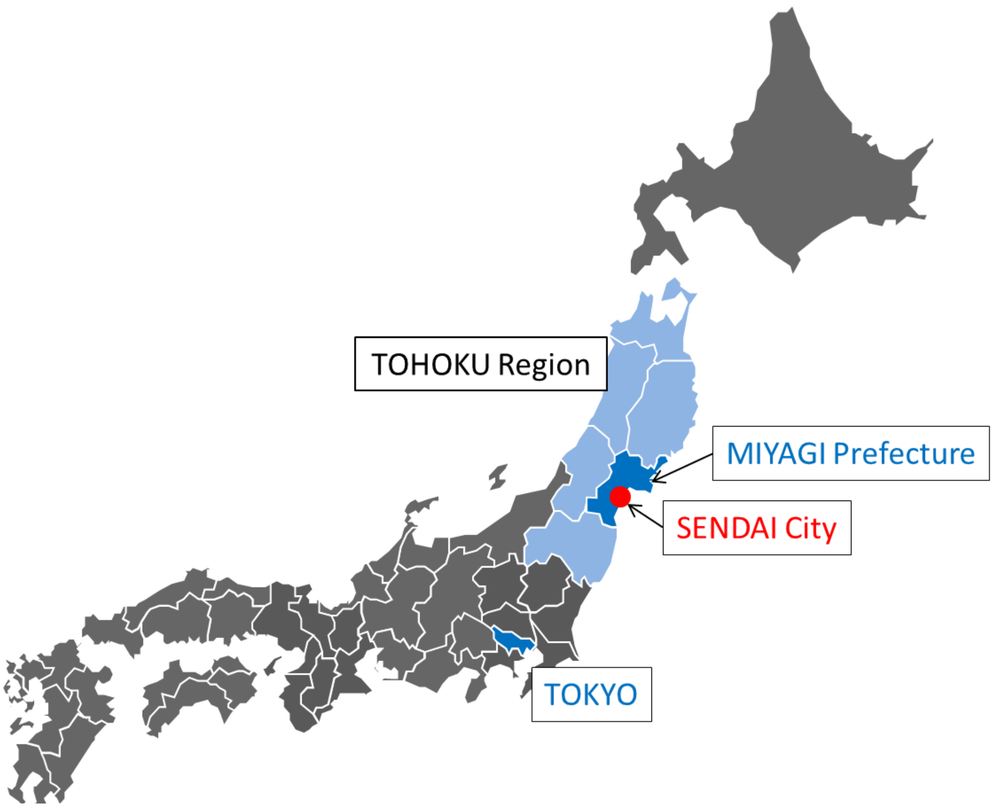


Figure 1. Location of Sendai City

2. The 3rd WCDRR

Four years after the Great East Japan Earthquake, The Third United Nation World Conference on Disaster Risk Reduction (hereafter referred to as WCDRR) was held in Sendai City from March 14th to March 18th in 2015. Finally, at the conference, the ‘Sendai Framework for Disaster Risk Reduction 2015-2030’ was adopted as a successor to the ‘Hyogo Framework for Action 2005-2015’. Some of its features include; the first agreement on the global targets, new ideas such as the concept of ‘Build Back Better’, and an emphasis on the roles of various parties in disaster prevention and disaster risk reduction, including women, children and various stakeholders such as companies.

Based on this knowledge, we held some outdoor exhibitions, hands-on experience events and a Symposium as a part of the public forum.

A) Outdoor exhibitions and hands-on experience events

① Emergency water supply demonstration: having people experience water being supplied by a water tank truck and a temporary sectional water tank.

② Water storage declarations by citizens: having visitors write their water storage declarations on post it notes, and putting them on a board to raise people’s awareness of the importance of storing water as a form of self-help.

③ Display of earthquake resilient pipes: showing people our countermeasures against disasters.

④ Demonstration of the restoration of leakage pipes: showing people one of our emergency responses to disasters. Held with the Miyagi Plumbing Constructor’s Association (hereafter referred to as MPCA)

A total of over 5,000 people visited the site over two days.

B) Symposium for Water Disaster Risk Reduction: Connecting all to the Water of Life

Sendai City Waterworks Bureau held a symposium for water disaster risk reduction with around 300 participants from industry, government, academics and citizens.

Firstly, The Japan Water Works Association, Sendai City Waterworks Bureau, MPCA and Niigata City Waterworks Bureau gave presentations about their responses to the Great East Japan Earthquake, and their efforts that are based on lessons learnt from the disaster. Secondly, we also held a panel discussion with citizens on the theme of ‘building a disaster-resilient water supply system, and the power of collaboration and cooperation’. Finally, based on the discussion, we proposed and published a model, the‘Disaster-resilient Waterworks Model, Connecting all to the Water of Life,’ (hereafter referred to as The Model) which combines ①Self Help by individual citizens, ②Mutual Help together with the local communities, schools and businesses, ③Public Support from water suppliers, and ④Cooperation with entire stakeholders including plumbing constructors and the national water supply network.

Photograph 1. The Third United Nation World Conference on Disaster Risk Reduction

3. Correspondence Between The Model and Our Current Countermeasures Against Disasters of The Management Plan (2015-2019)

We have a ten year basic plan for waterworks projects, and in order to execute the basic plan, we also draw up new Mid-term Management Plans every five years.However, when the Great East Japan Earthquake occurred in 2011, it became necessary to give priority to countermeasures against disasters. Therefore, we selected ten projects which we needed to focus on from the Mid-term Management Plan (2010-2014)', improved them and created the 'Earthquake Countermeasure Projects for Promotion.' Then, in March 2015, we drew up a new version of The Management Plan (2015-2019) (hereafter referred to as The Management Plan) which includes these ten countermeasures for promotion.

In this section, we verify the correspondence between The Model and our current countermeasures against disasters of The Management Plan. The countermeasures are divided into The Models four categories, and put into a table (Fig2: Countermeasures against disasters on the vertical axis, The Model on the horizontal axis). First, we will begin with 'Self Help'. An example which falls into this category is 'Enhancing interactive publicity' which includes 'visiting lectures' and 'waterworks fairs '.
'Mutual Help' examples include; 'Enhancing cooperation with local communities', 'Reflecting customer's opinions in our policy' and 'Enhancing business operations in collaboration with customers'. An example of 'Public Support' in addition to a large number of projects about the development of facilities along with projects such as 'Passing on the lessons learnt from the Great East Japan Earthquake'. 'Cooperation' is categorized by 'Enhancing cooperation with other cities and associations' and 'Enhancing cooperation with neighboring plumbing constructors'. It is not only these groups, but also the cooperation from all of the stakeholders that is required to accomplish a disaster-resilient waterworks.

From the above, the current countermeasures are clearly categorized into four categories; 'Self Help', 'Mutual Help', 'Public Support' and 'Cooperation' which are all based on The Model. As a result, we made sure that the concept of The Model is reflected in our current countermeasures against disasters.

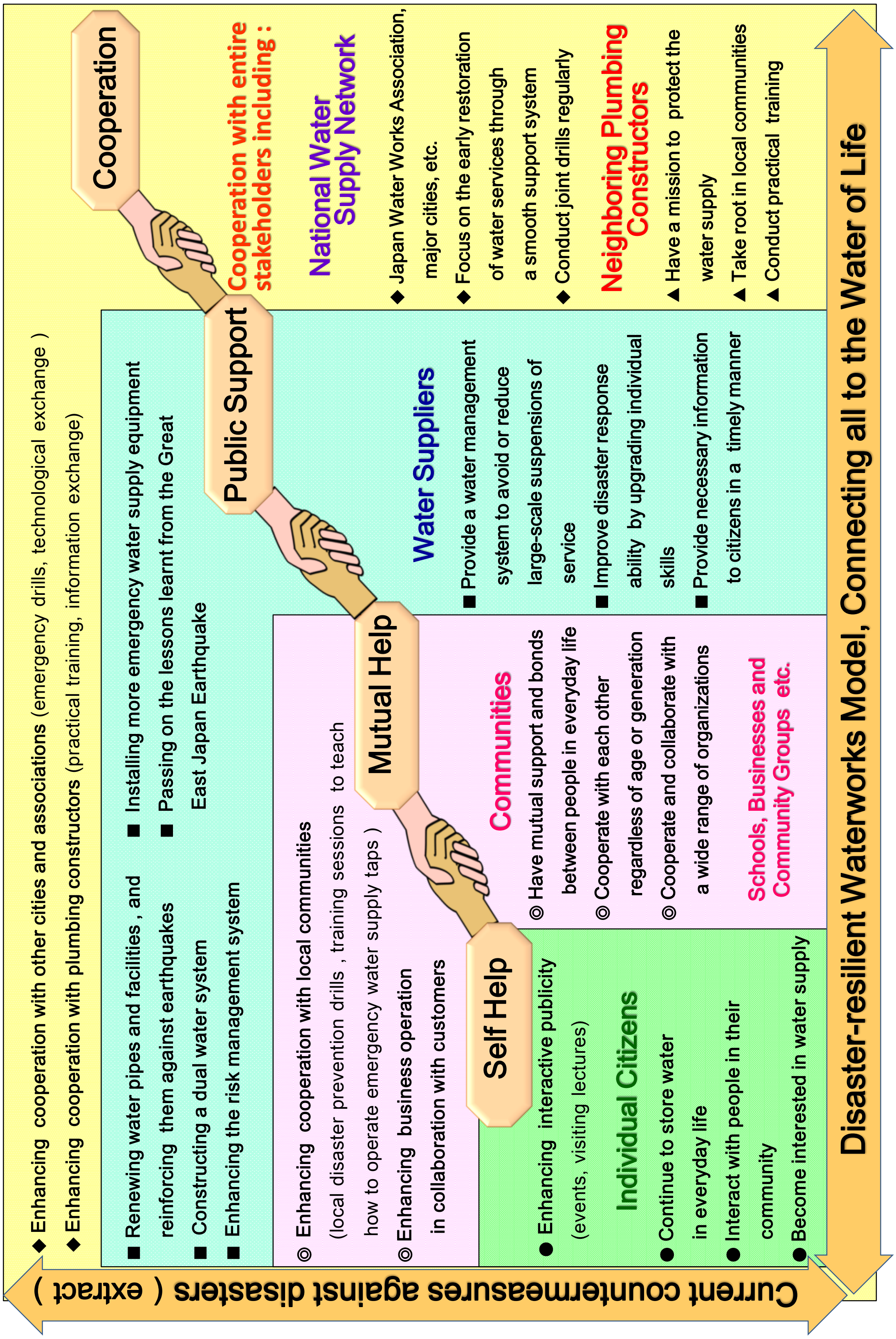


Figure 2. Correspondence between The Model and Sendai City Waterworks Bureau's current countermeasures against disasters

4. "Mutual Help" with local communities

Summary

The Sendai City Waterworks Bureau had established emergency water supply equipment in 60 places over the city before the Great East Japan Earthquake disaster.
However only Waterworks Bureau staff members were authorized to operate the equipment and due to a shortage in human resources, only twenty of the water supply facilities were able to be used.

In consideration of this issue, we have been carrying out the installation of ‘Emergency Water Taps’ at municipal elementary schools which are designated as refuge areas (excluding municipal elementary schools where emergency drinking water storage tanks are installed) and taps that local residents can set up and operate themselves since 2013. The ‘Emergency Water Tap’ is modeled on ground type fire hydrants that are connected to a pipe branched from an earthquake resilient pipe. The ‘Emergency Water Tap’ is easily installed by connecting the tap and a temporary water supply faucet to a Food Sanitation Act compliant water supply. In addition, the necessary equipment is kept in a disaster prevention stock warehouse on the premises.

By local residents setting up an ‘Emergency Water Tap’, the regional emergency water supply system is strengthened. Along with this it is considered to improve the human resources of the Waterworks Bureau to aid the early restoration of water facilities and emergency water supply to medical facilities etc.

Content of enlightenment activities for local residents

We request that local residents set up an ‘Emergency Water Tap’ when a designated refuge area is established after the occurrence of an earthquake measuring more than a lower 6 on the Japanese scale, regardless of whether or not the water supply is cut off. Sendai City Waterworks Bureau holds briefing sessions on how to use ‘Emergency Water Taps’ for evacuation center management committee members (consisting of local residents who operate the evacuation center, staff in charge of evacuation center, and school facility administrator), so that they can smoothly operate the equipment during or after a disaster. We also conduct enlightenment activities for citizens through our website and public information magazines by the Waterworks Bureau.

Progress status of ‘Emergency Water Taps’ installation

As of March 2017, ‘Emergency Water Taps’ have been installed in 78 out of 110 municipal elementary schools. We plan to finish installing these taps to all municipal elementary schools by March 2019. Furthermore, we plan to carry out installation to, in total 175 locations at elementary schools, junior high schools and high schools.

Photograph 2. Emergency water tap

Figure 3. Enlightenment activities from a public information magazine

5. “Cooperation” from local plumbing corporations or network of water supply utilities from all over Japan

Summary

In the past, every time an earthquake disaster occurred, the Sendai City Waterworks Bureau implemented an emergency water supply and emergency restoration to the water supply. In response to this, we have repeatedly re-examined and improved our system for sending personnel support. We then utilize these experiences for rescue activities at many disaster affected areas in Japan.

At the time of the Great East Japan Earthquake in 2011, Sendai City suffered serious damage, and about 50% of the water supply was cut. Sendai City received support in the form of water tank trucks from private companies and water supply utilities from all over Japan. It was due to this support that Sendai was able to carry out emergency water supply on a continuous basis and was able to achieve the early restoration of water services.

Based on experiences of rescue activities in the past and receiving support from other cities after the Great East Japan Earthquake. We will describe the mutual support system between major cities in Japan.

The JWWA mutual support framework

When an earthquake disaster occurs in Japan, the disaster affected water supply utilities make a “request for help” to the Japan Water Works Association (JWWA) based on the “Guidance for Response to Earthquakes and other Emergencies”. To correspond to the request, it is preferential that the neighboring communities and prefectural branches provide cooperative communication, emergency water supply, support and aid in restoring the water supply after a disaster. The JWWA mutual support framework consists of water supply utilities from all over Japan, which enables the assembly and dispatch of a large number of water tank trucks.

The framework of mutual support between major cities

Sendai City Waterworks Bureau has joined the “Memorandum of Understandings on Mutual Disaster Support between Waterworks Bureaus of 19 Cities”. When a disaster hits a major city, support is requested on a large scale from participating cities, putting in place the framework of mutual support between major cities.

The memorandum specifies designated leader cities and their roles when a disaster occurs. The designated Leader Cities take an initiative to collect information on the affected city, and convey their requests for support to other alliance cities.

By acting on behalf of the affected city, the Leader Cities will carry out support in the initial phase, it is expected that this leads to the early restoration of water services as the disaster affected city can concentrate their work on other restoration activities.

In the case of Sendai City, the Leader City of the first priority is Sapporo City and the following Leader City is Tokyo Metropolitan Government.

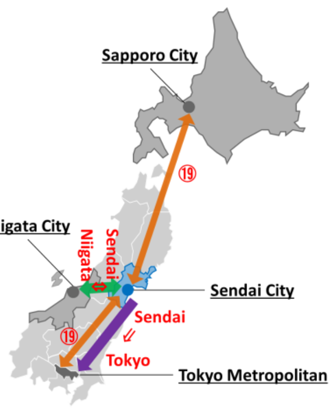
The other memorandums and agreement

Taking into account the geographical conditions, Sendai City has concluded the “Memorandum of Understandings on Mutual Disaster Support” with Niigata City, as there is a low possibility of an earthquake occurrence in both cities at the same time. In this Memorandum, the support city has the role of planning an emergency water supply, early restoration of water services and supplies fuels.

Furthermore Sendai City Waterworks Bureau has concluded with the Bureau of Waterworks, Tokyo Metropolitan Government the “Memorandum on Activities as a Waterworks utility responsible for Information Coordination between Tokyo Metropolitan Government and Sendai City”. Although Tokyo is positioned as the second Leader City to Sendai in the mutual support agreement, in the case that an earthquake with a seismic intensity larger than 6.0 occurs, independent support can begin, and has the advantage of a rapid initial response.

Additionally, in the occurrence that Sendai City is stricken by an earthquake disaster, Sendai City Waterworks Bureau has concluded the “Agreement of Restoration of Water Supply Facilities in Disasters” with the Miyagi Plumbing Sanitary Association（MPSA) for the early restoration of water services. In this agreement Sendai City Waterworks Bureau can request the MPSA to perform relief activities such as emergency water supply activities, emergency restoration and providing materials for restoration.

Beside this, Sendai City Waterworks Bureau has also concluded agreements with privately owned companies that provide engineers for leakage investigation and the dispatch of pressure type water tank trucks.



network of water supply utilities all over Japan

⑲: The “Memorandum of Understandings on Mutual Disaster Support between Waterworks Bureaus of 19 Cities”

Sendai⇒Tokyo: The Memorandum of Understandings on the Operation as information exchanging water utility between Tokyo Metropolitan Government and Sendai City.

Sendai⇔Niigata: The Memorandum of Understandings on the mutual support on disaster between Niigata Waterworks Bureau and Sendai City Waterworks Bureau

Figure 4. Network of water supply

Photograph 3. Practical training with other cities, private companies and citizens (Sapporo City and Niigata City)

6. CONCLUSION

This paper introduced and put together a comparison of the relationship between the Disaster-resilient Waterworks Model, Connecting all to the Water of Life proposed at the 3rd WCDRR, and our current countermeasures against disasters. We have highlighted the four necessary efforts; 'Self Help', 'Mutual Help', 'Public Support' and 'Cooperation' which together create a disaster-resilient water supply.

Sendai City Waterworks Bureau has made various measures to construct a disaster-resilient water supply, based on experiences from the Great East Japan Earthquake. However in this paper we only explained two of our measures 'Mutual Help' and 'Cooperation'. On the topic of 'Mutual Help', we explained that we have built a relationship of trust with citizens by constructing 'Emergency Water Taps' that enable citizens to set up a water supply station on their own after an event such as an Earthquake disaster and we explain to community residents how to use them. On the topic of 'Cooperation', we showed that we have established various relationships, for example we have signed memorandums of mutual support in a disaster with many cities and associations and hold joint disaster training with them.

In the future, we will continue to further our current countermeasures against disasters steadily, based on "The Management Plan (2015-2019)". Moreover, we will strive towards constructing a disaster-resilient waterworks in cooperation with various parties such as citizens, local communities, water suppliers, plumbing constructors and other cities. In order to achieve the above, we aim to raise everyone's awareness of disaster prevention including "Self Help" and "Public Support", two other necessary efforts of our city which were not addressed in this paper which enhance disaster prevention drills, and improve public relations.

Validation Accompanying the Introduction of a New Form of Energy (Fuel Cell System)

Kazuki Masaki, Hiroshi Hatsumi

ABSTRACT

In FY2014 fuel cell facilities were installed in radio relay stations owned by the Yokohama Waterworks Bureau. While there are multiple examples of fuel cells being installed in Japan, this marked the first time fuel cells were introduced by the Yokohama Waterworks Bureau. For this reason, demonstration tests were carried out verifying the stability of power supply and confirming fuel consumption amounts. This paper will provide a report on the details and results of said demonstration tests.

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INTRODUCTION

The Yokohama Waterworks Bureau installs uninterruptible power supply systems to instrument power supplies to ensure an uninterrupted power supply in the event of a disaster or other emergency. However, such a setup only allows for a short four hour power supply, leading to the distinct possibility that the power supply may be cut off before the emergency city workers arrive at the affected facility when a disaster occurs. To use the Great East Japan Earthquake as an example, it took three days to restore power after the power was cut off. Fuel cells began attracting attention as a means of supplying power for a 72 hour period, ensuring a long-term emergency power supply in circumstances where the main power grid is offline. This led to a fuel cell system being installed at the Nokendai High-zone Distribution Tank. This paper will report on the details leading up to the introduction of this fuel cell system, and evaluation results of demonstration tests on the system.

ISSUES WITH LONG-TERM POWER BLACKOUTS

The Yokohama Waterworks Bureau installs uninterruptible power supply systems as a backup power supply for instruments used for monitoring and controls for use in a power blackout caused by a disaster or other such emergency. These uninterruptible power supply systems are capable of supplying power for four hours. This causes concerns regarding in the difficulty of quickly restoring water supply as this short power supply prevents pressure and flow measuring of pumping stations and instrument control in extended blackout periods.

SUMMARY ON FUEL CELLS

Details on fuel cell use

The fuel cell installed by the Yokohama Waterworks Bureau is one of over 400 fuel cells found in Japan. Additionally, a communications company adopted the use of the same fuel cells in March 2013 as an emergency power supply at base stations as a countermeasure against long-term power outages resulting from a widespread disaster or other such emergency.

Power generation system

A methanol/water solution stored in the fuel cell itself is used to generate around 40 hours of continuous power supply. When the remaining fuel is insufficient, back up fuel stored in a plastic container can be used to provide an additional continuous power supply lasting at least 72 hours. Power is generated through a system whereby electricity is generated through a reverse water electrolytic process ($2H_2+O_2 \rightarrow 2H_2O$) where the methanol/water solution acts as the fuel, and hydrogen and oxygen as raw materials. (Fig. 1 Power generation flow reference for fuel cells)

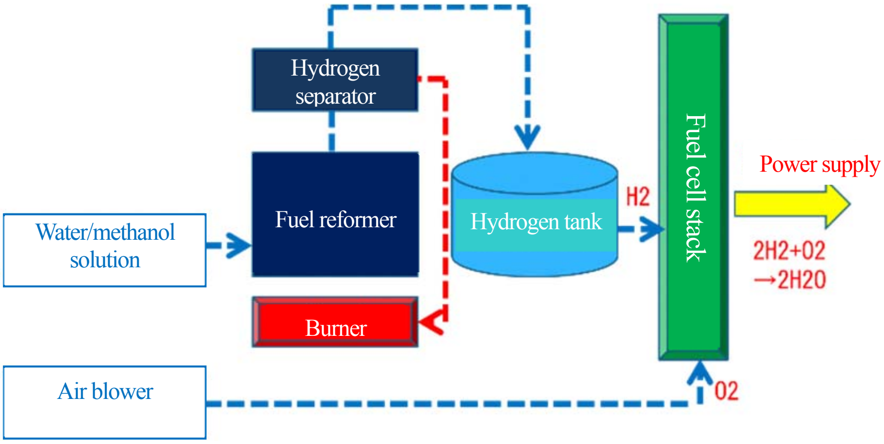

Figure. 1 Power generation flow of fuel cells

Procedure for switching power supplies in the event of a blackout

This section describes the procedure used to switch to the backup power supply when there is a blackout. Under normal circumstances a commercial power supply is used to supply power to radio equipment via a startup power supply. (See Fig. 2 Power supply procedure under normal circumstances.)

In the event of a blackout, a lithium-ion battery inside the startup power supply will start powering the fuel cell and the radio equipment. The fuel cell will then start supplying power using the power supplied from the lithium-ion battery inside the startup power supply. The fuel cell takes about three minutes to establish a power supply, and it begins supplying power to the radio equipment once the generator voltage has been established. (See Fig. 3 Procedure for switching power supplies in the event of a blackout.) This results in power being supplied from both the fuel cell and the startup power supply for a certain period of time. The power supply will switch to the higher voltage power supplied from the fuel cell as the voltage of the lithium-ion battery inside the startup power supply gradually continues to drop. This control method allows for an uninterrupted supply of power where radio equipment do not experience a down time.

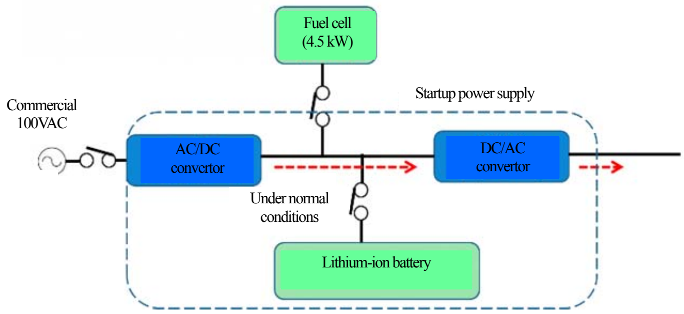

Figure. 2 Power supply procedure under normal circumstances

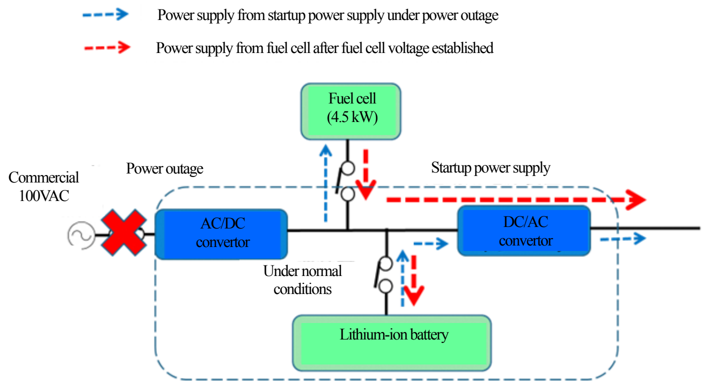

Figure. 3 Procedure for switching power supplies in the event of a blackout

Advantages of fuel cells

Environment

The power generation method used in fuel cells is friendlier to the environment — eliminating carbon dioxide emissions — and allows for a compact design that offers low noise generation.

Safety

The fuel used in fuel cells is a safe methanol/water solution (59% concentration) that is not recognized as a dangerous substance.

Long-term power supply capabilities

Fuel cells are capable of providing a long-term power supply, supplying 40 hours of power at a 4.5kW load. This duration can also be extended further through the supplement of fuel sources.

Fuel cell installation points

Fuel cells are installed at the Nokendai High-zone Distribution Tank, a site established as a radio relay station with the Kosuzume Purification Plant for monitoring information for the Kanazawa distribution reservoir and the Asahina dividing basin on the Kosuzume Purification Plant system, and for controlling and operating facilities over the radio system. (See Fig. 4 Outline diagram of the installation point.)

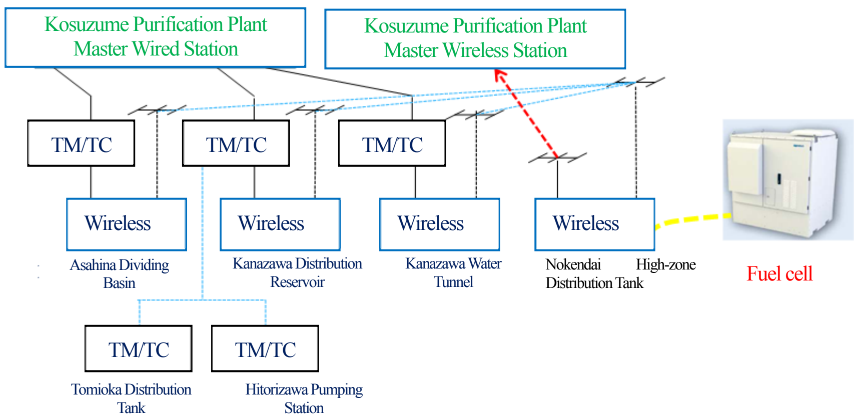

Figure. 4 Outline diagram of the installation point

EVALUATION TESTING DETAILS

Purpose of evaluation testing

Evaluation testing was performed twice to verify that the fuel cell system in place would be capable of operating over an extended period of time in the event of a disaster.

The first test was performed on July 28, 2015 and tested the fuel cell system running in continuous operation for an hour to verify that it was functioning normally.

The second test was performed from December 3, 2015 to December 4 and tested the fuel cell system running in continuous operation for 15 hours to test the soundness of the equipment when in continuous operation and to check the fuel consumption level.

Evaluation testing details

One hour operation test

The one hour operation test simulated a power blackout by shutting down the commercial 100VAC power source to perform two measurements of the voltage value of the fuel cell equipment and four measurements of its current value to verify that the fuel cell system was functioning normally. (See Fig. 5 Visual image of the test performed.)

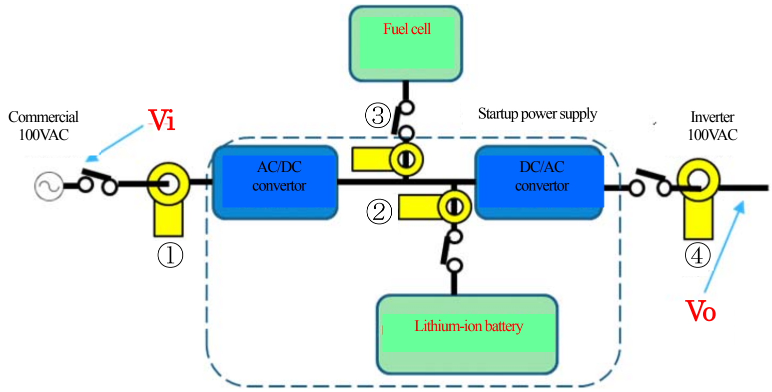

Figure. 5 Visual image of the test performed

15 hour operation test

The 15 hour operation test simulated a power blackout in the same manner as the one hour test to largely measure fuel consumption by the fuel cell equipment.

EVALUATION TESTING RESULTS

When power is out/restored

Voltage testing results are shown in Fig. 6. As we see in the diagram, the waveform of the voltage output by the fuel cell system after the commercial power supply is shut down/restored exhibits no signs of disarray, showing that the fuel cell outputs power at a stable voltage.

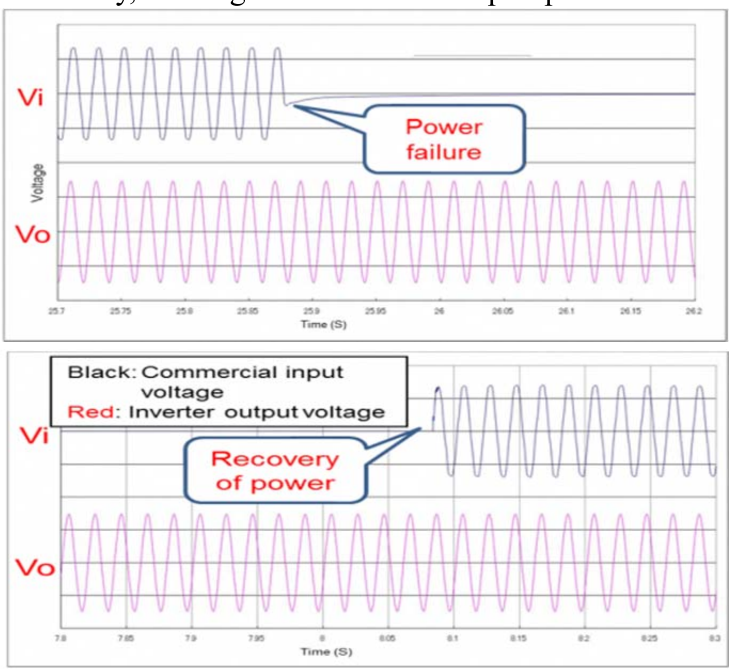

Figure. 6 Waveform diagram

Switching power supply when in a blackout

The results of tests performed on the output current when in a blackout are shown in Fig. 7. We can see that, when a blackout occurs, (1) the incoming current from the commercial power supply becomes zero, and (2) power is supplied from the lithium-ion battery inside the startup power supply to the load side. The fuel cell commences operation about three minutes after (3). As shown by (4), we can see that the power supply source has switched from the lithium-ion battery to the fuel cell. This is because the power supply source switches to the higher voltage fuel cell around 15 minutes after a drop in voltage from the lithium-ion battery. With this we can confirm that this allows for an uninterrupted supply of power where radio equipment do not experience a down time. (See Fig. 7 Power supply switch chart.)

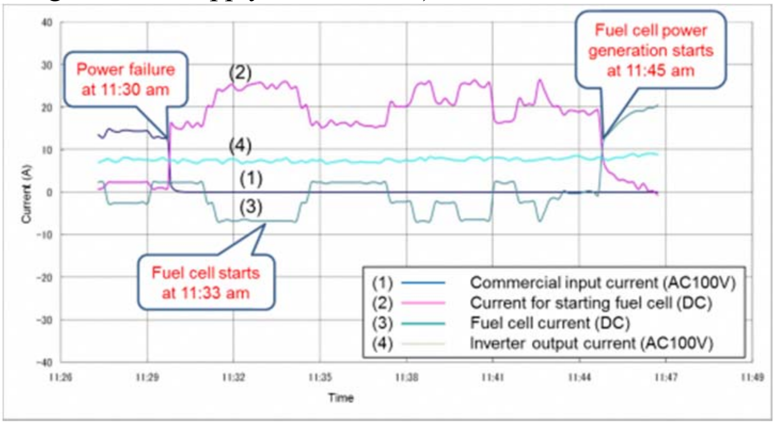

Figure. 7 Power supply switch chart

Fuel consumption amount

We were able to verify that the fuel amount dropped 12.5% as a result of 10 hours and 20 minutes of continuous operation. These results show that power could be supplied for approximately 82 hours and 40 minutes with a 225L tank stored in the main tank unit. (See Fig. 8 Fuel consumption graph.)

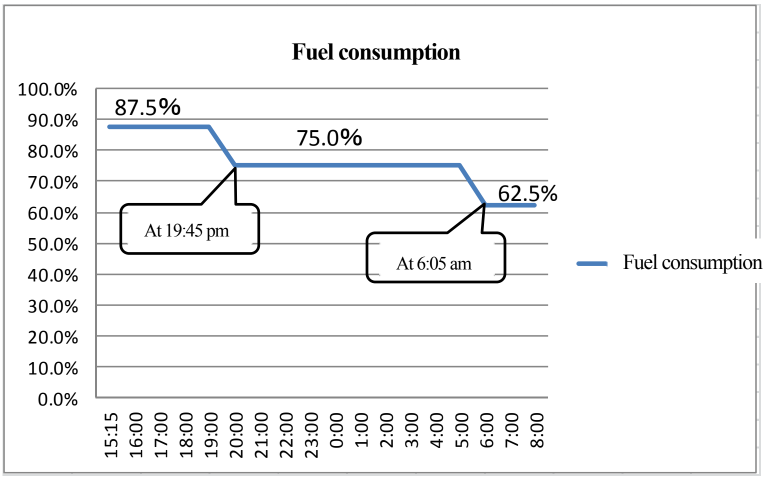

Figure. 8 Fuel consumption graph

CONCLUSION

The voltage test indicates that the system is functioning normally, showing no signs of disarray in the voltage output by the fuel cell system after the power outage/restoration, and that the fuel cell outputs power at a stable voltage.

The current test shows that power is supplied normally from the lithium-ion battery in the startup power supply for the 15 minute period it takes on average to start up the fuel cell system after a power outage. This test also indicates that the system is functioning normally by the lithium-ion battery inside the startup power supply starting to charge and output from the fuel cell being cut off once the power is restored.

In terms of fuel consumption, we were able to verify that the fuel tank alone is sufficient enough to generate power for over 72 hours, and testing showed the system clearing all reference values.

Based on these fuel cell evaluation results, we consider that a planned rollout of further fuel cell installations can be carried out.

Main Shock and After Shock Impact to Water System Seismic Fragility of Embankment Dams, Tank Reservoirs, and Large Diameter Pipelines

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ABSTRACT

The East Bay Municipal Utility District (EBMUD) is a major water utility providing drinking water to over 1.4 million people on the eastern side of the San Francisco Bay Area. The EBMUD water system comprises approximately 144 storage tanks, 132 pumping plants, 22 active dams, 7 water treatment plants, 6760 km of treated water distribution and transmission pipelines, and 270 miles of raw water aqueducts. The EBMUD service area encompasses over 331 square miles of varying topography. EBMUD has created a damage prediction model to aide in the rapid fragility assessment of all critical infrastructure, which can reduce recovery time.

The published document entitled "Water System Seismic Fragility of Embankment Dams, Tank Reservoirs, and Large Diameter Pipelines" (Prashar, et al. August 2012) provides the introductory framework to this paper. Estimating the level of ground shaking at any particular site is the critical input in developing the expected performance of any given structure. Forecasting aftershock levels at sites of critical facilities will assist in establishing the likelihood of further damage to our facilities and guide response and recovery decisions. The damage prediction models provide results for the water system components of EBMUD's water system.

This paper discusses the development of the damage prediction models for EBMUD's water system for embankment dam reservoirs, tank reservoirs, and large diameter pipelines; damage results related to the two Hayward Fault scenario earthquake and aftershock events; and the next steps for damage prediction to increase robustness in the water system. A revised approach to developing a more comprehensive EBMUD infrastructure risk model is presented. The probability of failure is revisited in this approach of considering the contribution of aftershocks in rapid modeling of infrastructure fragility.

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INTRODUCTION

About EBMUD

The East Bay Municipal Utility District (EBMUD) provides drinking water to over 1.4 million people on the eastern side of the San Francisco Bay. The EBMUD water system comprises approximately 144 supply reservoirs, 132 pumping plants, 22 embankment dams, 7 water treatment plants, 6760 km of treated water distribution and transmission pipelines, and 435 km of raw water aqueducts.

Figure 1 shows EBMUD's service area which encompasses over 860 square kilometers of varying topography. With such a large water system to manage and operate in an area prone to destructive earthquakes, emergency response can be an overwhelming task following an earthquake. As a result, EBMUD created damage prediction models to prioritize field inspections of the water system and help accelerate emergency response and recovery time.

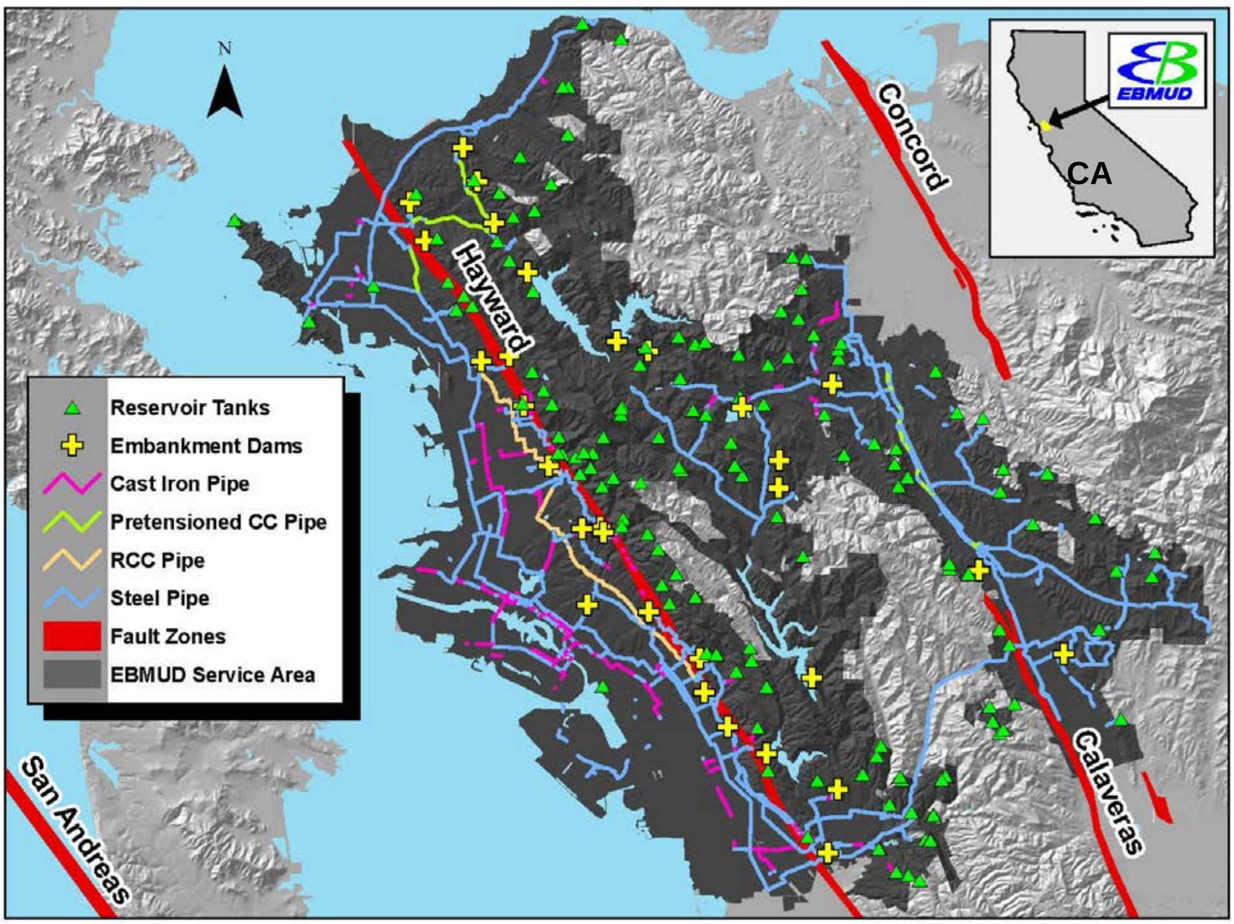

Figure 1: EBMUD Location Map

Background

The published document entitled “Water System Seismic Fragility of Embankment Dams, Tank Reservoirs, and Large Diameter Pipelines” [5] provides the introductory framework to this paper. Estimating the level of ground shaking at any particular site is the critical input in developing the expected performance of any given structure. United States Geological Survey (USGS) provides computational tools in developing these estimates of ground motions. Additionally, spreadsheet tools containing the Next Generation Attenuation relationships can be calculated to estimate ground motions based on earthquake magnitude, distance, and shear wave velocity. Fortunately for EBMUD, the USGS has developed a revised set of specific scenario events [16] for the rupture of the Hayward Fault which is the main fault of concern in the service area. This study relied on using GIS as an evaluation tool by injecting scenarios and extracting strong ground motions (acceleration, velocity) parameters at specific sites. The site-specific results were evaluated and are presented below for District Dams, tanks and large diameter pipelines.

USGS Earthquake Scenario Events

A scenario represents one realization of a potential future earthquake by assuming a particular magnitude, location, and fault-rupture geometry and estimating shaking using a variety of strategies. In planning and coordinating emergency response, utilities, local government, and other organizations are best served by conducting training exercises based on realistic earthquake situations—ones similar to those they are most likely to face. ShakeMap Scenario earthquakes can fill this role. They can also be used to examine exposure of structures, lifelines, utilities, and transportation corridors to specified potential earthquakes. A ShakeMap earthquake scenario is a seismic map based on with an assumed magnitude and location, and, optionally, specified fault geometry.

The Hayward-Rodgers Creek fault system has the highest probability (33%) for a large rupture (Mw>6.7) on the major faults in the region [16]. For the Haywired study, the USGS developed a 2-year aftershock sequence scenario, and ran thirteen different aftershock sequence models and selected one with 175 aftershocks Mw>4, and 16 aftershocks Mw>5, and then moved the modeled aftershocks on to actual faults in the San Francisco Bay Region. Figure 2 shows the location of the main shock and significant aftershocks within EBMUD service area.

Main and Aftershocks

EBMUD downloaded data from the USGS ShakeMap website for the Hayward M_w 7.05 scenario event for the main and 16 aftershocks. Figure 2 presents the scenario events in the vicinity of our service area. For modeling purposes we only used 5 aftershock events listed below. Scenario earthquakes are based upon an approach that assumes a particular fault or fault segment will rupture over a certain length relying on consensus-based information about the potential behavior of the fault. For historic events, the actual rupture dimensions may be constrained based on existing observations or models. Second, estimate ground motions at all locations in a chosen region surrounding the causative fault. These earthquake scenarios are not earthquake predictions.

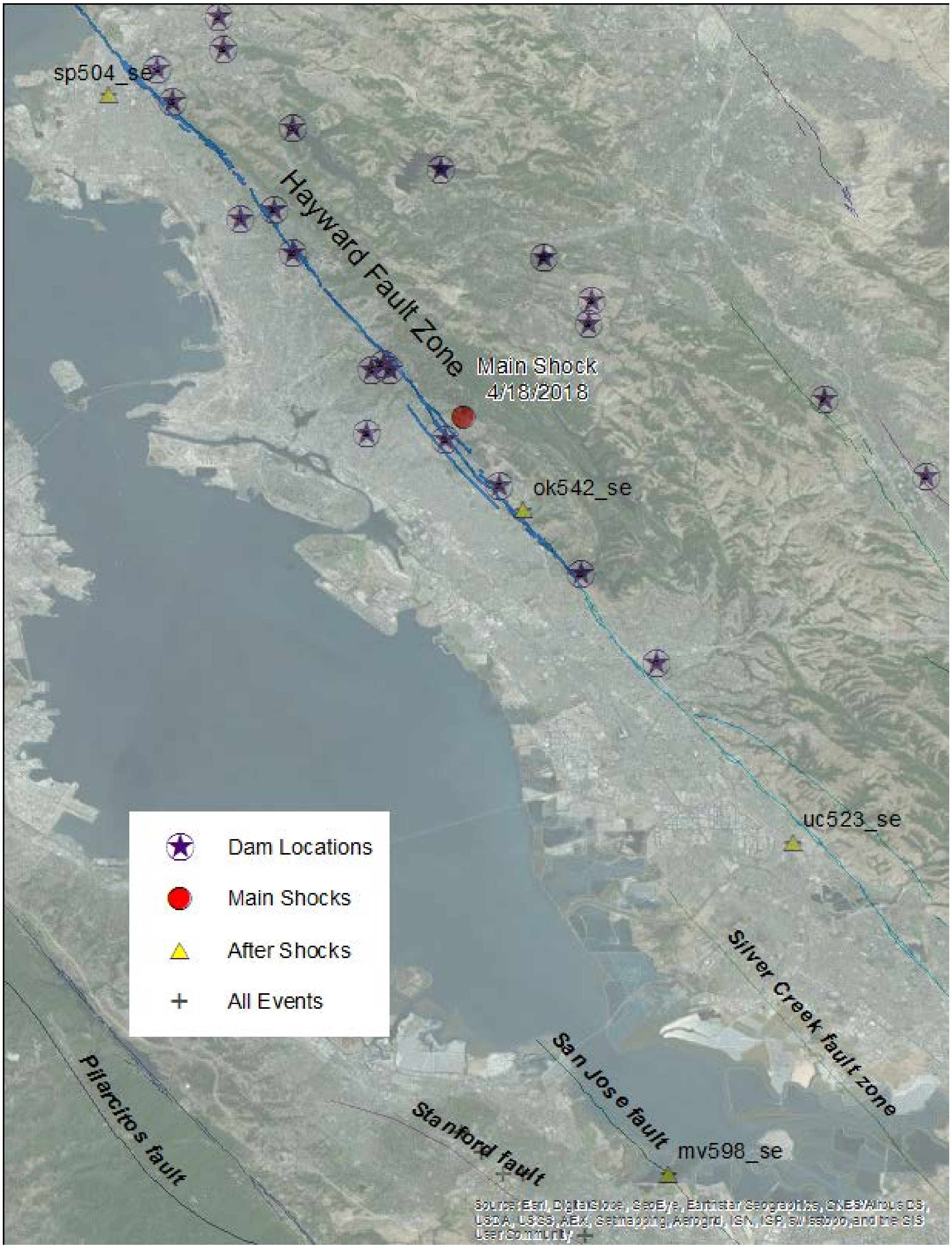

Figure 2: USGS Main and Aftershock Model [16, 17]

The scenario earthquakes given on the Northern California ShakeMap website represent 34 possible future earthquakes in the greater San Francisco Bay Area as determined by the USGS-led Working Group on California Earthquake Probabilities. This Working Group (WG02) concluded that the likelihood of one or more large (M>=6.7) earthquakes in the San Francisco Bay region in the next 30 years is 62%. Table 1 presents the Main shock and 5 aftershocks available through USGS [18]. The Scenario ID's used in this study are: 1-MS705, 17-UC523, 8-OK542, 13-PA621, 7-MV598, and 3-CU640. These scenarios were used in reservoir and structural assessment of District facilities and are used throughout the remainder of the report.

TABLE 1: EBMUD SELECTED MS AND MS+AS SCENARIO

USGS #	Scenario_ID	Event	Mw	Date of Exercise	Lat	Long	Depth_KM
1	Main Shock	Main Shock - Scenario	7.05	18-Apr-18	37.805	-122.179	8.0
3	cu640_se	Cu640 Scenario	6.40	1-Oct-18	37.310	-122.060	15.4
7	mv598_se	Mv598 Scenario	6.00	1-Oct-18	37.440	-122.080	11.3
8	ok542_se	Ok542 Scenario	5.40	20-May-18	37.760	-122.150	8.4
13	pa621_se	Pa621 Scenario	6.20	28-May-18	37.390	-122.180	19.0
15	sp504_se	Sp504 Scenario	5.00	19-Apr-18	37.960	-122.350	2.6
17	uc523_se	Uc523 Scenario	5.20	18-Apr-18	37.600	-122.020	2.6

EMBANKMENT DAMS

Figure 1 shows EBMUD's 22 dam reservoirs denoted as yellow crosses, along with major active faults. As the figure presents, most of the dam reservoirs are near the Hayward Fault. The embankment dams were previously evaluated and published in the paper titled: "Developing Embankment Dam Fragilities for Emergency Modeling and Response for 22 EBMUD Reservoirs." [5]

Overview

To develop the dam fragility curves, EBMUD engineers first estimated the crest settlement during the postulated seismic shaking for each dam. Next, the settlement estimate was divided by the dam height to provide an estimate of axial compressive strains induced within the dam during or following an earthquake. The percent settlement magnitude was used as a proxy to establish the performance/fragility of the dam. Based on the percent settlement strain for the EBMUD dams, four performance classes were established. Newmark double integration procedure was used to determine the settlement of a dam for varying peak ground acceleration (PGA) values and the result was a fragility curve that models the performance of the dam for recorded ground motions.

The fragility evaluations resulted in estimated crest settlement versus varying peak ground accelerations for each embankment, which were used as a baseline to establish the relative rankings for each dam. The final modeling step uses the USGS input scenario events to calculate the level of fragility. The scenario event shape files were input into ArcGIS and ground motion parameters were extracted and tabulated for each reservoir, tank, and pipeline locations.

Damage Model Development

Tables 2A and 2B present the four reservoir dam class categories corresponding to four performance (fragility) level limits for the main shock alone (MS) and for the main shock plus aftershocks (MS+AS). It can be seen that values corresponding to the low and high ranges for the various levels of dam classes correspond to the axial strain values. The performance levels are simply related to percent settlement values assuming 5% is a maximum value. Figure 3 (following page) shows how the individual dams were categorized, which were based on the settlement percent shown for each dam. These varying performance levels were used to develop the four dam classes.

TABLE 2A: DAM CLASS FRAGILITY LIMITS – MS ONLY

Fragility	Limit 1 (L1)		Limit 2 (L2)		Limit 3 (L3)		Limit 4 (L4)	
	Low	High	Low	High	Low	High	Low	High
Minimal	0	0.63	0	0.58	0	0.53	0	0.48
Light	0.63	0.85	0.58	0.8	0.53	0.75	0.48	0.7
Moderate	0.85	0.93	0.8	0.88	0.75	0.83	0.7	0.78
Severe	0.93	-	0.88	-	0.83	-	0.78	-

TABLE 2B: DAM CLASS FRAGILITY LIMITS – MS + AS

Fragility	Limit 1 (L1)		Limit 2 (L2)		Limit 3 (L3)		Limit 4 (L4)	
	Low	High	Low	High	Low	High	Low	High
Minimal	0	0.57	0	0.52	0	0.46	0	0.42
Light	0.57	0.83	0.52	0.78	0.46	0.73	0.42	0.68
Moderate	0.83	0.89	0.78	0.84	0.73	0.79	0.68	0.74
Severe	0.89	-	0.84	-	0.79	-	0.74	-

The fragility for each dam was developed based on the shape of curves shown in Figure 3. Additional details of the background and approach are provided in Ref No. 5, and 6.

Damage Model Results

Tables 2A and B show the qualitative performance limits for dams, which were extracted from Figure 3. In addition, Tables 2A and B shows the definition of failure/damage versus PGA. The four classes will have four different ranges of damage: L1, L2, L3, and L4. Figure 3 shows a second set of curves representing the MS + AS that were developed by assuming a 20% capacity reduction (accounting for temporary loss of shear strength) following the main shock. The 20% strength loss of geo-materials is a standard practice in geotechnical engineering and is considered appropriate for these set of simplified assumptions and purposes intended. Future such studies may consider delve into additional details on this approach and explore the possibility of dam-specific strength reductions to account for site-specific properties.

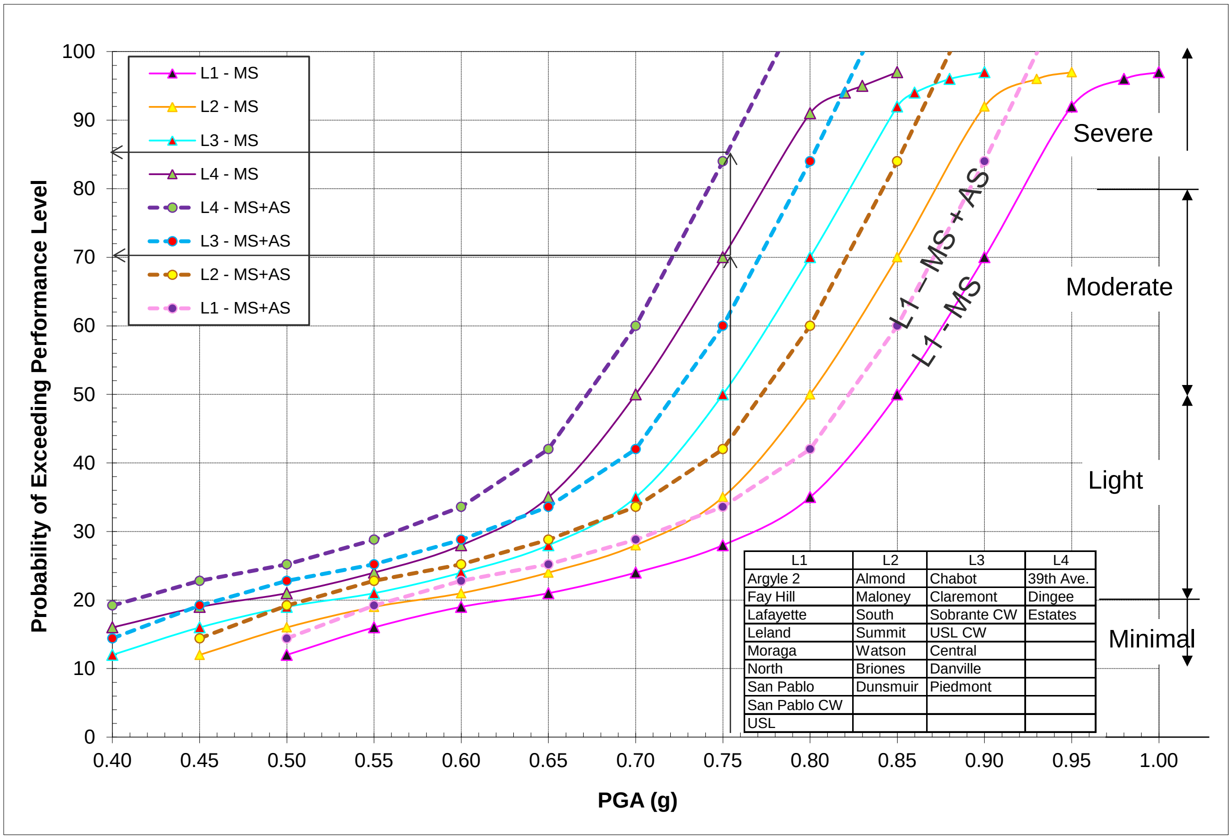

Figure 3. Fragility Limits for 4 Different Levels (L1, L2, L3, L4) of Dam

TABLE 3: MS AND MS +AS SCENARIO RESULTS

Dam No.	RESERVOIR	Reservoir Classes	PF - MS (%)	Damage Level	PF - MS+AS (%)	Damage Level	MCE Site PGA (g)	Damage Level MS	Damage Level MS+AS
14	39th Ave.	L4	16.0	Minimal	19.2	Minimal	0.80	Severe	Severe
20	Almond	L2	24.0	Light	28.8	light	0.78	light	Moderate
30	Argyle 2	L1	21.0	Light	25.2	light	0.86	Moderate	Moderate
15	Briones	L2	12.0	Minimal	14.4	Minimal	1.00	Severe	Severe
00	Central	L3	16.0	Minimal	19.2	Minimal	0.71	light	light
05	Chabot	L3	12.0	Minimal	14.4	Minimal	1.05	Severe	Severe
01	Claremont	L3	35.0	Light	42.0	light	1.00	Severe	Severe
28	Danville	L3	16.0	Minimal	19.2	Minimal	0.65	light	light
03	Dingee	L4	16.0	Minimal	19.2	Minimal	1.00	Severe	Severe
18	Dunsmuir	L2	16.0	Minimal	19.2	Minimal	1.09	Severe	Severe
09	Fay Hill	L1	10.0	Minimal	12.2	Minimal	0.57	Minimal	light
02	Lafayette	L1	16.0	Minimal	19.2	Minimal	0.60	Minimal	light
21	Leland	L1	8.0	Minimal	10.0	Minimal	1.19	Severe	Severe
24	Maloney	L2	16.0	Minimal	19.2	Minimal	0.85	Moderate	Severe
22	Moraga	L1	9.0	Minimal	11.0	Minimal	0.66	light	light
27	North	L1	12.0	Minimal	14.4	Minimal	0.87	Moderate	Moderate
06	San Pablo	L1	13.0	Minimal	15.2	Minimal	1.00	Severe	Severe
29	San Pablo CW	L1	9.0	Minimal	11.0	Minimal	0.75	light	light
23	Sobrante CW	L3	24.0	Light	28.8	light	0.83	Severe	Severe
17	USL CW	L3	35.0	Light	42.0	light	0.80	Moderate	Severe
31	Upper San Leandro	L1	35.0	Light	42.0	Light	1.02	Severe	Severe
33	Watson	L2	19.0	Minimal	22.8	Light	0.76	light	light

Table 3 presents the dam damage level results. Evaluation of all embankments for MS only and MS+AS levels, all of the facility's damage levels were Minimal to Light. The revised fragility curves (Tables 2A and B), were compared against one another using the Maximum credible earthquake (MCE) based site specific peak ground acceleration. As anticipated the damage levels for our reservoirs were higher when considering the MS +AS scenario case.

RESERVOIR TANKS

Overview

EBMUD currently has 144 water distribution tank reservoirs in service, consisting of 58 concrete tanks, 4 wood tanks, and 82 steel tanks. The types of concrete tanks in EBMUD's system include cable stressed, reinforced buried, wire stressed, bar stressed, and reinforced concrete tanks. EBMUD's steel tanks include welded and bolted tanks. EMBUD's wood tanks are made of redwood. All of EBMUD's steel and concrete tanks have been retrofitted to have a positive connection between the tank wall and supporting concrete ring wall. Therefore, the steel and concrete tanks were assessed under the classification of anchored tanks.

For the main shock event, tanks were assessed using fragility relationships developed by HAZUS [6]. Tanks were assessed after each subsequent aftershock event by shifting the HAZUS curves by approximations developed by Li, et al. [15].

Damage Model Development

EBMUD developed a prediction model to estimate damage to distribution reservoirs experiencing a local magnitude scenario seismic event and subsequent local aftershock seismic events. The prediction model required the collection of EBMUD GIS data for the reservoir location (longitude and latitude), classification (capacity and anchorage) of the tanks, and the PGA for the scenario earthquake event.

Damage to a water storage tank has been predicted using fragility curves. For this study, fragility curves are based on the probability of reaching or exceeding different damage states for a given level of PGA. Main shock damage states describing the level of damage to each of the water storage tanks have been defined by Table 8.9 of the HAZUS-MH-MR3 Technical Manual. Table 4 summarizes the damage state versus PGA for the steel, concrete, and wood tanks considered.

TABLE 4. WATER ON-GROUND STORAGE TANKS DAMAGE ALGORITHMS

Damage	Anchored Concrete Tank	On-Ground Anchored Steel Tank	On-Ground Wood Tank
	Median PGA (g)	Median PGA (g)	Median PGA (g)
Slight/Minor	0.25	0.30	0.15
Moderate	0.52	0.70	0.40
Extensive	0.95	1.25	0.70
Complete	1.64	1.60	0.90

Aftershock damage states describing the level of damage to each of the water storage tanks have been defined by shifting the median PGA of the HAZUS curves for each damage state. The amount of shifting is dependent on the damage level to the tank after the previous event. The approximated percent reduction in the tank's seismic collapse capacity was determined by incremental dynamics analysis (IDA). The collapse capacity losses used in this study were approximated by Li, et al. [15] and are summarized in the tables below. Table 5 and 6 shows how much the collapse capacity of a tank could be reduced after a seismic event.

TABLE 5. WATER TANK COLLAPSE CAPACITY REDUCTIONS

Damage	Main Shock	Aftershock
Minor :	0%	0%
Moderate :	13%	14%
Extensive/Complete :	40%	53%

TABLE 6. CUMULATIVE COLLAPSE CAPACITY

Damage	Before	Main Shock	Aftershock				
			1	2	3	4	5
Minor	100%	100%	100%	100%	100%	100%	100%
Moderate	100%	87%	75%	64%	55%	48%	41%
Extensive/Collapse	100%	60%	28%	13%	6%	3%	1%

For example, before an earthquake event, we can assume that a reservoir will have 100% of its collapse capacity, as it has not sustained any structural damage. After the main event, a reservoir that sustains moderate damage will have a remaining structural collapse capacity of 87%. Each subsequent aftershock event will further reduce the structural collapse capacity by 14% if the damage level remains in the Moderate range or by 54% if the damage increases to the "Extensive/Complete" level.

Damage Model Results

EBMUD executed the damage prediction model using the six scenario events – one main shock event, followed by five aftershock events. Tables 7 through 10 presents the predicted number of damaged tanks for each damage state. 94% of EBMUD's tanks are expected to withstand the scenario events and suffer a level of damage that causes minor or no loss of contents.

TABLE 7. TANKS WITH NO/SLIGHT/MINOR DAMAGE

TYPE	MS705	UC523	OK542	PA621	MV598	CU640
STEEL	53	53	53	53	53	53
CONC.	26	26	26	26	26	26
WOOD	2	2	2	2	2	0
TOTAL	81	81	81	81	81	79
% OF ALL TANKS	56%	56%	56%	56%	56%	55%

TABLE 8. TANKS WITH MODERATE DAMAGE

TYPE	MS705	UC523	OK542	PA621	MV598	CU640
STEEL	25	25	25	25	25	25
CONC.	30	30	30	30	30	30
WOOD	1	1	1	1	1	1
TOTAL	56	56	56	56	56	56
% OF ALL TANKS	39%	39%	39%	39%	39%	39%

TABLE 9. TANKS WITH EXTENSIVE DAMAGE

TYPE	MS705	UC523	OK542	PA621	MV598	CU640
STEEL	0	0	0	0	0	0
CONC.	1	1	1	1	1	0
WOOD	1	1	1	1	0	2
TOTAL	2	2	2	2	1	2
% OF ALL TANKS	1.4%	1.4%	1.4%	1.4%	0.7%	1.4%

TABLE 10. TANKS WITH COMPLETE DAMAGE

TYPE	MS705	UC523	OK542	PA621	MV598	CU640
STEEL	0	0	0	0	0	0
CONC.	0	0	0	0	0	1
WOOD	0	0	0	0	1	1
TOTAL	0	0	0	0	1	2
% OF ALL TANKS	0%	0%	0%	0%	0.7%	1.4%

LARGE DIAMETER PIPELINES

Overview

EBMUD operates approximately 580 km of large diameter pipelines. These pipelines include 50.8 cm (20-inch) and larger diameter welded steel pipe, 91.4 cm (36-inch) and larger reinforced concrete cylinder pipe, 40.6 cm (16-inch) and larger diameter cast-iron pipe, and 50.8 cm (20-inch) and larger pre-tensioned concrete cylinder pipe.

Damage Model Development

EBMUD developed a damage prediction model to estimate the number of pipe repairs using empirical vulnerability formulations and specific hazard settlement relationships. The damage model followed a three step approach, as presented below:

a. Assemble EBMUD and seismic GIS Data;
b. Define scenario earthquake events; and
c. Estimate pipeline fragility.

The 360 miles of large diameter pipelines were processed into midpoints representing 1,000-foot pipe segments. Using a point, rather than a polyline, simplified the GIS processing of spatial data. Figure 1 presents a GIS map of the large diameter pipeline study area showing fault lines and symbology for cast iron, RCC (reinforced concrete cylinder), Pretensioned CC (concrete cylinder), and S (steel) pipe materials.

The seismic hazards evaluated in the damage prediction model included ground shaking, liquefaction, landslide, and fault rupture. EBMUD collected the latest GIS data from USGS and CGS to incorporate in the model. Refer to the Yogesh papers [6] and [7] for a detailed explanation of each seismic hazard and description of the model input metrics.

The pipeline damage model used empirical formulas developed by the ALA Seismic Fragility Formulation for Water Systems [14]. The damage model provided output in terms of repairs per 1,000 feet of pipeline using PGV, PGD, and fault offset input data. EBMUD selected pipe characteristic constants based on the pipe material and joint types. Welded and riveted steel, as well as pre-tensioned concrete cylinder pipe were modeled as continuous pipe. All remaining large diameter pipeline materials (cast iron and reinforced concrete) were modeled as segmented pipe. For a more detailed explanation of the damage prediction model, specifically the calculation of PGD, see references [6] and [7].

Damage Model Results

EBMUD executed the damage prediction model using the main shock and five aftershock scenarios. Tables 11 through 15 present the number of repairs computed for each pipe material type, seismic hazard, total damage, and percent of total pipe segments damaged. Where: C (cast iron), L (reinforced concrete cylinder), T (pretensioned concrete cylinder), S1 (steel riveted joints < 1950), S2 (steel welded joints between 1950 and 1970), S3 (steel welded joints >1970), and R/Segment (repairs per pipe segment or 1,000 feet of modeled large diameter pipe).

TABLE 11. REPAIRS DUE TO GROUND SHAKING

PIPE	MS705	UC523	OK542	PA621	MV	CU640	TOTAL
C	0	0	0	0	0	0	0
L	0	0	0	0	0	0	0
T	0	0	0	0	0	0	0
S1	0	0	0	0	0	0	0
S2	0	0	0	0	0	0	0
S3	0	0	0	0	0	0	0
TOTAL	0	0	0	0	0	0	0
%	0%	0%	0%	0%	0%	0%	0%

TABLE 12. REPAIRS DUE TO LIQUEFACTION

PIPE	MS705	UC523	OK542	PA621	MV	CU640	TOTAL
C	120	0	77	0	0	0	197
L	28	0	7	0	0	0	35
T	3	0	0	0	0	0	3
S1	36	1	19	1	0	1	58
S2	0	0	0	0	0	0	0
S3	0	0	0	0	0	0	0
TOTAL	187	1	103	1	0	1	293
%	10%	0%	5%	0%	0%	0%	15%

TABLE 13. LANDSLIDE

PIPE	MS705	UC523	OK542	PA621	MV	CU640	TOTAL
C	27	0	0	0	0	0	27
L	18	0	0	0	0	0	18
T	0	0	0	0	0	0	0
S1	9	0	0	0	0	0	9
S2	0	0	0	0	0	0	0
S3	0	0	0	0	0	0	0
TOTAL	54	0	0	0	0	0	54
%	3%	0%	0%	0%	0%	0%	3%

TABLE 14. FAULT RUPTURE

PIPE	MS705	UC523	OK542	PA621	MV	CU640	TOTAL
C	9	0	0	9	9	9	36
L	4	0	0	4	4	4	16
T	0	0	0	0	0	0	0
S1	24	0	0	24	24	24	96
S2	36	0	0	36	36	36	144
S3	8	0	0	8	8	8	32
TOTAL	81	0	0	81	81	81	324
%	4%	0%	0%	4%	4%	4%	17%

TABLE 15. TOTAL DAMAGE

PIPE	MS705	UC523	OK542	PA621	MV	CU640	TOTAL
C	156	0	77	9	9	9	260
L	50	0	7	4	4	4	69
T	3	0	0	0	0	0	3
S1	69	1	19	25	24	25	163
S2	36	0	0	36	36	36	144
S3	8	0	0	8	8	8	32
TOTAL	322	1	103	81	81	82	671
%	17%	0%	5%	4%	4%	4%	35%

CONCLUSIONS

Embankment Dams

The above approach of categorizing 22 dams into fragility classes enables EBMUD emergency response team to prioritize an emergency response approach. Rapid prediction allows EBMUD emergency response efforts staff on the most important facilities. Mobilizing properly trained staff to the facilities in a timely basis could even help prevent impending failures. This approach can easily be duplicated by other public agencies in seismically active areas where critical infrastructure is geographically spread out. The assessment for these 22 dams was completed primarily for emergency response purposes. It should be noted that all EBMUD dams have been evaluated using current design standards and have been found to be safe under the postulated shaking.

Reservoir Tanks

The ability to predict the relative likelihood of damage to tanks within EBMUD's extensive system of distribution reservoirs enables EBMUD to prioritize the emergency response approach. The damage modeling also helps to ensure that enough water is available for emergency response purposes, such as fire-fighting and supplying emergency response efforts. This study found that 94% of the distribution tanks are predicted to remain functional and in-service after the considered earthquake and aftershocks. Using these damage predictions can help EBMUD prioritize which tanks to send emergency responder and repair crews to following a seismic event.

Large Diameter Pipelines

No repairs were computed for the ground shaking seismic hazard, which confirms historical pipeline damage. Liquefaction damaged 187 (10%) pipe segments during the main shock and 293 (15%) total pipe segments with the combined aftershocks. Landslide damage included 54 (3%) pipe segments with the main shock. And, fault rupture accumulated 81 (4%) segment repairs during the main shock and 324 total pipe segments following the combined aftershocks. The segmented pipes (cast iron and reinforced concrete pipe) showed high levels of damage. The fault rupture accounted for the most damage to the large diameter pipelines.

The main shock and combined aftershocks damaged 322 and 349 pipe segments, respectively. A total of 671 pipe segments or 35% of the total pipe segments are estimated to be damaged after both the main shock and aftershocks.

ACKNOWLEDGMENTS

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Review of an Equation to Estimate Seismic Damage to Water Mains in Light of the 2016 Kumamoto Earthquake

Yuko Tsuruda, Yuichi Ishikawa, Fumio Sasaki, and Masakatsu Miyajima

ABSTRACT

In 2011, the Japan Water Research Center established an equation to estimate (predict) the number of pipe failures in earthquakes. The equation estimates relative damage to mains per 250-meter grid cell of a service area. It was developed based on an analysis of major seismic disasters in the past. As the equation aims to facilitate an efficient seismic reinforcement of water supply facilities by water utilities, it needs to be reviewed and updated properly based on new knowledge and findings from relevant seismic disasters. Most recently, in April 2016, the Kumamoto Region of Japan was hit directly by two earthquakes of magnitude greater than Mw 6.0 that occurred consecutively over a three-day period. In the wake of the Kumamoto Earthquake, we reviewed the equation to see whether it needs an update to improve its accuracy for damage estimation.

The review result showed that overall, the correction factors of the equation and its reference damage rate have similar tendencies to the characteristics of the actual damages although the total number of estimated pipe damages in Kumamoto City was about 4.1 times larger than the number of the actual pipe damages, this can be partly explained from the fact that the equation is designed to estimate on the safe side. From these results, we decided that the equation is valid, requiring no immediate modifications to the correction factors and the reference damage rate. One concern remains, however, that the equation might have estimated a little too far on the safe side. Therefore, this aspect would need a further consideration.

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INTRODUCTION

In FY2011, the Japan Water Research Center ("JWRC") made an equation to estimate (predict) the number of pipe failures in earthquakes ("equation") [1]. The equation was developed based on the analysis of major seismic disasters in the past, including the 1995 Kobe Earthquake. In FY2013, the equation was revised upon the 2011 Great East Japan Earthquake in order to improve its accuracy for damage estimation and to incorporate newly obtained knowledge from the earthquake [2].

In April 2016, the Kumamoto Region of Japan was hit directly by two earthquakes of magnitude greater than Mw 6.0 that occurred consecutively over a three-day period. In the wake of the Kumamoto Earthquake, JWRC reviewed the equation to see if it would need a further update to improve its damage estimation.

THE EQUATION AND ITS CORRECTION FACTORS

Figure 1 and Table I show the procedure of estimating pipe damage using the equation and its correction factors as updated upon the 2011 Great East Japan Earthquake [3]. The equation is to estimate pipe damage per 250-meter grid cell of a service area. The estimation is carried out using the information on pipe material/joint, diameter, microtopography, peak ground velocity (PGV) of earthquakes, as well as liquefaction data (if applicable). The result is expressed in the number of damaged locations per kilometer. Another characteristic of the equation is that it is designed to estimate on the safe side to avoid an underestimate of seismic impact.

The reference damage rate of the equation refers to the damage rate of the pipe that has a reference material/joint, diameter, and microtopographic data, and is obtained using PGV. As for liquefaction, if a target area has liquefaction data, the reference damage rate will be calculated with a reference liquefaction damage rate set to 5.5 uniformly for all the relevant estimations.

The equation has a set of correction factors for different pipe materials/joints, diameters, and microtopographies. The reference correction factor is 1.0 with DIP (A) as the reference pipe material/joint while the reference diameter is 100-150 mm and the reference microtopography is either a valley lowland, alluvial fan, humid lowland plain, delta, or coastal lowland. Each correction factor was determined based on a comparison between the damage rate of DIP (A) and the damage rate of other pipe materials/joints, diameters, and microtopographies in major earthquakes in the past.

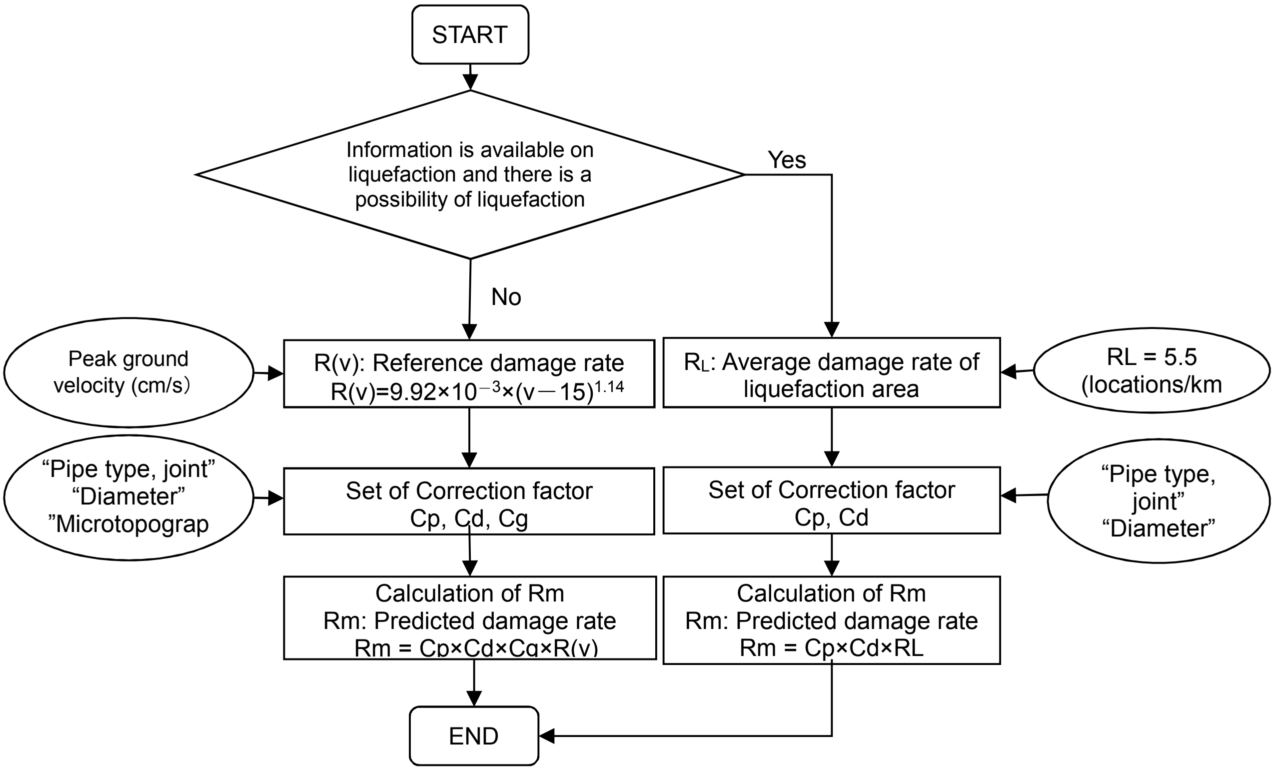


Figure 1. Process of estimating the number of pipe failures in earthquakes

TABLE I. EQUATION AND ITS CORRECTION FACTORS

If there is no information available on liquefaction or there is no possibility that liquefaction occurs	If there is an information available on liquefaction and there is a possibility that liquefaction may occur
$\boldsymbol{R_m = C_p \times C_d \times C_g \times R(v)}$ R_m: Estimated damage rate [locations/km] C_p: Correction factor for pipe and joint type C_d: Correction factor for pipe diameter C_g: Correction factor for microtopography R(v): Reference damage rate[locations/km] $R(v)=9.92\times10^{-3}\times(v-15)^{1.14}$ v: Peak ground velocity (cm/s) $(15 \leqq v < 120)$	$\boldsymbol{R_m = C_p \times C_d \times R_L}$ R_m: Predicted damage rate [locations/km] C_p: Correction factor for pipe and joint type C_d: Correction factor for pipe diameter R_L: Average damage rate of liquefaction area [locations/km], R_L = 5.5

<table>
<tr><th colspan="6">Correction factor</th></tr>
<tr><th>Pipe and joint type</th><th>Cp</th><th>Diameter (mm)</th><th>Cd</th><th>Microtopography where pipes are installed</th><th>Cg</th></tr>
<tr><td>DIP (A)</td><td>1.0</td><td rowspan="3">φ50−80</td><td rowspan="3">2.0</td><td rowspan="3">Mountain, mountain foot, hill, volcanic area, volcanic mountain foot, volcanic hill</td><td rowspan="3">0.4</td></tr>
<tr><td>DIP (K)</td><td>0.5</td></tr>
<tr><td>DIP (T)</td><td>0.8</td></tr>
<tr><td>DIP (disengagement prevention)</td><td>0</td><td>φ100−150</td><td>1.0</td><td>Gravel upland, loam upland</td><td>0.8</td></tr>
<tr><td>CIP</td><td>2.5</td><td rowspan="2">φ200−250</td><td rowspan="2">0.4</td><td rowspan="3">Valley lowland, alluvial fan, humid lowland plain, delta, coastal lowland</td><td rowspan="3">1.0</td></tr>
<tr><td>VP (TS)</td><td>2.5</td></tr>
<tr><td>VP (RR)</td><td>0.8</td><td rowspan="2">φ300−450</td><td rowspan="2">0.2</td></tr>
<tr><td>SP (welding)</td><td>0.5/0</td><td rowspan="2">Natural levee, former river channel, sandbar, gravel bar, dune</td><td rowspan="2">2.5</td></tr>
<tr><td>SP (non-welding)</td><td>2.5</td><td rowspan="2">φ500−900</td><td rowspan="2">0.1</td></tr>
<tr><td>ACP</td><td>7.5</td><td rowspan="2">Reclaimed land, drained land, lakes and marshes</td><td rowspan="2">5.0</td></tr>
<tr><td>PE (electrofusion)</td><td>N/A</td><td></td><td></td></tr>
</table>

REVIEW OF THE EQUATION UPON 2016 KUMAMOTO EARTHQUAKE

Review Process

Figure 2 shows the review process of the equation. The validity of the equation was tested using the data on pipe damage in the 2016 Kumamoto Earthquake. The assessment covered and considered the transmission, conveyance and distribution mains with over 50 mm diameter that sustained damage (but excludes those used for water pipe bridges as well as other above-ground, exposed mains).

Develop a database on pipe damage of the 2016 Kumamoto Earthquake

↓

Analyze and compare the data with pipe damage of other major earthquakes

↓

Compare the estimation result and the actual damage

↓

Evaluate the validity of the equation

Figure 2. Review process of the equation.

Development of a Database on Pipe Damage

First, regarding the 2016 Kumamoto Earthquake, we collected related data on pipe damage, ground motions, ground conditions, and the distribution of the liquefaction that occurred. Next, a GIS-based database was produced out of these data. As for the pipe damage, Kumamoto City provided relevant data from their mapping system. Based on the provided data, we plotted the location of the pipe damage on GIS. Further, to produce a database, we entered the data on pipe material, joint, diameter, year of installation, the level of ground motions in each 250-meter grid cell of the service area as well as their ground conditions. Table II shows a list of the items in the database.

TABLE II. ITEMS OF THE DATABASE

Item	Details	Shape on GIS	Source
Pipe attributes	Pipe material/joint, diameter, year of installation	Line	Mapping data provided by Kumamoto City Water and Sewerage Waterworks Bureau
Location of pipe damage	Plot on GIS	Point	Mapping data provided by Kumamoto City Water and Sewerage Waterworks Bureau
Damage attributes	Damage type and level, pipe material/joint, diameter, year of installation	Point	Mapping data provided by Kumamoto City Water and Sewerage Waterworks Bureau
Ground motion	PGV per grid cell on GIS	Grid cell (250 m)	Mesh data of PGV distribution in the main shock of the 2016 Kumamoto Earthquake at 1:25 pm on April 16th, 2016. Available from the website of the National Research Institute for Earth Science and Disaster Resilience

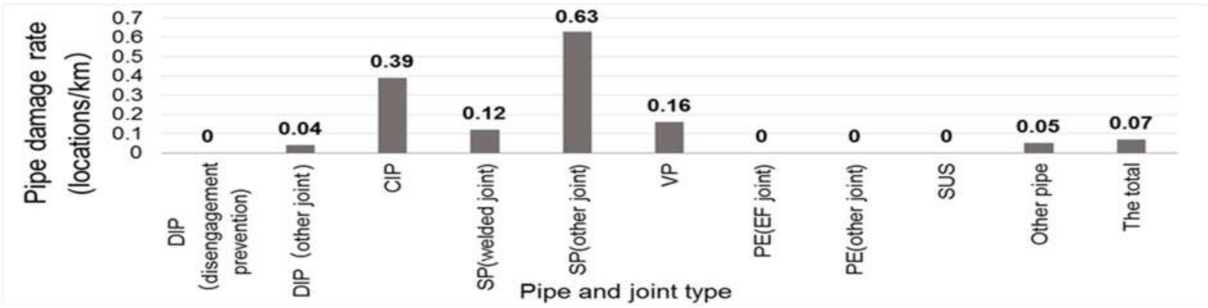
Ground condition	Microtopography per grid cell on GIS	Grid cell (250 m)	Database of topography and ground classifications [5]. Available from the website of the National Research Institute for Earth Science and Disaster Resilience
Distribution of liquefaction	Locations of liquefaction shown per grid cell as well as plotted on GIS	Grid cell (250 m) & Point	Mesh and point data of liquefaction distribution in the 2016 Kumamoto Earthquake [6]. Available from the website of the National Research Institute for Earth Science and Disaster Resilience available

CHARACTERISTICS OF PIPE DAMAGE IN 2016 KUMAMOTO EARTHQUAKE AS COMPARED WITH PIPE DAMAGE IN OHER MAJOR EARTHQUAKES

Pipe Damage in Kumamoto City

The pipelines in Kumamoto City stretches 3,238 km. The total number of pipe damages was 233, which translates into 0.07 per kilometer. As Figure 3 shows, the number of damage by pipe material was 0.63/km for SV (other joint), 0.39/km for CIP, 0.16/km for VP, 0.12/km for SP (welded joint), and 0.04/km for DIP (other joint). Overall, the damage rate was lower for larger diameter pipes (Figure 4).

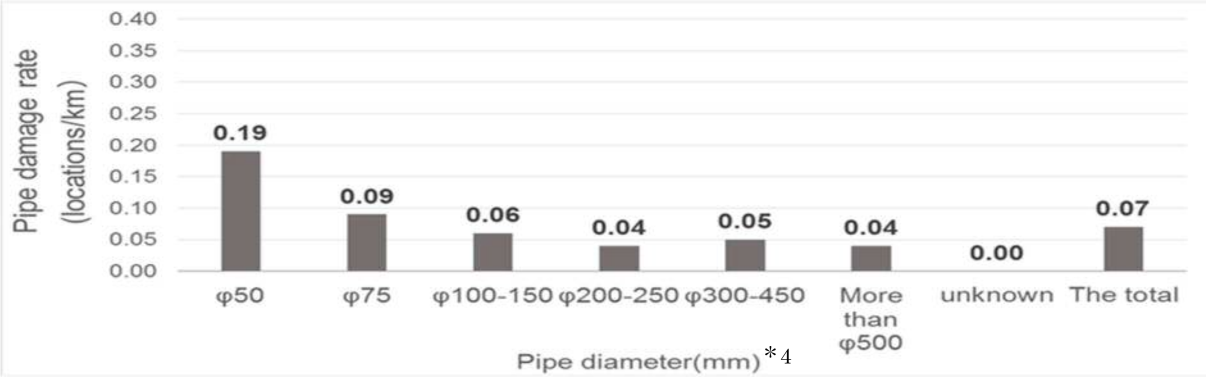
Figure 5 shows the pipe damage rate by microtopography. As it shows, the former river channel shows the highest damage rate. We consider this is partly because the mains installation lengths along the former river channel is only 5 km, which is shorter compared to other locations. In average, weaker gronds showed larger damage rates.



Pipe material*1	DIP (disengagement prevention)	DIP (other joint)	CIP	SP (welded joint) *2	SP (other joint)*3	VP	PE (EF joint)	PE (other joint)	SUS	Other pipe
Pipe damage (no. of locations)	0	72	36	8	59	55	0	0	0	3
Pipe Installation length (km)	583	1882	92	68	93	346	97	8	5	63

*1: Covers only mains with over 50 mm diameter
*2: SP (welded joint) does not include SP with expansion/flange joint. The latter is included in SP (others).
*3: SP (others) includes SP with threaded joint and others but excludes SP with welded joint.

Figure 3. Pipe damage rate by pipe material in Kumamoto City



*4: Covers only mains with over 50 mm diameter

Figure 4. Pipe damage rate by pipe diameter in Kumamoto City

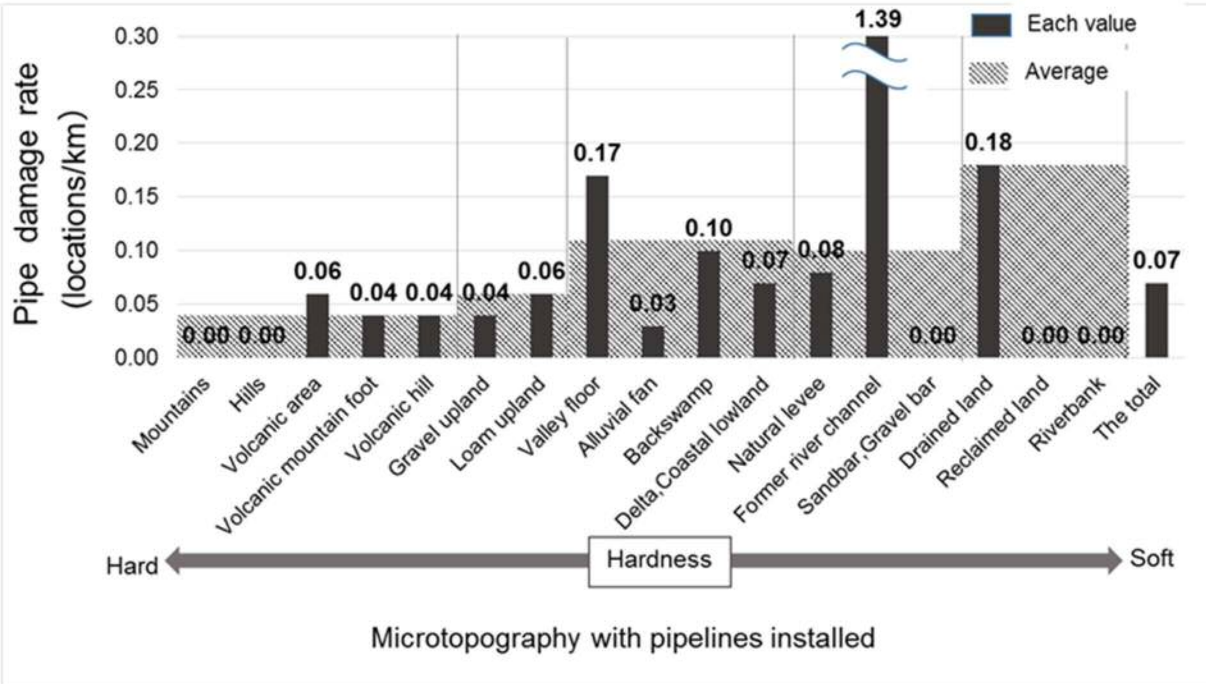


Figure 5. Pipe damage rate by microtopography in Kumamoto City

PGV and Pipe Damage Rate

Figure 6 shows the PGV distribution and pipe damage in the main shock of the 2016 Kumamoto Earthquake. And Figure 7 shows the pipe damage rate by PGV. As is shown in Figure 7, the pipe damage rates are larger where PGVs are greater. And this tendency corresponds to the current reference damage rate curve of the equation.

Also, some of the damaged areas show a PGV of over 120 cm/s. This value is beyond the maximum PGV covered by the equation, which considers the range of $15 \leqq v < 120$ (cm/s). However, since the mains installation lengths in Kumamoto City in the areas that recorded a PGV of over 120 cm/s was as short as 20 km in total, we were not able to collect sufficient amount of data as to reconsider the current PGV range of the equation.

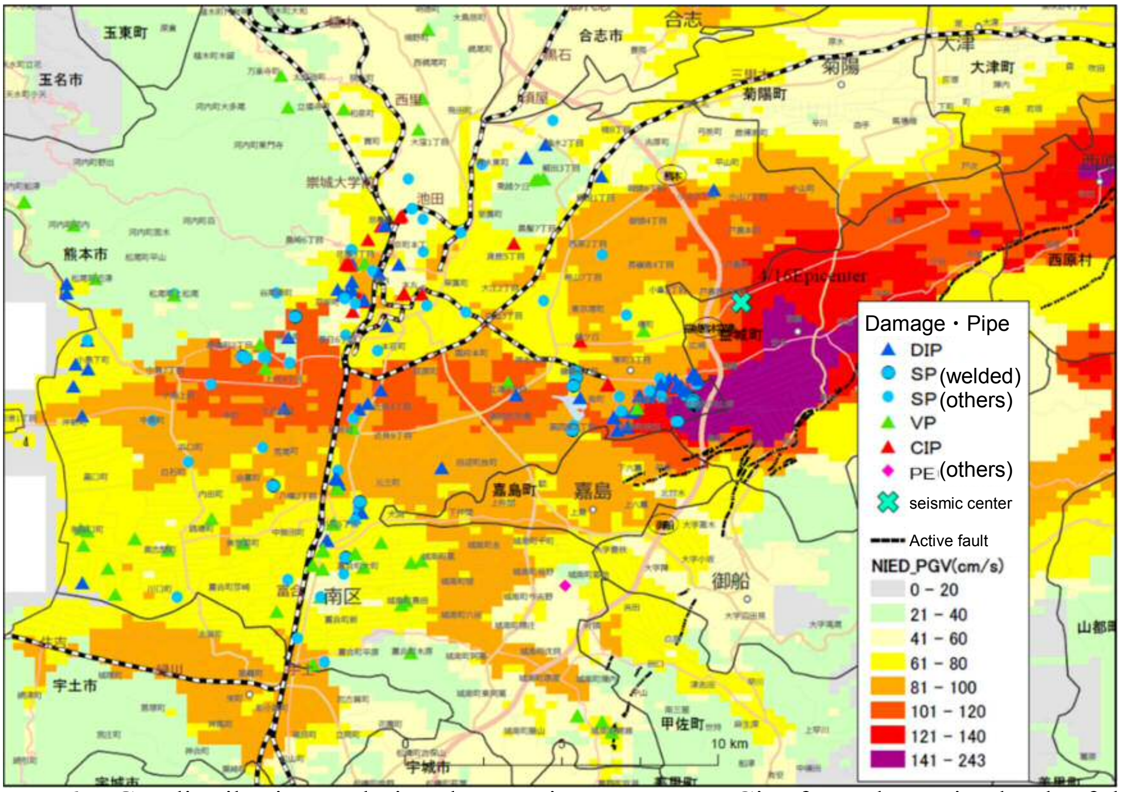
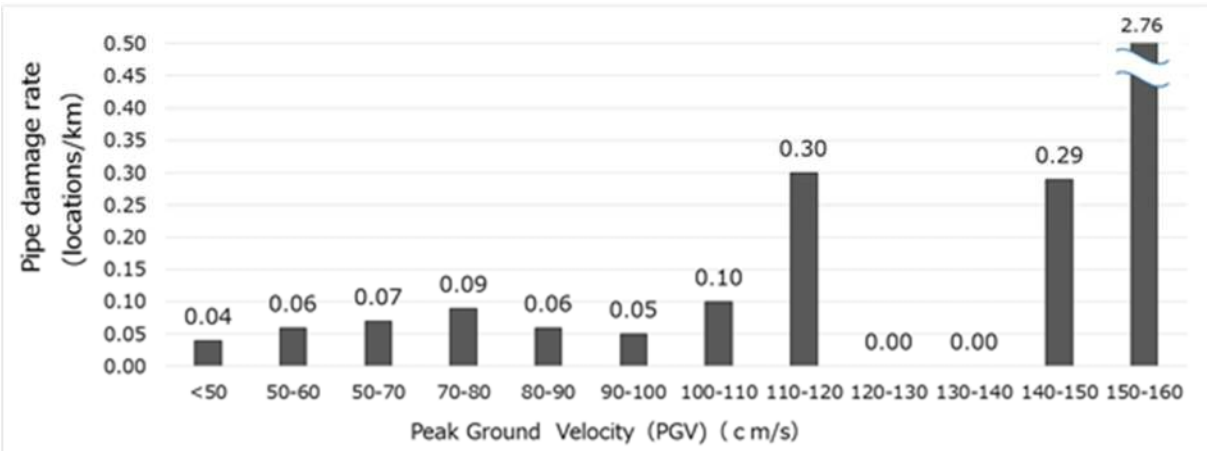


Figure 6. PGV distribution and pipe damage in Kumamoto City from the main shock of the 2016 Kumamoto Earthquake

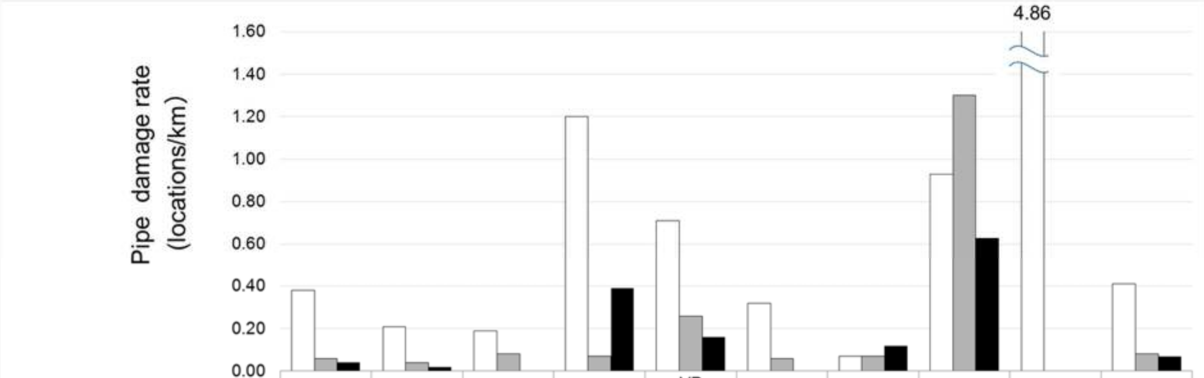


PGV (cm/s)	<50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120-130	130-140	140-150	150-160
Pipe damage (no. of locations)	32	15	33	46	33	13	37	15	0	0	1	8
Pipe Installation length (km)	750	254	452	519	568	268	358	50	6.9	5.5	3.4	2.9

Figure 7. Pipe damage rate by PGV

Comparison between Kumamoto Earthquake and Other Major Earthquakes

Figure 8 shows the pipe damage rates in the 2016 Kumamoto Earthquake and some of the other major earthquakes that occurred in the past in Japan. The damage rate in the Kumamoto Earthquake was about 1/10 compared to the 1995 Hanshin Awaji Earthquake, 2004 Niigata Prefecture Chuetsu Earthquake, and 2007 Niigata Prefecture Chuetsu-oki Earthquake [7] while it was about the same as Sendai City in the 2011 Great East Japan Earthquake [3].



Pipe and joint type	DIP (A)	DIP(K)	DIP(T)	CIP	VP (TS)	VP(RR)	SP(welded)*5	SP(other)	ACP	The total
□ Hyogo pref and Nigata pref *6	0.38	0.21	0.19	1.20	0.71	0.32	0.07	0.93	4.86	0.41
▩ Sendai city	0.06	0.04	0.08	0.07	0.26	0.06	0.07	1.30		0.08
■ Kumamoto city	0.04	0.02		0.39	0.16		0.12	0.63		0.07

*5: SP (welded joint) does not include SP with expansion/flange joint.
*6: For Hygo Pref., we analyzed the damage rate in Kobe City, Nishinomiya City and Asiya City in the 1995 Hanshin Awaji Earthquake; for Niigata Pref., we analyzed the damage rate in former Nagaoka City and Ojiya City in the 2004 Niigata Prefecture Chuetsu Earthquake and in Kashizawaki City and Kariwa Village in the 2007 Niigata Prefecture Chuetu-oki Earthquake.

Figure 8. Comparison of pipe damage rate between Kumamoto Earthquake and other major earthquakes

ASSESSMENT OF ESTIMATION ACCURACY OF THE EQUATION

Evaluation of Validity of the Correction Factors

To see the appropriateness of the correction factor Cp for pipe material/joint, we compared the damage rates of the reference pipe material/joint (DIP (A)) and other pipes that have the reference diameter (φ100-150) and are installed in the reference microtopography (valley lowland, alluvial fan, humid lowland plain, delta, or coastal lowland). Also, to see the appropriateness of the correction factor Cd for pipe diameter, we compared the damage rate of the reference diameter and other diameters in relation to the reference pipe material/joint. Further, to see the appropriateness of the correction factor Cg for microtopography, we compared the damage rate of the reference microtopography and other microtopographies in relation to the reference pipe material/joint as well as the reference diameter.

Table III shows the evaluation result of Cp in Kumamoto City. It shows that the actual damage rate of CIP is 12.5 times the rate of DIP (A) when the CIP's correction factors is 2.5, which shows a large gap between the two. On the other hand, the actual damage rate of DIP (K) is 0.8 times the rate of DIP (A) when the DIP (K)'s correction factor is 0.5. And the actual damage rate of VP is 2.9 times the rate of DIP (A) when the VP's correction factor is 2.5. Therefore, it can be said that for DIP (K) and VIP, their actual damage rates in relation to DIP (A) are close to the correction factors. As for why there is a large gap between the CIP's correction factor and its damage ratio to DIP (A), we consider CIP's damage rate was more susceptible to the number of pipe damages than other pipes since its installation length is shorter.

Table IV and Table V show the evaluation result of Cd and Cg, respectively. The result shows that overall, the actual damage rates are close to the correction factors.

TABLE III. DAMAGE RATE BY PIPE MATERIAL/JOINT FOR THE REFERENCE DIAMETER AND REFERENCE MICROTOPOGRAPHY (KUMAMOTO CITY)

	CIP	DIP(K)	DIP(A)	SP (welded)	SP (other)	VP
Pipeline length(m)	26,124	211,508	515,753	3,981	1,664	63,678
Pipe damage (no. of locations)	14	7	22	1	10	8
Pipe damage rate (locations/km)	0.536	0.033	0.043	—	—	0.126
Ratio to the damage rate of DIP (A)	12.50	0.80	1.00	—	—	2.90
Correction factor(Cp)	2.5	0.5	1.0	0.8/0	2.5	2.5

TABLE IV. DAMAGE RATE BY PIPE DIAMETER FOR THE REFERENCE MATERIAL/JOINT (DIP (A)) (KUMAMOTO CITY)

	<φ50	φ75	φ100-150	φ200-250	φ300-450	More than φ500
Pipeline length(km)	0	313	765	160	72	9
Pipe damage (no. of locations)	0	23	30	6	0	0
Pipe damage rate (locations/km)	0	0.073	0.039	0.038	—	—
Ratio to the damage rate of DIP (A)	—	1.9	1.0	1.0	—	—
Correction factor(Cd)	2.0		1.0	0.4	0.2	0.1

TABLE V. DAMAGE RATE OF THE REFERENCE MATERIAL/JOINT (DIP (A)) WITH THE REFERENCE DIAMETER (Φ100-150) BY CORRECTION FACTOR CG FOR MICROTOPOGRAPHY (KUMAMOTO CITY)

Microtopography	Mountain, Mountain foot, Hill, Volcanic area, Volcanic mountain foot, Volcanic hill	Gravel upland, Loam upland	Valley floor, Alluvial fan, Backswamp, Delta, coastal lowland	Natural levee, Former river channel, Sandbar,Gravel bar, Dune	Reclaimed land, Drained land, Lakes and marshes
Pipeline length(km)	157	310	205	69	24
Pipe damage (no. of locations)	3	14	8	2	3
Pipe damage rate(locations/km)	0.019	0.045	0.039	0.029	0.125
Ratio to the damage rate of DIP (A)	0.5	1.2	1.0	0.7	3.2
Correction factor(Cd)	0.4	0.8	1.0	2.5	5.0

Evaluation of Validity of the Equation

To evaluate the accuracy of the equation, we compared the number of estimated pipe damage with the number of actual pipe damage in Kumamoto City for each grid cell of the service area. The damage was compared for the reference pipe material/joint (DIP (A)) with the reference diameter (φ100-150).

The equation estimated a total of 251 grid cells to have one or more than one pipe damage (Figure 9). On the other hand, the number of pipe damages that actually occurred was 30 in 19 grid cells out of these 251 ones (Figure 10). The estimate was on the safe side, which corresponds to the design principle of the equation*.

*as for the comparison of all kinds of pipes with over 50 mm diameter, the total number of estimated pipe damages in Kumamoto City was about 4.1 times larger than the number of actual pipe damages.

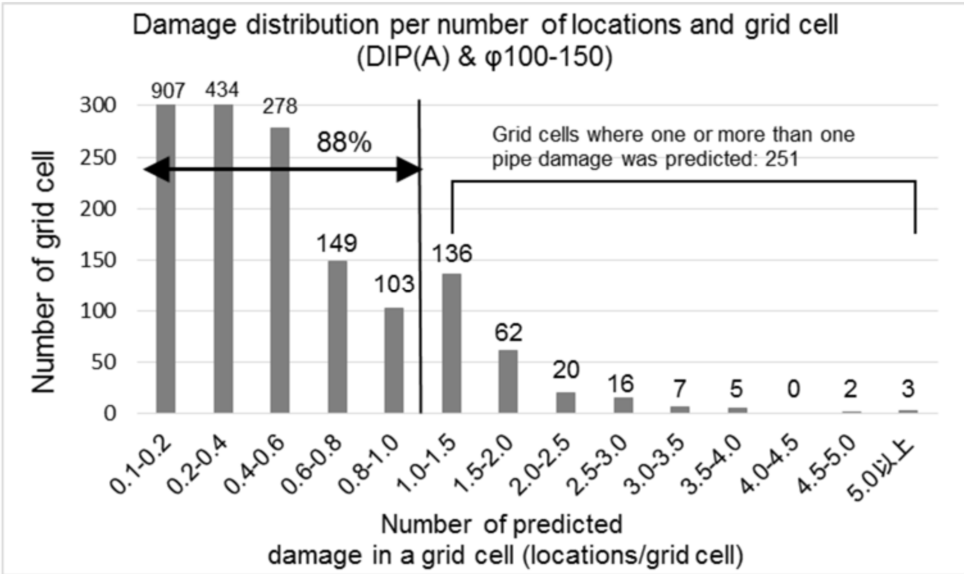


Figure 9. Number of pipe damage estimated by the equation for the reference pipe material/joint with the reference diameter

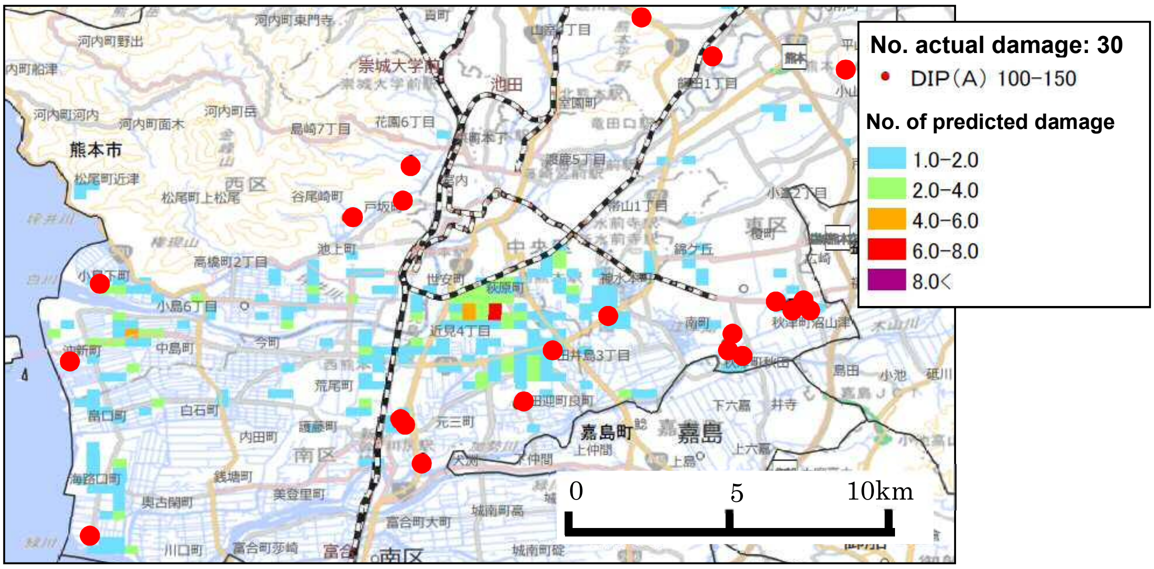


Figure 10. Locations of actual pipe damage and the distribution of estimated pipe damage for the reference pipe material/joint with reference diameter

In addition, for DIP (A) with 100-150 mm diameter, we also compared its damage rate in the 2016 Kumamoto Earthquake with the damage rate in other major earthquakes. Figure 11 shows the result by PGV levels along with the reference damage rate curve obtained from this comparison. It shows that the distribution of pipe damage is similar between the Kumamoto Earthquake and the other earthquakes.

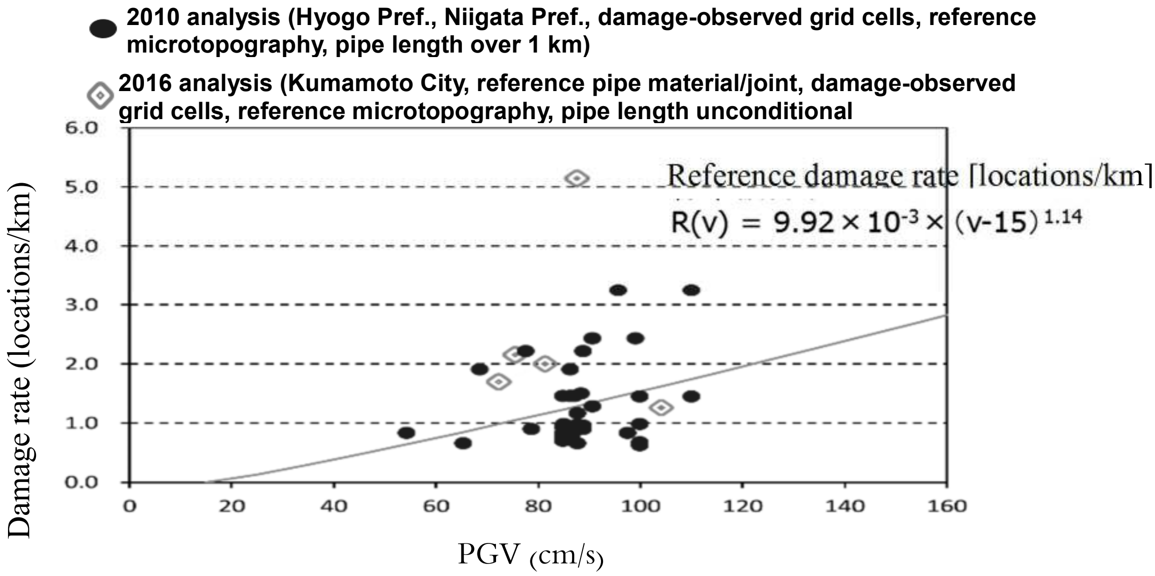


Figure 11. Damage rate of DIP (A) with 100-150 mm diameter in the 2016 Kumamoto Earthquake and in other major earthquakes along with the reference damage rate curve

CONCLUSION

The pipe damage analysis in Kumamoto City shows that for some pipe with short installation lengths, there a gap between the damage rates when compared to past earthquakes as well as between the correction factor and its damage ratio to the reference pipe material/joint. Overall, however, the correction factors of the equation and its reference damage rate had similar tendencies to the characteristics of the actual pipe damage. Also, the estimate given by the equation was on the safe side, which corresponds to its design principle.

From these results, we decided that the equation is still valid and requires no immediate modifications to the correction factors and the reference damage rate. One concern remains, however, that the equation might have estimated a little too far on the safe side, providing the number of estimated pipe damage a few times larger than the actual number of damage. Therefore, this aspect would need more considerations to further increase the accuracy of the equation.

We expect this equation will be utilized by more utilities to help an effective pipe renewal and replacement for an improved preparedness against future seismic risks.

ACKNOWLEDGMENTS

We would like to extend our gratitude to the Kumamoto City Water and Sewerage Waterworks Bureau for their data provision as well as to the water utilities and private companies that participated in this review process.

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Seismic Evaluation and Retrofit of Existing Water Pipe Bridges in Taipei

Wei-Hsiang Lee, Kuan-Hua Lien , Po-Ming Cheng and Chii-Jang Yeh

ABSTRACT

Taipei is the capital city of Taiwan and its population is more than 2.7 millions, so water supply system is especially important. Moreover, the four existing water pipe bridges managed by Taipei Water Department play a pivotal role in the water supply system. The four existing water pipe bridges were designed according to the old version of the seismic code. If the existing water pipe bridges are damaged during the earthquake and unable to supply the water. It will bring people's livelihood problem; enlarge secondary disasters and delay post-earthquake reconstruction. Therefore, this paper presents the seismic assessment of Yuanshan, Yongfu, Hsintien arch water pipe bridges and Jiantan cable-stayed water pipe bridge. The seismic performance criteria follow Draft of the Taiwan Bridge Performance-Based Seismic Design and Water Facilities Seismic Design Guide and Commentary to examine the seismic capacity of existing water pipe bridges and check whether the corresponding retrofits are necessary or not. The static nonlinear pushover analysis is carried out using SAP2000 to capture the overall seismic capacity of existing water pipe bridges, respectively. The nonlinear time history analysis is also carried out using SAP2000 to obtain the member force and displacement of superstructures for the existing water pipe bridges. According to the analysis results, Yuanshan, Hsintien and Jiantan water pipe bridges have enough seismic capacity to satisfy the seismic performance criteria but the seismic capacity of Yongfu water pipe bridge in longitudinal direction fails to meet the seismic performance criteria. The piers of Yongfu water pipe bridge had been retrofitted by steel jacket for insufficiency of ductility. The relative displacements between superstructure and the abutment are larger than the flexible capacity of pipe expansion joint for the Yongfu and Jiantan water pipe bridges, respectively. There are two retrofit options are considered. One is the replacement pipe expansion joint scheme, the other is the additional Outer flexible expansion joint scheme. The bearings of existing water pipe bridges fail to meet the seismic performance criteria, therefore there are two retrofit options are considered. One is the replacement bearings scheme, the other is the additional RC or steel anti-shock devices scheme.

Keyword: Existing Water Pipe Bridge, Seismic Evaluation, Seismic Retrofit, Static nonlinear pushover analysis, nonlinear time history analysis

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INTRODUCTION

Chichi Earthquake on September 21, 1999, caused severe property losses and casualties to central Taiwan. Since earthquakes are unpredictable, they often cause more severe disasters if they are not treated carefully. Taipei is the capital city of Taiwan and its population is more than 2.7 millions, so water supply system is especially important. Moreover, the four existing water pipe bridges managed by Taipei Water Department play a pivotal role in the water supply system. The four existing water pipe bridges were designed according to the old version of the seismic code. If the existing water pipe bridges are damaged during the earthquake and unable to supply the water. It will bring people's livelihood problem; enlarge secondary disasters and delay post-earthquake reconstruction. Therefore, Taipei Water department took preventive measures to review and evaluate the four existing water pipe bridges. In this paper, Yuanshan, Yongfu, Hsintien arch water pipe bridges and Jiantan cable-stayed water pipe bridge are used as an example to illustrate the seismic assessment and retrofit of existing water pipe bridge.

STRUCTURE DESCRIPTION OF EXISTING WATER PIPE BRIDGES

The four existing water pipe bridges are shown in Figure 1. Yuanshan water pipe bridge is single-span simply supported arch steel bridge having the total length of 100.6 m. It is supported and transversely connected on abutments. The abutments are supported on pile foundations, respectively. The pipe diameter is 2000mm. Yongfu water pipe bridge is multi-span simply supported arch steel bridge having the total length of 360 m with 3 equal spans of 80 m length. It is support on four-column bents, which are transversely connected by the bent cap. The bridge piers and abutments are supported on pile foundations. The pipe diameter is 2400mm. Hsintien water pipe bridge is multi-span simply supported arch steel bridge having the total length of 290 m with 3 equal spans of 80 m length. It is support on single pier type bents, which are transversely connected by the bent cap. The bridge piers and abutments are supported on pile foundations. The pipe diameter is 2400mm. Jiantan water pipe bridge is multi-span simply supported cable-stayed steel bridge having the total length of 140 m with main span of 72 m length. It is support on single pier type bents, which are transversely connected by the bent cap. The bridge piers and abutments are supported on pile foundations. The pipe diameter is 2000mm.

Yuanshan arch water pipe bridge

Yongfu arch water pipe bridge

Hsintien arch water pipe bridge

Jiantan cable-stayed water pipe bridge

Figure 1. Four existing water pipe bridges

SEISMIC RETROFT PERFORMANCE CRITERIA OF WATER PIPE BRIDGE

As the seismic retrofit standard of the existing water pipe bridge should be another 50-year service life, and based on Seismic Retrofitting Manual for Highway Bridges[1], Draft of the Taiwan Bridge Performance-Based Seismic Design [2] and Water Facilities Seismic Design Guide and Commentary [3], the seismic performance criteria for water pipe bridge worked out are shown in TABLE I.

TABLE I. SEISMIC RETROFT PERFORMANCE CRITERIA OF WATER PIPE BRIDGE

Earthquake level	Horizontal acceleration coefficient		Seismic restraint concept	Service performance	Damage grade
Moderate earthquake	Divided by administrative region		Structure keeps elastic	Normal water supply after earthquake	Slight
	1/3.25 of earthquake of 475-year return period				
Design earthquake (I=1.2) Return period:975years 50-year exceeding probability:5%	Divided by administrative region		Component has plastic hinge, exerting admissible toughness capacity	Limited water supply after earthquake	Repairable
	S_S^D	0.72			
	S_1^D	1.60、1.30、1.05			

The seismic performance requirements for water pipe bridges in terms of performance PL3 and PL1(2), respectively, according to bridge safety, bridge serviceability and bridge reparability were described in TABLE II. The performance object is shown TABLE III. The allowable displacements as a fraction of the displacement capacity are provided in TABLE IV, so that to identify and distinguish the acceptance point 3 and 1 as shown in Figure 2. Therefore, the structural capacity is predetermined by using static nonlinear pushover analysis, and the goal is to verify the water pipe bridge behavior at multiple performance points.

TABLE II. SEISMIC PERFORMANCE OF WATER PIPE BRIDGE

Performance level	Safety		Serviceability	Reparability	
	structure	foundation		Short period	Long period
PL3	Structure remains elastic and no unseating	elastic	As same as prior to the earthquake	none	
PL1(2)	limited damages and no unseating	elastic	Normal water supply	Partially repair or replace damaged member	

TABLE III. SEISMIC PERFORMANCE MATRIX

Seismic hazard	Performance level
Moderate earthquake	PL3
Design earthquake (I=1.2)	PL1(2)

TABLE IV. ALLOWABLE DISPLACEMENT OF THE DISPLACEMENT CAPACITY

Performance state	Taipei Basin
PL3	0
PL1(2)	1/2(1/4)

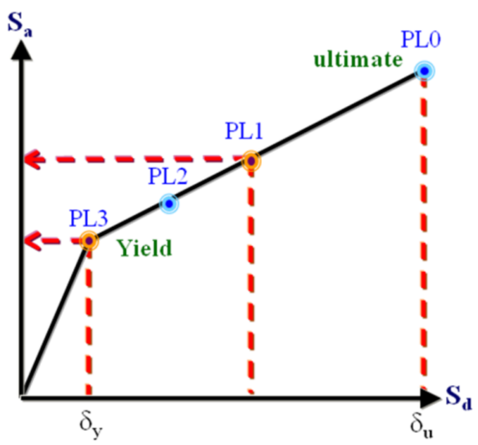


Figure 2. Seismic object and verification at Taipei Basin

EVALUATION OF THE SEISMIC CAPACITY

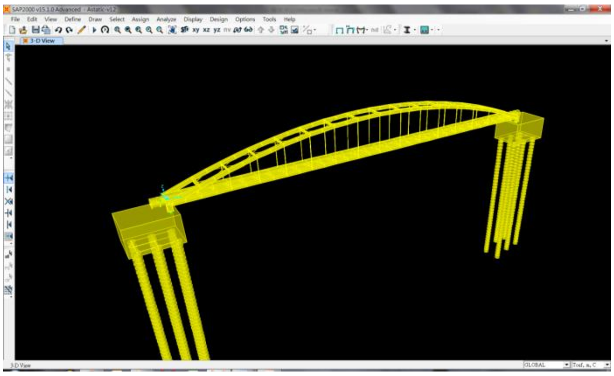
There are two detailed evaluation methods for bridge seismic capacity: (1) static nonlinear pushover analysis, (2) nonlinear time history analysis.

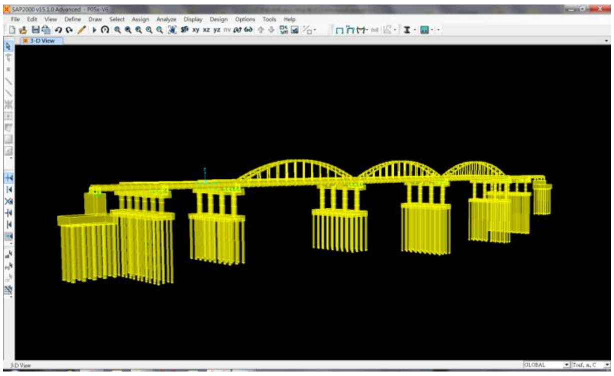
The pushover analysis analyzes the force-deformation behavior when the whole bridge collapses under increasing lateral force, so it lays emphasis on capacity of pier and foundation for the existing water pipe bridges. The time history analysis lays emphasis on capacity of superstructure. The method can master the key points in component reinforcement clearly, the member force and displacement of superstructures for the existing water pipe bridges can be evaluated b using this method.

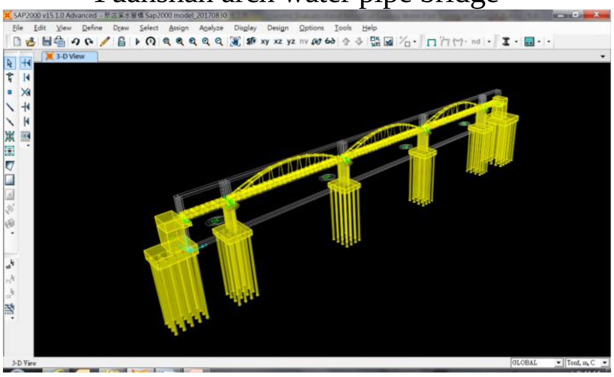
Numerical Modeling

The four three dimensional finite element model of existing water pipe bridges were created using Structural Analysis and Program software SAP2000 as shown in Figure 3, respectively. The structural model includes the complete foundation which considers the nonlinear force-displacement characteristics of foundations as well as the soil stiffness. The pier cap and the piers were modeled as beam-column elements and the hinge properties were assigned to each end of the column.

The eigenvalue analysis was carried out as the first step to obtain the mode shapes and frequencies of the bridges as shown in Figure4, respectively. In the next step, static nonlinear pushover analysis and nonlinear time history analysis were performed to capture the seismic capacity of the existing water pipe bridges.


Yuanshan arch water pipe bridge


Yongfu arch water pipe bridge


Hsintien arch water pipe bridge

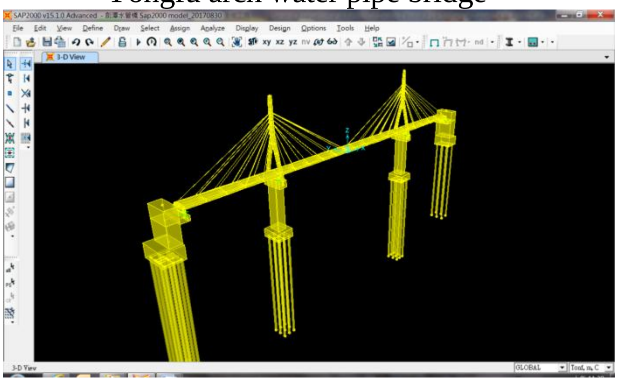
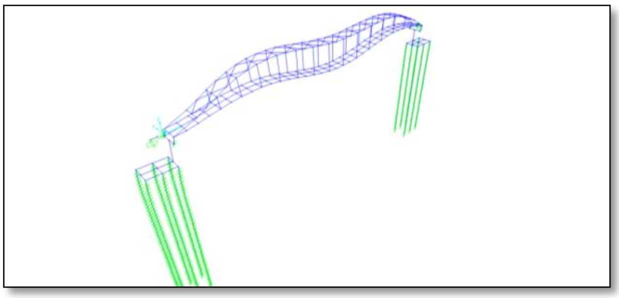
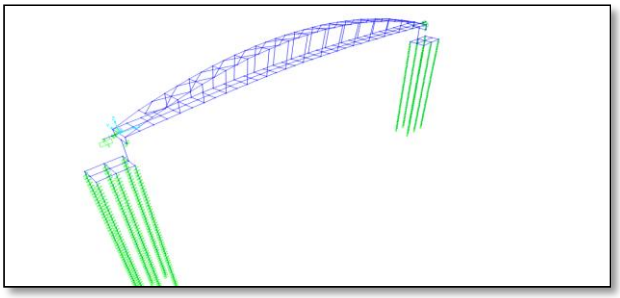

Jiantan cable-stayed water pipe bridge

Figure 3. 3D analysis Model of existing water pipe bridges in SAP2000

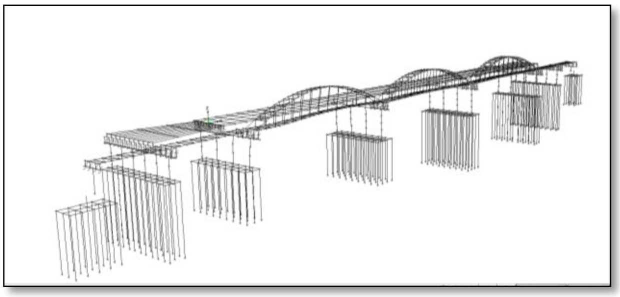


First mode in longtitudinal direction,
Period=0.27 sec

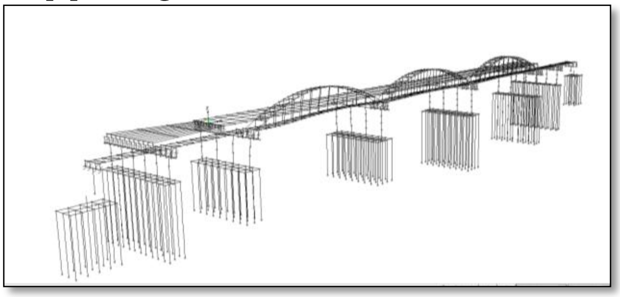


Mode 1 in transverse directon,
Period=2.07 sec

Yuanshan arch water pipe bridge

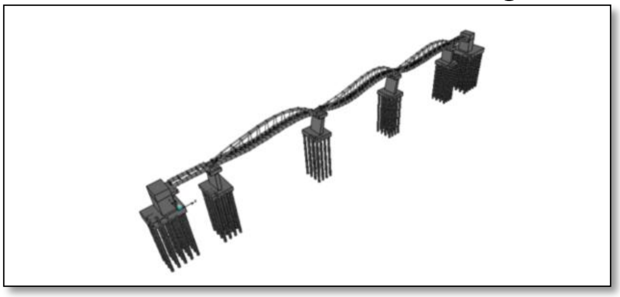


First mode in longtitudinal direction,
Period=0.76 sec

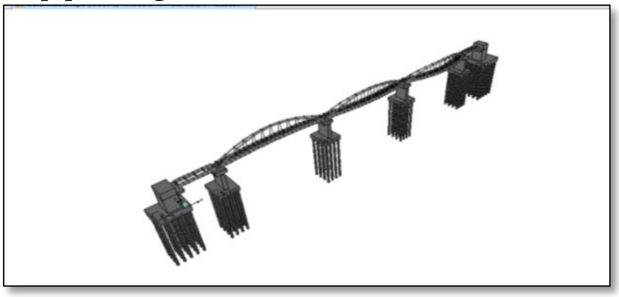


Mode 1 in transverse directon,
Period=0.74 sec

Yongfu arch water pipe bridge

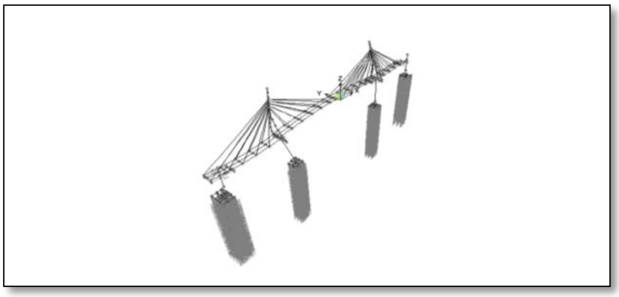


First mode in longtitudinal direction,
Period=0.804 sec

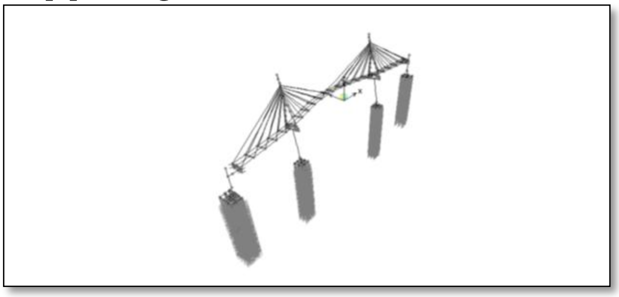


Mode 1 in transverse directon,
Period=0.843 sec

Hsintien arch water pipe bridge



First mode in longtitudinal direction,
Period=1.365 sec



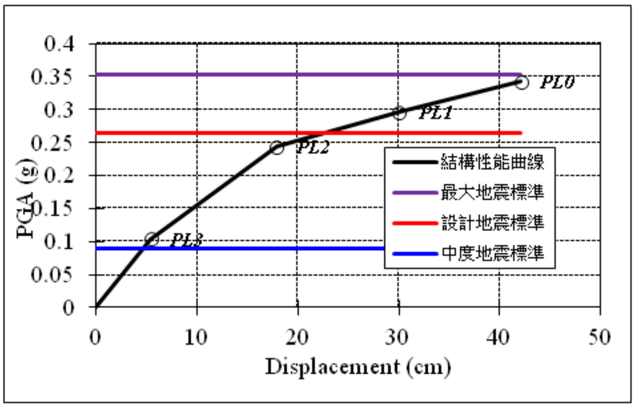
Mode 1 in transverse directon,
Period=1.115 sec

Jiantan cable-stayed water pipe bridge

Figure 4. Mode shapes and frequencies of existing water pipe bridges in the longitudinal direction

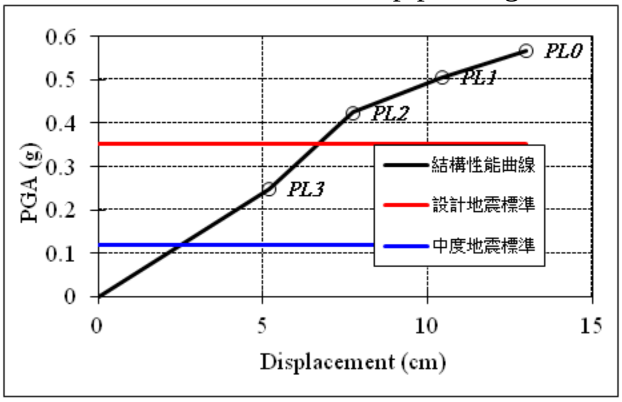
Pushover Analysis Results

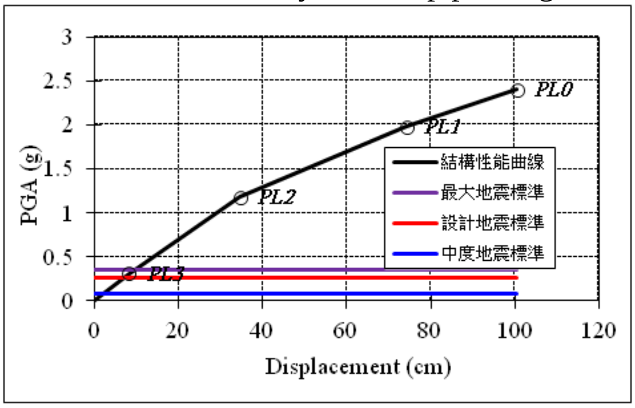
The static nonlinear pushover analysis was conducted for existing water pipe bridges, respectively. According to the pushover curve, the ground acceleration corresponding to existing water pipe bridges in different seismic points (see Figure 2) are obtained. The design ground acceleration corresponding to the existing water pipe bridges within the expected service life are obtained in concept of damage evaluation. Based on the seismic capacity of existing water pipe bridges are evaluated and listed in TABLE V. The performance curve of existing water pipe bridges in the longitudinal direction are shown in Figure 5, respectively. According to the analysis results (TABLE V), Jiantan, Yongfu(retrofitted by steel jacket) Hsintien water pipe bridges have enough seismic capacity to satisfy the seismic performance criteria, respectively.



Yuanshan arch water pipe bridge

Jiantan cable-stayed water pipe bridge





Yongfu arch water pipe bridge

Hsintien arch water pipe bridge

Figure 5. Mode shapes and frequencies of existing water pipe bridges in the longitudinal direction

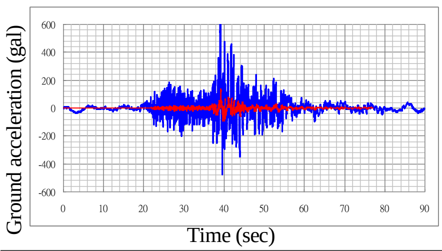
TABLE V. SEISMIC CAPACTITY OF EXISTING WATER PIPE BRIDGES (LONGITUDINAL DIRECTION)

Bridge	Performance objective		Performance capacity	
	Earthquake level	Ground acceleration (g)	Performance level	Ground acceleration (g)
Yuanshan (single-span)	Moderate earthquake	-	-	-
	Design earthquake	-	-	-
Jiantan	Moderate earthquake	0.07	PL3	0.104
	Design earthquake	0.24	PL1	0.296
Yongfu(retrofitted by steel jacket)	Moderate earthquake	0.07	PL3	0.25
	Design earthquake	0.24	PL1	0.50
Hsintien	Moderate earthquake	0.07	PL3	0.31
	Design earthquake	0.24	PL2	1.18

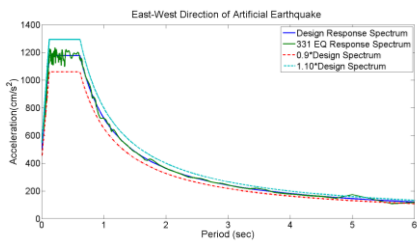
Time History Analysis Results

The four earthquakes are selected based on two parameters; the closest distance to site and the moment magnitude. Based on the four earthquakes, most of the artificial time histories are generated from the design response spectra, respectively, as shown in Figure 6 (left). The response spectra of the original and artificial acceleration in comparison with the design spectrum are shown in Figure 6 (right).

Nonlinear time history analyses with artificial time histories were performed using SAP2000 to capture the overall dynamic response of the existing water pipe bridges, respectively. The relative displacements between superstructure and the abutment are smaller than the flexible capacity of pipe expansion joint for the four water pipe bridges, respectively¸ as shown in TABLE VI. The bearings of existing water pipe bridges fail to meet the seismic performance criteria.



(a) Original vs. Artificial ground motion



(b) Artificial response spectrum

Figure 6. Artificial ground acceleration time history

TABLE VI. DISPLACEMENT CAPACTITY OF EXISTING WATER PIPE BRIDGES

Bridge	Earthquake station/record	Axial displacement (Demand/Capacity)	Bridge	Earthquake station/record	Axial displacement (Demand/Capacity)
Yuanshan	TAP007/0206	1.45/± 20 cm	Hsintien	TAP033/0331	3.5 /± 8.8 cm
	TAP008/0331	2.03/± 20 cm		TAP053/0401	5.8 /± 8.8 cm
	TAP013/0921	2.11/± 20 cm		TAP034/0921	4.6 /± 8.8 cm
Yongfu	TAP029/0206	22.0/± 24.3 cm	Jiantan	TAP007/0206	11.8/± 24.8 cm
	TAP028/0331	23.8/± 24.3 cm		TAP008/0331	23.4/± 24.8 cm
	TAP028/0921	21.2/± 24.3 cm		TAP006/0921	15.8/± 24.8 cm

SEISMIC RETROFIT STRTEGY

According to the seismic evaluation results of the existing water pipe bridges, the seismic capacity of Yongfu water pipe bridge in longitudinal direction fails to meet the seismic performance criteria. The piers of Yongfu water pipe bridge had been retrofitted by steel jacket for insufficiency of ductility, as shown in Figure 7.

Figure 7. The piers of Yongfu water pipe bridge with steel jacket

The relative displacements between superstructure and the abutment are larger than the flexible capacity of pipe expansion joint for the Yongfu and Jiantan water pipe bridges, respectively. There are two retrofit options are considered. One is the replacement pipe expansion joint scheme, the other is the additional Outer flexible expansion joint scheme as shown in Figure 8.

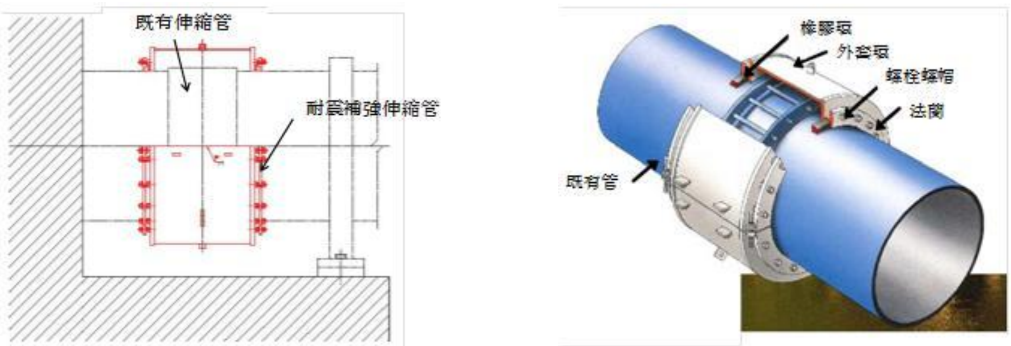


Figure 8. Outer flexible expansion joint

The bearings of existing water pipe bridges fail to meet the seismic performance criteria, therefore there are two retrofit options are considered. One is the replacement bearings scheme, the other is the additional RC or steel anti-shock devices scheme as shown in Figure 9.

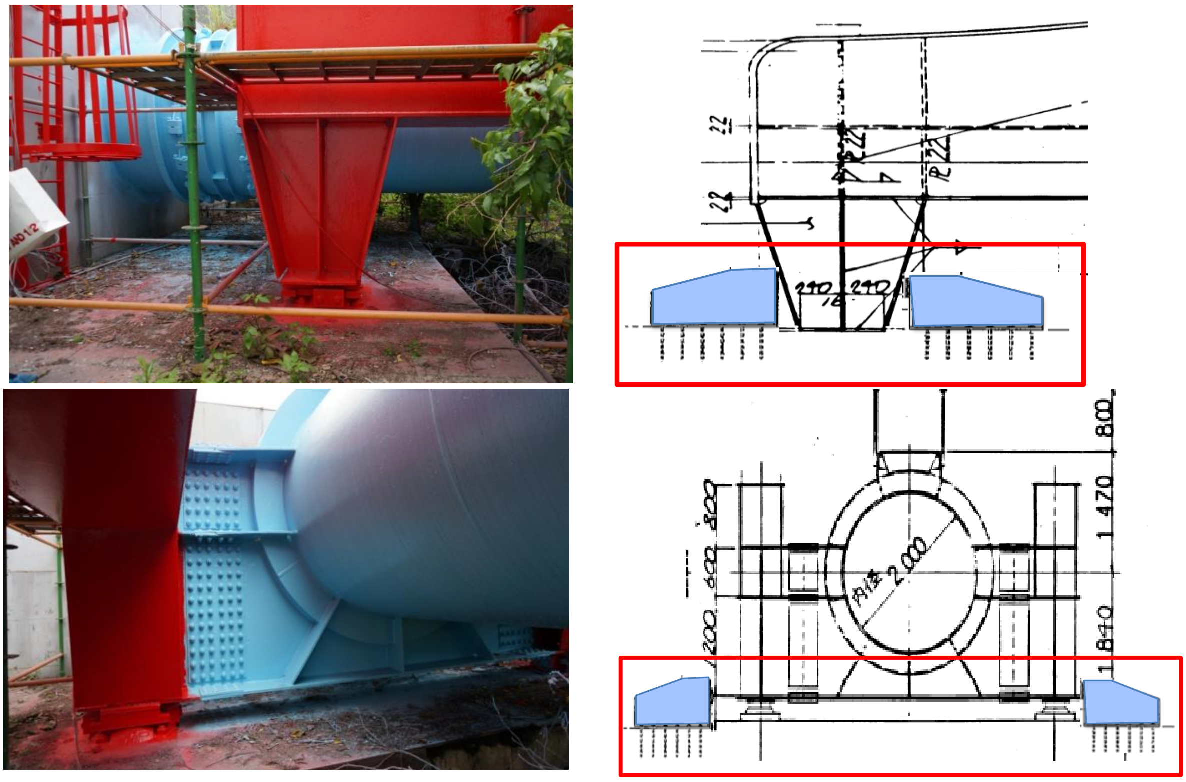


Figure 9. The bearings of existing water pipe bridge with steel anti-shock devices

CONCLUSON

Following conclusion are drawn from the present general review of seismic evaluation for the four existing water pipe bridges managed by Taipei Water Department using static nonlinear pushover analysis and nonlinear time history analysis.

- **Pushover Analysis Results:**Yuanshan, Hsintien and Jiantan water pipe bridges have enough seismic capacity to satisfy the seismic performance criteria but the seismic capacity of Yongfu water pipe bridge in longitudinal direction fails to meet the seismic performance criteria. The piers of Yongfu water pipe bridge had been retrofitted by steel jacket for insufficiency of ductility.
- **Time History Analysis Results:**The relative displacements between superstructure and the abutment are larger than the flexible capacity of pipe expansion joint for the Yongfu and Jiantan water pipe bridges, respectively. There are two retrofit options are considered. One is the replacement pipe expansion joint scheme, the other is the additional Outer flexible expansion joint scheme. The bearings of existing water pipe bridges fail to meet the seismic performance criteria, therefore there are two retrofit options are considered. One is the replacement bearings scheme, the other is the additional RC or steel anti-shock devices scheme.

ACKNOWLEDGMENTS

Authors would like to acknowledge Taipei Water Department, for providing the information on the four existing water pipe bridges. Special thanks to Dr. Gee-Yu Liu (National Center for Research on Earthquake, NCREE) for his suggestions on various aspects of this project.

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Damage Analysis of Air Valves of Drinking Water Pipeline in the 2016 Kumamoto Earthquake

Taichiro Inui, Mitsuyasu Tamase and Masakatsu Miyajima

ABSTRACT

This paper deals with the damage to air valves of drinking water pipelines in the 2016 Kumamoto earthquake. Not only damage to pipe body and joints but also valves were severely caused by the 2016 Kumamoto earthquake. Firstly, a questionnaire survey on the damage to air valves was conducted to waterworks bureaus in Kyushu region in order to clarify the causes of the damage. The results show that the damage to air valves was caused not only in areas near the epicenter but also in areas far from the epicenter. This suggests that the cause of the damage to air valves is not only strong seismic motion. Since many damages were occurred at floating valve body and float valve body of air valve, an abrupt increase of water pressure in air valves is seems to be one of causes of the damage to valve.

Next, a relation between the distribution of the peak ground velocity and the location of the damage to air valves are studied in Kumamoto City. The damages to air valves were occurred not only in the areas of large peak ground velocity but also in the areas of not so large peak ground velocity in Kumamoto City. About 50% of damage to valves in the areas of large peak ground velocity seems to be caused by abrupt increase of water pressure in air valve according to the damaged part of the air valve.

The result of this study shows that one of causes of damage to air valves is abrupt increase of water pressure and abrupt decrease of water flow just after the earthquake. The cause of the abnormal behavior of water supply system just after an earthquake must be clarified and countermeasure of valves should be developed in the near future.

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INTRODUCTION

The 2011 Tohoku earthquake of magnitude 9.0 occurred on 11th March 2011, off the Ojika peninsula of Miyagi prefecture. Even in areas where direct damage such as rupture of water pipes did not occur in this earthquake, abnormal behaviors of the water distribution system such as rapid flow rate increase and water pressure decrease occurred immediately after the earthquake, and cases where the water supply system remarkably deteriorated a lot of it was seen. Changes in the water distribution and water pressure at the western part of Saitama City during the 2011 Tohoku earthquake are shown in Figure 1. The red line shows the change in the water distribution, the blue line shows the change in the water pressure. The water distribution rapidly increases around 14:46 when the earthquake occurred, and the water pressure is decreasing. Such abnormal behaviors have been reported in Tokyo and Osaka so far. Also, in the 2011 Tohoku earthquake a lot of damage to the air valve was reported, causing many leakage damage. An air valve is a valve having a function of automatically sucking and exhausting the air accumulated in the pipe and is installed in places where air bubbles are likely to occur, such as a continuous downward slope of a water distribution pipe and a convex portion of a pipe. Also, it is said that it is desirable that a few are installed for 1 km of water distribution pipe, even if it is not a place where air bubbles are likely to occur. Such water cutoff caused by damage to air valve may cause secondary disasters such as hindrance to firefighting activities in a large scale earthquake that may cause a fire from houses or the like. Even in the 2016 Kumamoto earthquake that occurred in April 2016, similar damage to air valves and other valves was reported. Table 1 shows the number of damaged places and damage rates of pipes and valves in the 2016 Kumamoto earthquake. It is known that damage rate to valves such as air valves is not small compared with damage of water pipes in the 2016 Kumamoto earthquake. Therefore, in order to investigate the actual condition of the air valve damage and to investigate the cause, this research will be conducted from the viewpoint of the form of the air valve, the difference of the surrounding situation, the characteristics of the seismic motion and the ground property.

The purpose of this research is to investigate the ground characteristics and the characteristics of the earthquake ground motion at the point where the damage to air valves occurred, to clarify the influence of the magnitude of the shaking caused by the earthquake on the air valve, and to elucidate the cause of the air valve damage.

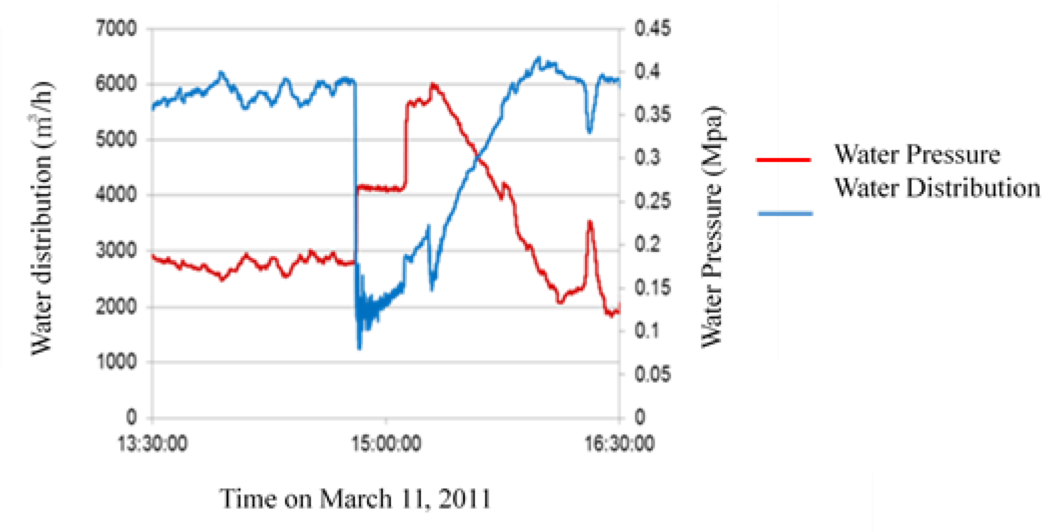

Figure 1. Changes in water distribution and water pressure at the western part of Saitama City during the 2011 Tohoku earthquake [1]

TABLE I. DAMAGES TO PIPELINES AND VALVES IN THE 2016 KUMAMOTO EARTHQUAKE[2]

	Number of damage points	**Damage rate(point/km)**
Pipes	**296**	**0.087**
Valves	**144**	**0.042**

A QUESTIONNAIRE SURVEY ON DAMAGE TO AIR VALVE OF WATER SUPPLY SYSTEM IN THE 2016 KUMAMOTO EARTHQUAKE

The purpose of the questionnaire survey was to investigate the actual condition and cause of the damage, such as the form of the damaged air valve in the 2016 Kumamoto earthquake, the difference in damage due to the surrounding situation such as installation location and downstream piping form.

The target area shall be the entire Kyushu region so that data can be obtained from the area where the seismic intensity is large to the small area. Also, the number of target water utility is 209 in seven prefectures excluding Okinawa Prefecture in the Kyushu district.

The number of damage to air valves in each prefecture in the 2016 Kumamoto earthquake is shown in Figure 2. According to Figure 2, it is understood that the damage was concentrated in Kumamoto Prefecture and Oita Prefecture where the epicenter is located. On the other hand, air valve damage has also occurred in areas relatively far from the epicenter such as Saga City in Saga Prefecture and Nobeoka City in Miyazaki Prefecture.

Figure 3 shows the structure of the air valve, and Figures 4 and 5 show the broken part and factor of the air valve, respectively. Concerning on the damaged part, the floating valve body (Photo 1) had the most damage and then the float valve body (Photo 2). The floating valve body / float valve body is a part for efficiently exhausting the air contained in the water in the pipeline. As mechanism, when the air contained in the water in the pipeline accumulates in the air valve, as the water level drops, the floating valve body / float valve body descends, the air hole valve seat is opened, and the air is exhausted. When the exhaust is completed, the float valve body rises and the air hole closes. This movement is automatically repeated to discharge the air in the pipeline. In addition, the float valve body guide / cover are also a part susceptible to the influence of water pressure fluctuation, and it is thought that it was influenced this time as well. On the other hand, the flange joint part (Photo 3), which was damaged next to the floating valve body and the float valve body, is in contact with the outside at the part which plays a role of connecting the water pipe and the air valve, and is not affected by the water pressure fluctuation. Therefore, this damage is considered to be caused by aged deterioration and direct external force caused by earthquake vibration. According to Figure 6, the damage of the flange joint portion occupies about 15% of the whole and is the third most damaged portion.

Figures 6 and 7 show the breakage points for each damage factor. Figure 6 indicates that the damages to the floating valve body and the float valve body account for 70% or more of the total in the case of breakage due to water pressure fluctuation in the pipe. In addition, Figure 7 explains that the breakage of the flange joint portion accounts for 70% by the damage due to external force to the valve body. As a result, measures against sudden changes in water pressure to the floating valve body and the float valve body are of utmost importance as countermeasures against earthquakes. On the other hand, countermeasures against earthquake shaking are, however, indispensable for the part in contact with the outside such as the flange joint part.

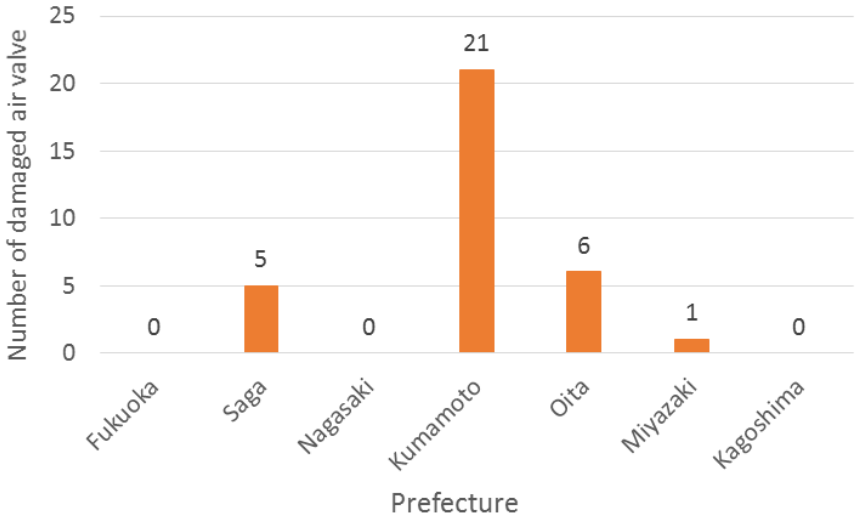

Figure 2. Number of damage to air valve in each prefecture

TABLE II. SURVEY COLLECTION RATE

Prefecture	Number of distibution	Collected number	Collected rate(%)
Fukuoka	62	40	64.5
Saga	20	13	65.0
Nagasaki	21	18	85.7
Kumamoto	29	19	65.5
Oita	16	11	68.8
Miyazaki	23	17	73.9
Kagoshima	38	18	47.4
Overall	209	136	65.1

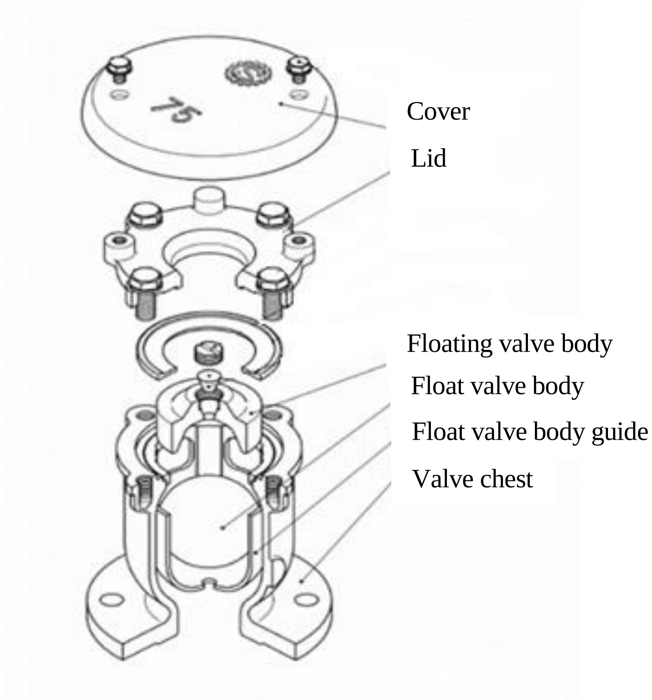

Figure 3. The structure of air valve [3]

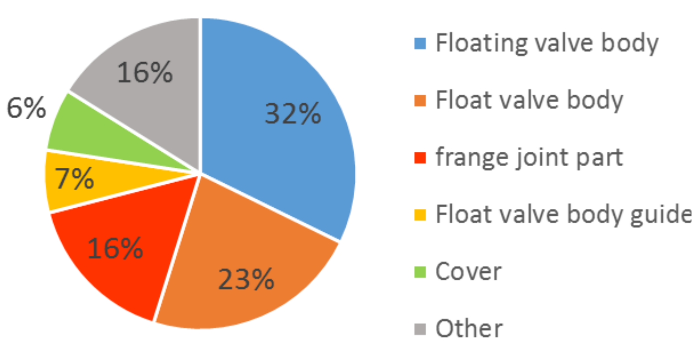

Figure 4. Broken part of air valve

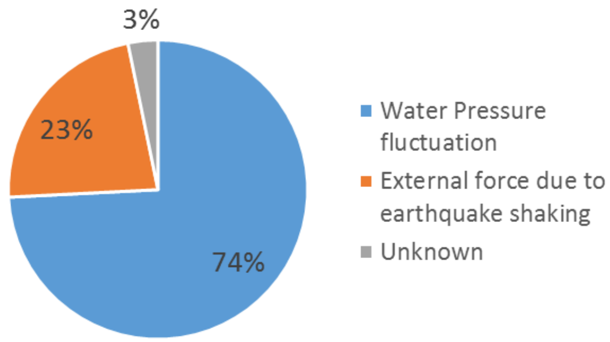

Figure 5. Factor of damage to air valve

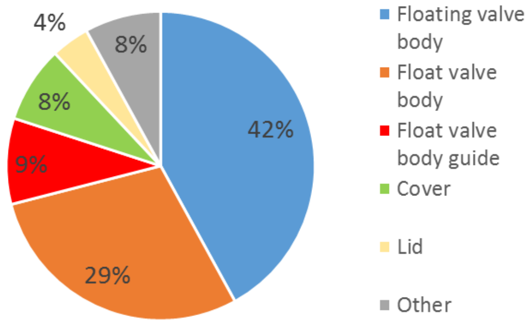

Figure 6. Damage parts due to water pressure variation in pipe

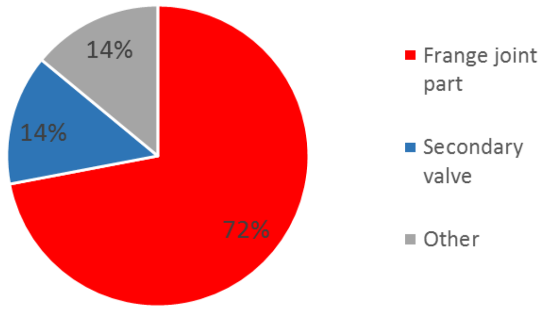

Figure 7. Damage parts due to external force applied to the valve body

Photo 1. Damaged floating valve body

Photo 2. Damaged float valve body

Photo 3. Leakage from flange joint

RELATION BETWEEN LEAKAGE FROM AIR VALVE AND THE PEAK GROUND VELOCITY

Figure 8 shows the distribution of the peak ground velocity (PGV) in the 2016 Kumamoto Earthquake and damage to pipe fittings. The relation between PGV and the damage to pipe fittings is discussed here. The damage to pipe fittings occurred almost entirely around the central and eastern parts of Kumamoto City. This figure suggests that more than half of them occurred in the area where PGV was 80 cm / s or more, but some damage occurred even in the area of PGV of 40 cm / s to 80 cm / s where PGV was relatively small. Figure 9 shows the number of damage to pipe fittings in each PGV range. This figure also indicates that the damage to pipe fitting occurred in the area where PGV is more than 80 cm / s. These figures clarify that the damage to pipe fittings concentrated in the central and eastern parts of the city where the distribution pipeline is dense, and in the region where PGV was large. However, it was found that some damage to pipe fittings occurred even in the areas where PGV was relatively small. These areas are sparse distribution of pipelines in case of Kumamoto City. Therefore, it is the magnitude of the seismic vibration affects fittings damage, but it is possible that factors other than seismic vibration affect pipe fittings and cause damage and leakage even if the seismic vibration is small.

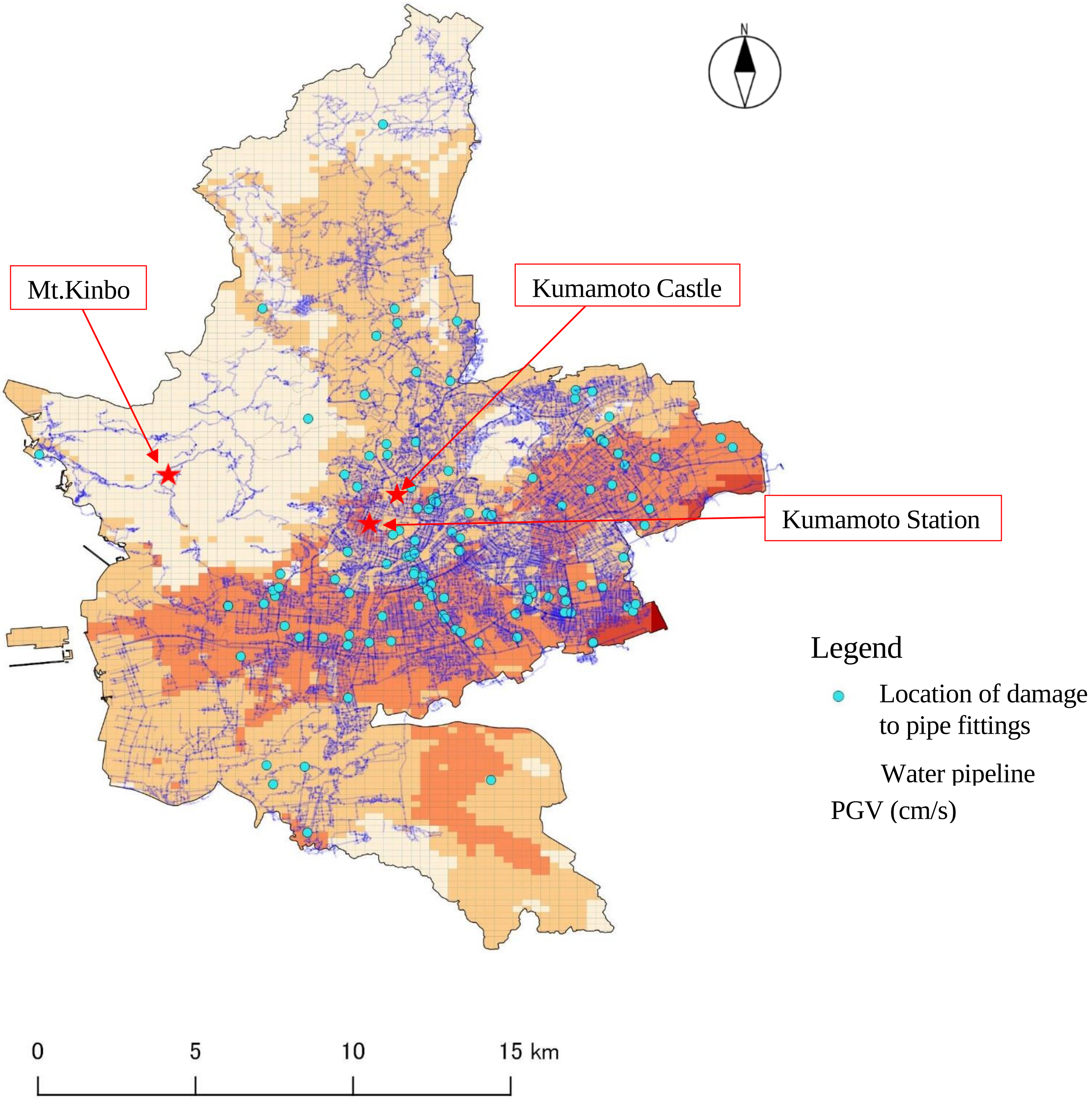

Figure 8. Distribution of PGV and damage to pipe fittings

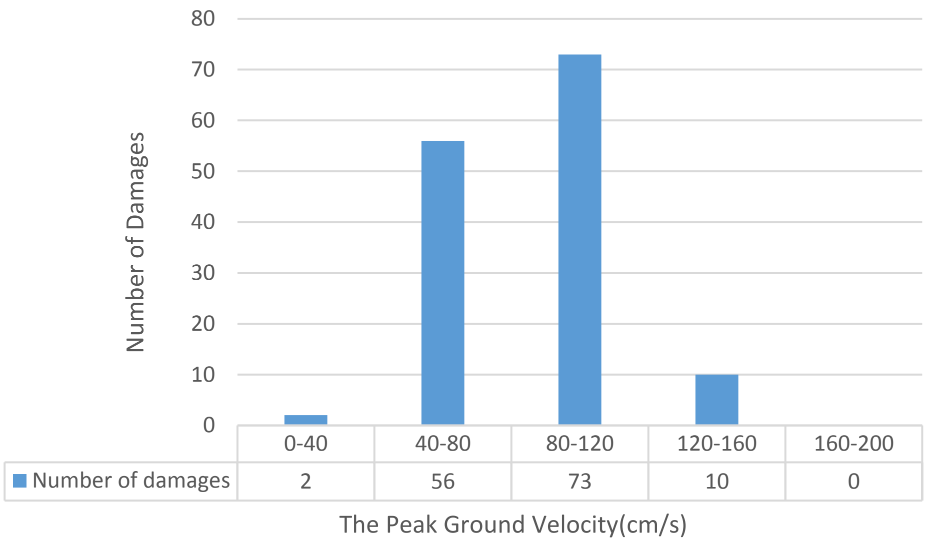

Figure 9. Number of damage to fitting in each PGV range

CONCLUSION

This paper studied the damage to air valves of drinking water pipelines in the 2016 Kumamoto Earthquake. The following results were obtained.

First, we investigated the breakage point of the air valve and the cause of the damage from a questionnaire. As a result, breakage of the floating valve body / float valve body accounted for a large proportion as the damaged part. Also, the damage of the flange joint portion occupies about 15% of the whole and is the third most damaged portion. Therefore, measures against sudden changes in water pressure to the floating valve body and the float valve body are of utmost importance as countermeasures against earthquakes. On the other hand, countermeasures against earthquake shaking are, however, indispensable for the part in contact with the outside such as the flange joint part.

Next, we focused on the distribution of PGV in the 2016 Kumamoto earthquake and the damage to pipe fittings. This study clarified that the damage to pipe fittings concentrated in the central and eastern parts of the city where the distribution of pipeline is dense, and in the region where PGV was large. However, it was found that some damage to pipe fittings occurred even in the areas where PGV was relatively small. Therefore, the magnitude of the seismic vibration affects damage to pipe fittings, but it is possible that factors other than seismic vibration affect pipe fittings and cause damage and leakage even if the seismic vibration is small.

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Seismic Evaluation and Retrofit of Existing Distribution Reservoirs in Taipei City

Chen-Hsiang Lu[1], Ching-Yang Huang[2], Ing-Sen Yuan[3], and Chuan-Chiang Fan[4]

ABSTRACT

This paper presents the main results of the seismic safety assessment for the Nangang distribution reservoir in Taipei city. The distribution reservoir is an underground rectangular RC tank with maximum storage of 5000 m^3. In a recent on-site inspection, it was found that some of the support columns suffered severe damage, where significant cracking occurs at the top of the columns accompanied by buckling of the reinforcing bars inside. It was inferred that the damage was due to the so called “short column effect” resulted from the connection of the guide walls to the columns in partial height. To further exploit the cause of the damage as well as to assess the impact of the damage to the distribution reservoir, a 3D finite element model was developed using analysis package SAP2000 and was then employed to conduct seismic analysis of the distribution reservoir. The inference that the damage was mainly due to the short column effect was confirmed by the analysis results. In addition, the earthquake-resistant capability of the distribution reservoir was assessed using a draft code for seismic design of tank structures newly prepared by NCREE. In this code, the Housner’s approach (Housner, 1963) is adopted instead of the conventionally used simplified Westergaard formula for calculation of the hydrodynamic forces acting on the distribution reservoir. To realize the difference between the forces calculated using the two approaches, a comparative study was carried out for tanks of different sizes with varying water depths. It was indicated that the simplified Westergaard formula produces higher hydrodynamic force than the Housner’s approach does when the ratio of the tank length to the water depth is relatively small. Therefore, for larger tanks in Taipei city designed during 1980s~1990s like the Nangang distribution reservoir, the hydrodynamic force calculated by using the simplified Westergaard formula in design was probably under-estimated, which may fail to meet the requirements of the new design code. Finally, some retrofit measures were proposed to prevent the distribution reservoir from further development of the damage.

Keywords: Water facilities, Seismic evaluation, Distribution reservoir

INTRODUCTION

Water distribution system is the vital part of a city’s potable water supply system. It ensures that water is delivered to the citizens with proper quality, quantity and enough pressure. Once the water distribution system was not able to operate as required, the water supply service will be severely impaired. Moreover, if the distribution system was damaged during an earthquake, the secondary disaster such as fire or plaque in the city will be hard to

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control because the water could not be properly delivered. Distribution reservoirs are one of the key parts of the water distribution system, the purpose of which is to store the treated water for delivery and to maintain constant pressure within the distribution pipes. The distribution reservoirs can also provide with water in case of emergent situations.

There are many distribution reservoirs in the Taipei city. Because of their importance, the authority, i.e., the Taipei Water Department has commissioned projects in the past years to assess the safety and operation function of the distribution reservoirs during earthquakes and to propose suitable retrofit measures if necessary. This paper presents the main results of the safety assessment for the Nangang distribution reservoir, which is an underground rectangular RC tank with maximum storage of 5000 m^3. The distribution reservoir was built and started operating in 1988 and has been in service over almost 30 years.

In the analysis of the tank-like structures, the hydrodynamic pressure induced by the fluid contained inside the tank during earthquakes is an important loading to be considered. For the distribution structures in Taipei city designed over 20 years ago, the earthquake-induced hydrodynamic force was almost calculated using the simplified Westergaard (1931) [1] formula assuming infinite fluid domain. It is obvious that the assumption of infinite fluid domain is not appropriate for the case of tank structures where the water domain is finite. As a result, the Housner's approach (Housner, 1963) [3] that is capable of calculating the hydrodynamic force for the case of finite fluid domain was employed in the new code "Seismic Design of Potable Water Tank Structure" [2] drafted by the National Center for Research on Earthquake Engineering (NCREE) of Taiwan in 2016. The Housner's approach employed in the new code is the same as that suggested in ACI 350.3-06 (Seismic Design of Liquid-Containing Concrete Structures and Commentary)[4]. The above-mentioned new code was adopted for the safety assessment of the Nangang Distribution Reservoir. As a part of the safety assessment, a case study was conducted to exploit the difference of the hydrodynamic forces calculated by using the two approaches, which will be presented in the paper.

ON-SITE INSPECTION

The dimension of the Nangang distribution reservoir is 34.02m long, 27m wide and 5.8m high(Fig. 1). There are 30 circular columns with 45cm in diameter placed equally in the reservoir base. Interim walls connecting the columns are provided to guide the water flow. These guide walls are 15cm in thickness with one layer of reinforcing steel bars (Fig. 2). The compressive strength of the concrete of the walls and columns f_c'is 280 kgf/cm^2 and the yielding strength of the steel bars f_y is 2,800 kgf/cm^2.

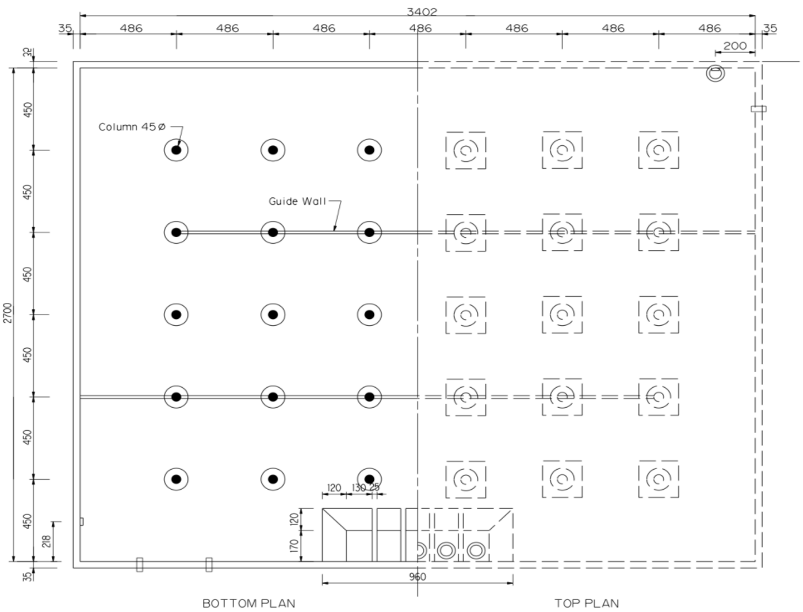


Figure 1. Plan View of Nangang Distribution Reservoir

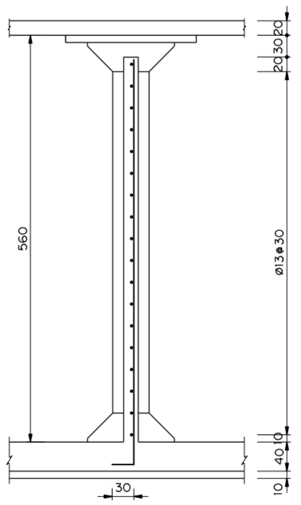


Figure 2. Section of Guide Walls of Nangang Distribution Reservoir

The on-site inspection reveals that the reservoir has suffered from some damages (Fig. 3). Visible cracks were found appearing on the columns, guide walls and bottom slab. Among these cracks, those occurring at the top of the columns (Fig. 4) are relatively sever. In addition to cracking, some of the reinforcing bars within the columns were exposed and buckled (Fig. 4).

Figure 3. Damages of Nangang Distribution Reservoir by On-Site Inspection

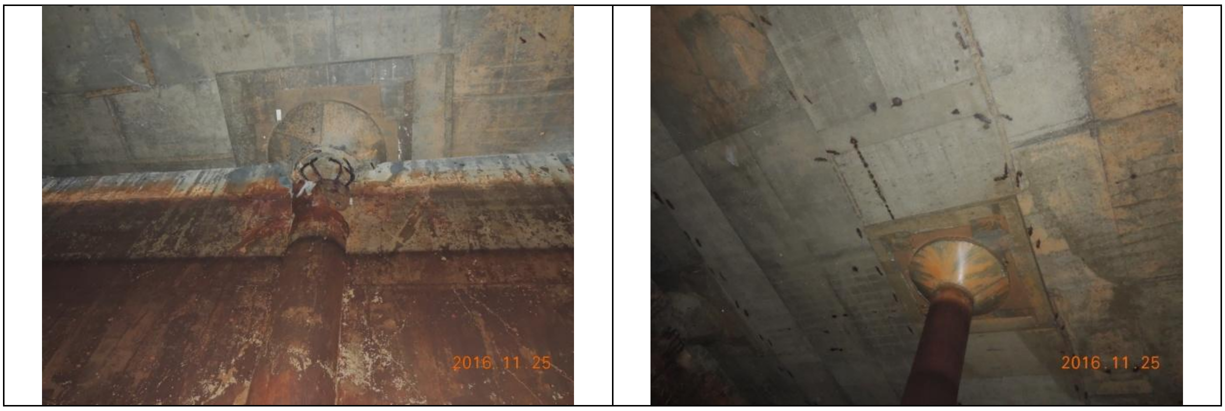


Figure 4. Exposure of Reinforcing Bars Within Columns of Nangang Distribution Reservoir

It was also found that only columns connecting to the guide walls were damaged and the others, i.e., not connecting to the guide walls are nearly intact. Based on the fact, it was inferred that the damage was mainly due to the so called “short column effect” resulted from the connection of the guide walls to the columns in partial height. This “short column” effect is often seen in school buildings with window openings. The guide walls connecting to the column were also damaged, where several 45-degree cracks can be observed on the wall panel.

STRUCTURAL ANALYSIS AND SEISMIC ASSESSMENT

The structural analysis of the distribution reservoir was carried out using finite element package SAP2000. A 3D finite element model of the distribution reservoir was developed, in which the slab and the walls were modeled using SHELL element, while the columns were modeled using BEAM element (Fig. 5).

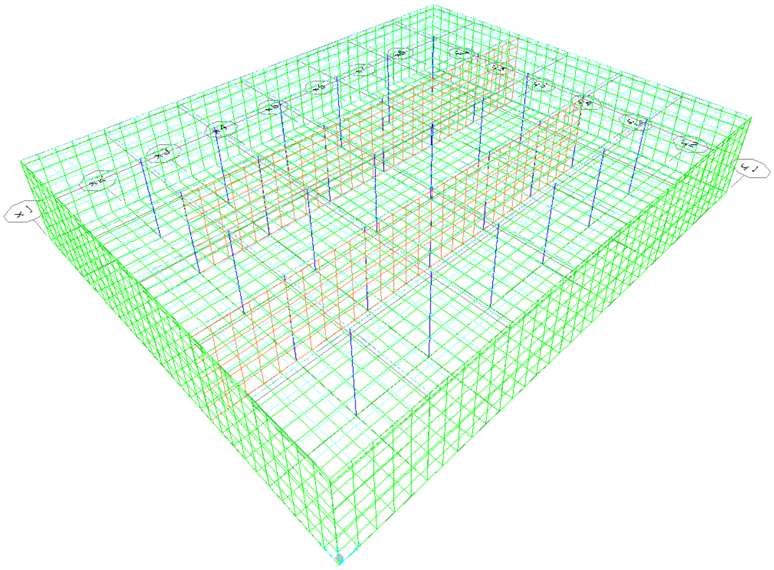
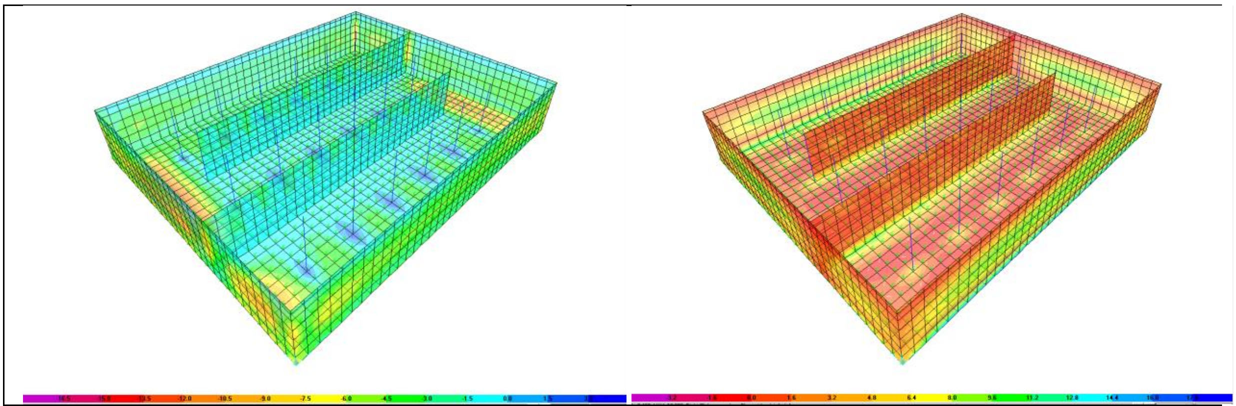


Figure 5. A 3D Finite Element Model for Nangang Distribution Reservoir

Loadings considered in the analysis include self weight, static and dynamic soil pressures and hydrostatic and hydrodynamic pressures of the liquid inside the reservoir, the calculation of which followed the approaches specified in the draft code. The results of the analysis are presented in what follows.

The contour of the moments of the reservoir along the two principle directions, i.e., M11 and M22 are shown in Figure 6.



M11	M22

Figure 6. Moment Contours of Nangang Distribution Reservoir (roof slab removed for clarity)

The flexural and shear capacities of the slab and of the walls are both enough. However, some of the columns connecting to the guide walls fail to the shear capacity check (Fig. 7). The shear capacity of the columns is 0.056cm^2, which is far less than the demand obtained by the analysis. The inference that the damage was mainly due to the short column effect posed by on-site inspection results was confirmed by the analysis result. The results of the structural analysis agree generally well with those by the on-site inspection (Fig. 8).

In general, the Nangang distribution reservoir satisfies the requirements for seismic case suggested by the newly proposed code.

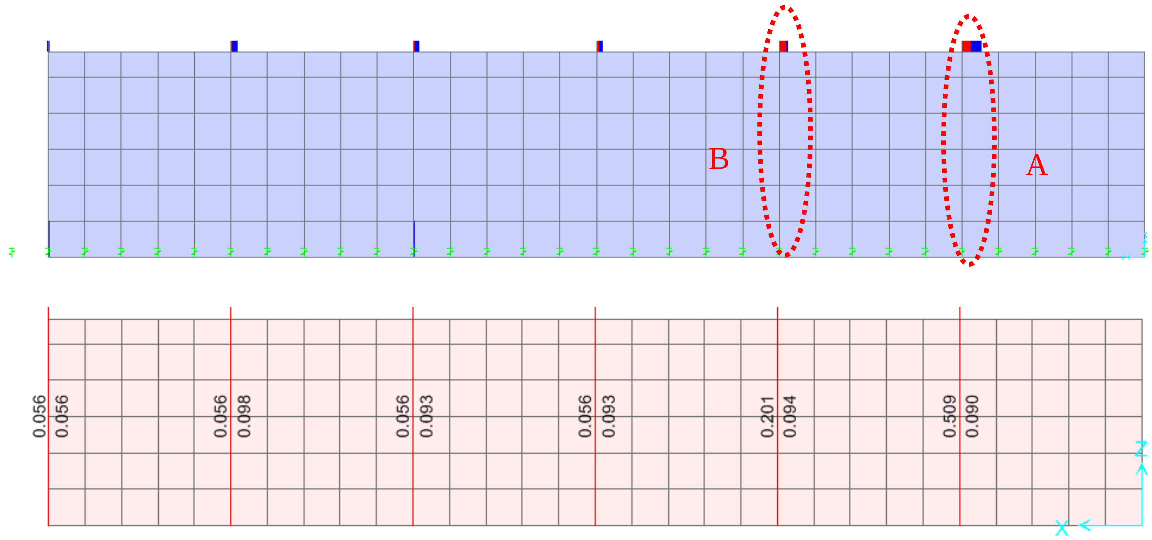


Figure 7. Shear Demand and Capacity of Columns

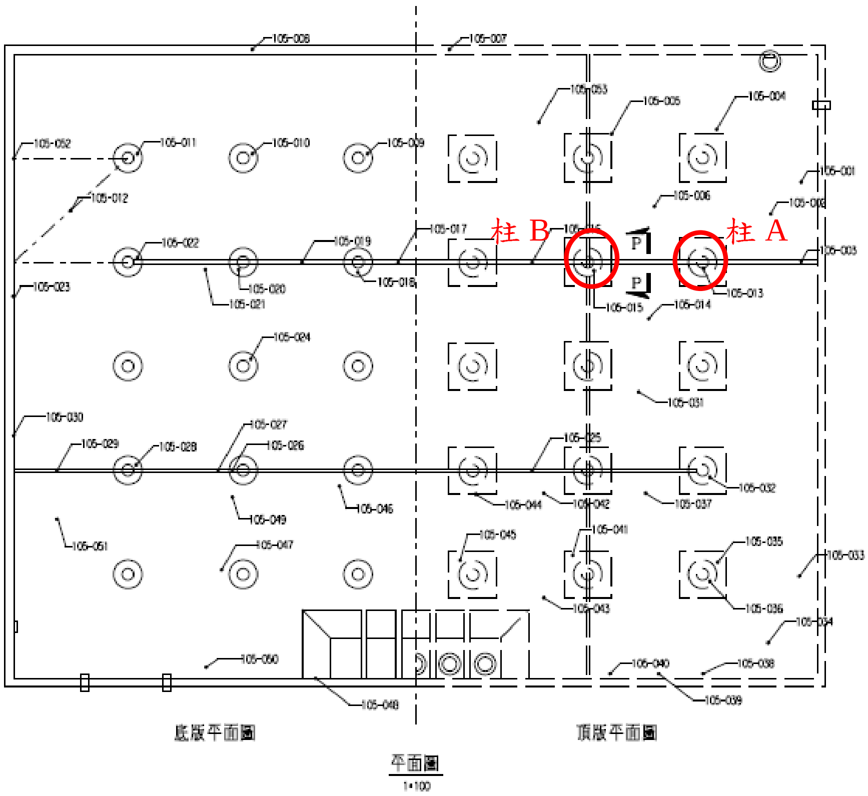


Figure 8. Damage Distribution of Nangan Distribution Reservoir

Due to the constraint of the guide walls, the non-constrained length of the columns is drastically reduced, which produces the short column effect. As a result, the columns closer to the side walls (denoted as A and B in Fig. 8) are constrained more largely than the others, resulting in more damages.

COMPARISON OF WESTERGAARD ANG HOUSNER APPROACHES

The simplified Westergaard's formula has long been widely used for calculating the hydrodynamic force induced by earthquakes in hydraulic and dam engineering. It was also used for tank design [5] in Taiwan during 1980s~1990s. The simplified Westergaard formula assuming infinite fluid domain can be written as follows,

$$P = \frac{7}{12} k_h \gamma_w {H_L}^2$$

where P= total hydrodynamic force, k_h =0.4S_{DS} and H_L=water depth.

The Housner's approach considers the sloshing effect of the water containing in the tank during earthquakes. In the approach, the hydrodynamic force is divided into convective (Pc) and impulsive (Pi) parts, as depicted in Fig. 12.

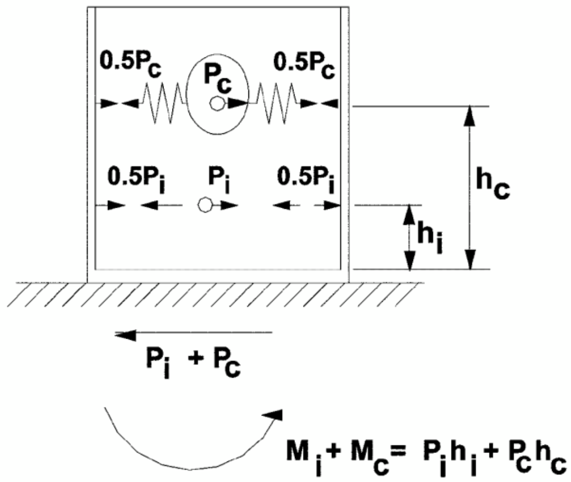


Figure 12. Dynamic Model of Liquid-Containing Tank [Fig. R9.1 ACI 350.3]

The simplified Westergaard formula only involves the height of the water, but the Housner's approach takes into account the size of the tank in addition. To realize the difference of the two approaches, various L/H_L ratios were considered, where L and H_L are respectively the depth of the water and the length of the tank. Impulsive and convective forces were both calculated and the moments at the base of the tank wall were then obtained. Since the maximum value of the impulsive force and that of the convective force do not occur simultaneously, the combined moment M_{comb} was used, which is determined as

$$M_{comb} = \sqrt{M_{imp}^2 + M_{conv}^2}$$

The forces calculated for different L/H_L ratios by the Housner's approach are listed in Table 1. In addition, the moments for different cases are plotted in Figure 13 to better display the differences.

TABLE I. Forces for Different L/H_L Ratios Calculated by Housner's Approach

L (m)	H_L (m)	L/H_L	P_i (tf/m)	P_c (tf/m)	M_{imp}(tf-m/m)	M_{conv}(tf-m/m)	M_{comb} (tf-m/m)
1.25	5.0	0.25	2.46	0.49	0.49	0.49	0.49
2.5	5.0	0.5	4.94	0.98	0.98	0.98	0.98

5.0	5.0	1.0	8.64	1.94	1.94	1.94	1.94
10.0	5.0	2.0	11.59	3.31	3.31	3.31	3.31
15.0	5.0	3.0	12.31	3.60	3.60	3.60	3.60
20.0	5.0	4.0	12.44	3.40	3.40	3.40	3.40
25.0	5.0	5.0	12.46	3.06	3.06	3.06	3.06
30.0	5.0	6.0	12.47	2.74	2.74	2.74	2.74
35.0	5.0	7.0	12.47	2.45	2.45	2.45	2.45
40.0	5.0	8.0	12.47	2.21	2.21	2.21	2.21
45.0	5.0	9.0	12.47	2.01	2.01	2.01	2.01

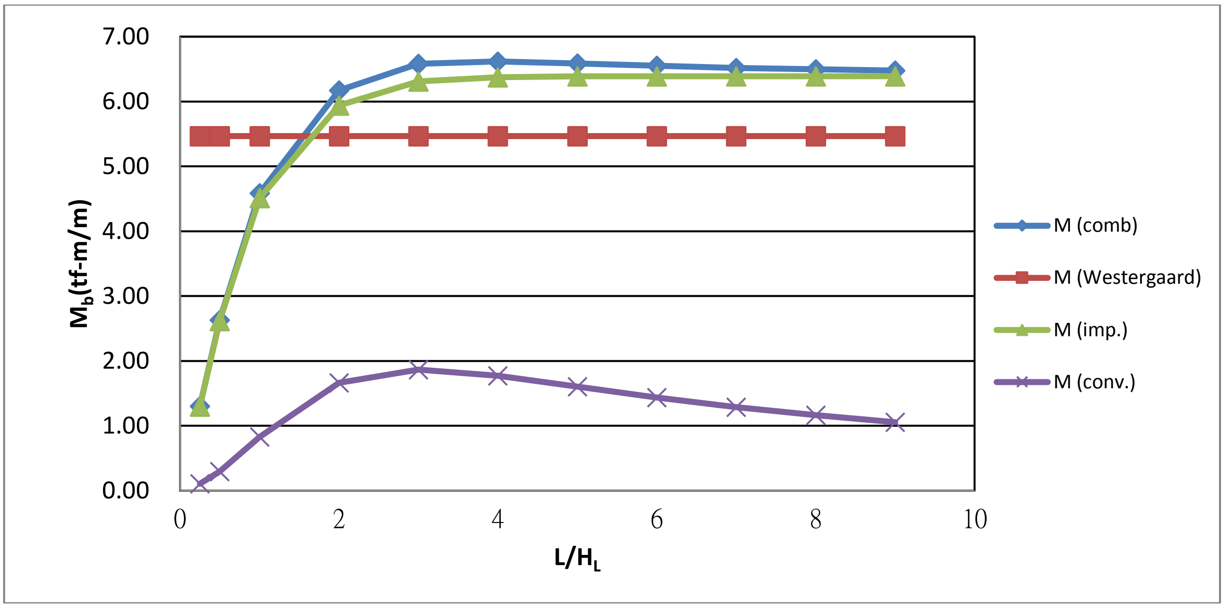


Figure 13. Moments at the Base of Wall by Two Approaches

Because the simplified Westergaard formula only takes into account the water depth H_L, the moment at the base of the wall does not vary with the tank length. When the L/H_L ratio is smaller than 2.0, which stands for "taller" tanks, the Westergaard formula produces larger moments than the Housner's approach does. While as the L/H_L ratio gets larger, the Housner's approach produces larger moments.

It can be concluded from the comparison that for smaller tanks, which usually have lower L/H_L ratios, the hydrodynamic force was probably over-estimated if the simplified Westergaard formula was used, while on the contrary for larger tanks such as distribution reservoirs the hydrodynamic force may be under-estimated.

RETROFIT MEASURES

The following measures were proposed to retrofit the columns of the distribution reservoir to prevent the columns from appearing the short column effect.

1. Column Retrofitting

The direct way is to increase the column strength. The columns were designed to be retrofitted with 20cm thickness jacket of concrete. Additional longitudinal and transversal reinforcement would be placed in the concrete jacket. To achieve a proper bond for the RC jacket, the longitudinal rebars should be fixed in top and bottom slabs using chemical anchors.

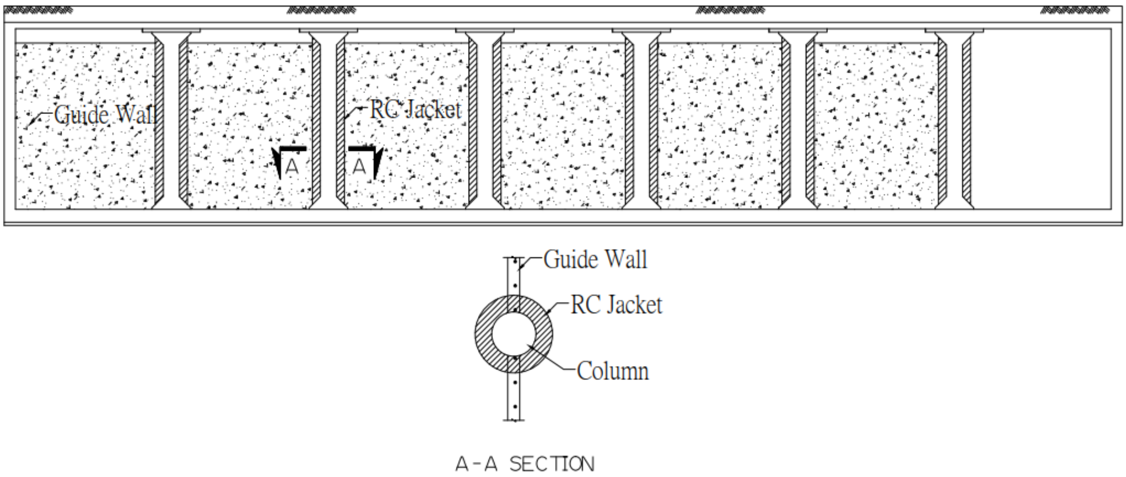


Figure 9. Retrofit with RC Jacket

2. Guide Wall Retrofitting

Since the “short column” effect is due to the partial height wall adjacent to columns, one simply way to eliminate the effect is to increase the wall height to its full height. Partial top wall should be demolished first and rebuilt to full height. Additional reinforcements should be provided to splice existing reinforcement and fixed at top slab by chemical anchor.

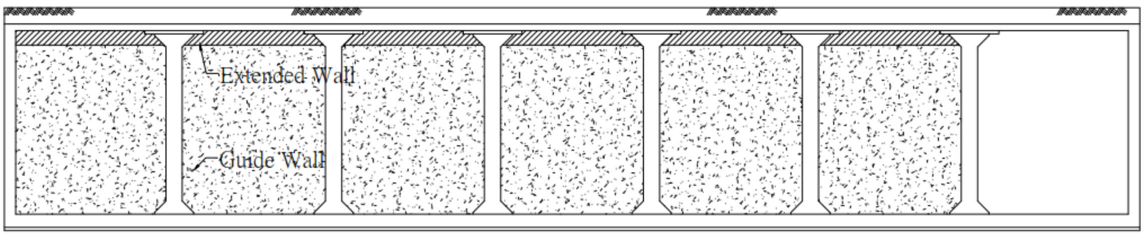


Figure 10. Retrofit the Wall to Full Height

3. Lower the Height of Guide Wall

Different from the second retrofit measure, part of the guide walls is demolished to increase the effective length of the columns. If the height of the wall is decreased by half, the strength of the column will be enough to resist lateral force. This is the most easy and economical way to cut down the short column effect. However, function of the guide wall will be compromised and the flow efficiency may be impaired.

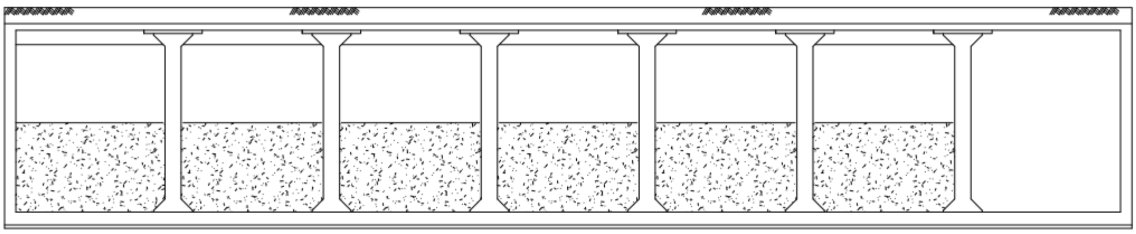


Figure 11. Guide Wall Reduced to 50% Height

CONCLUSIONS

Seismic assessment of the Nangang reservoir was carried out by employing the draft code "Seismic Design of Potable Water Tank Structure " prepared by NCREE in 2016. Overall, the earthquake-resistant capacity of the distribution reservoir is still sufficient according to the code. However, some of the support columns do not have enough capacity to sustain the shear load amplified by unfavorable "short column" effect. Measures that retrofit the columns with 20 cm thickness RC jackets or increase the height of the guide walls to its full height are advised to eliminate the short column effect. For design of distribution reservoirs with interior walls in the future, the "short column" effect should be carefully avoided or properly resisted.

From the results of comparison study, it was indicated that the simplified Westergaard formula produces higher hydrodynamic force than the Housner's approach does when the ratio of the tank length to the water depth is relatively small (<2.0). Therefore, larger tanks in Taipei city designed during 1980s~1990s like the Nangang distribution reservoir, the hydrodynamic force calculated by using the simplified Westergaard formula in design was probably under-estimated, which may fail to meet the requirements of the new design code.

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Napa Water System Earthquake Response: like fine wine, the right blend of self-help and mutual aid

Joy Eldredge, Water General Manager

ABSTRACT

On August 24, 2014 at 3:20am the south Napa Earthquake struck 5 miles southwest of the City of Napa and 2 miles west of one of two major water treatment plants. The energy radiated north and affected the west side of the pressurized pipe network that makes up the transmission and distribution systems that carry potable water to over 84,000 residents throughout City of Napa and surrounding areas. The event, the largest earthquake in the San Francisco Bay Area since 1989, unveiled newly identified surface faults and wreaked havoc on water infrastructure.

The water system was impacted and the event instantly compromised a storage tank and caused the equivalent of more breaks than typically experienced over an entire year within the distribution system. It was apparent within hours, while the extent of damage was still being assessed, that mutual aid was required to protect public health, and effectively reinstate water service in a timely manner. CALWARN the established California Water and Wastewater Agency Response Network, offered to assist with the emergency response within one hour of the event.

The City of Napa coordinated with CALWARN, and water managers ordered 6 fully-functioning crews stocked with heavy equipment and materials. By the middle of day two, a production assembly line of pipe repair was established: digging, repairing, backfilling, trench plating, flushing, water quality analyzing, and paving each site. Local private contractors kept a steady supply of trucks for off-hauling spoils, delivering sand and aggregate bedding for backfill, setting up and closing down traffic control and barricades as needed. The operation quickly became an efficient operation of pipeline repair and site clean-up. Information and status of repairs was coordinated back to the Emergency Operations Center (EOC), status tracked and information pushed out to the public and media. Before the end of day two, an additional two crews were ordered and inserted into the leak repair assembly process. This paper is written to provide a brief description and background of the City of Napa's water system, describe the event and thought process during the uncertainty of the immediate aftermath, and share the successes of the response as well as the lessons learned to improve preparedness and execution for when the next one hits.

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CITY OF NAPA WATER SYSTEM

The City of Napa's drinking water system is relatively small when compared to most water systems in the Bay Area, but is the largest potable water system in Napa Valley serving over 84,000 persons including 76,000 persons within the City of Napa, over 2,000 persons in unincorporated Napa County, retail service to over 6,150 persons in the City of St Helena. In addition, the Cities of Calistoga and American Canyon serve 5,300 and 20,450 persons respectively with water systems reliant on treat & wheel services provided by City of Napa (Napa.) In addition, 2,000 persons in the Town of Yountville are provided water from Napa's system on an emergency basis. Napa's water system stretches eight miles from the southern end of City limits, seventeen miles from the northern end of City limits, and is composed of 350 miles of pipe ranging in size from 4-inch to 42-inches diameter. The oldest portions of the system that remain today are mostly located in the heart of downtown. These pipes were constructed of cast iron in the 1880s. The transmission system includes twelve storage tanks totaling 30 million gallons located along the east and west hillsides of Napa and nine pump stations serving the higher elevations.

Napa water system consists of three water sources each with a corresponding treatment plant as follows:

Lake Hennessey is located 17 miles north of City limits and is the largest local reservoir with a storage capacity of 31,000 acre feet (AF) of water as established by construction of Conn Dam in 1948. The treatment plant is conventional treatment originally constructed in 1981. Maximum treatment capacity is 20 million gallons per day (MGD.) A double chamber 5 million buried gallon concrete storage tank serves as the clear well on site. Water is conveyed to the City via a 36-inch diameter steel transmission main.

Milliken Reservoir is located 3.5 miles northeast of City limits and stores 1390 AF of water stored behind a concrete radial arch dam that was established in 1923. The reservoir capacity was reduced by 16 feet in 2008 to address seismic concerns associated with the max probable earthquake occurring with the dam at full capacity. The project cored 5 holes in the dam to allow passive flow of water through the dam to reduce the water level. Raw water is released from the dam and flows via open channel flow to a point approximately two miles downstream. A 16-inch diameter above ground raw water steel pipe conveys water along a limited access trail to the water treatment plant. The plant, constructed in 1976 is direct filtration with a maximum capacity of 4 MGD. The clear well is a 2 MG steel tank and the transmission line is 14-inch welded steel.

State Water Project supplies are conveyed through the North Bay Aqueduct (NBA) originating in the Sacramento-San Joaquin Delta and diverted at the Barker Slough pumping plant east of Vacaville. The 21-mile NBA is shared with cities in Solano County and water is further pumped from the Cordelia Forebay to the two 5 MG steel terminal tanks adjacent to Napa's Barwick Jamieson Treatment Plant (BJTP.) BJTP is located eight miles south of City limits and in 2011 upgrades were completed to the original 1968 treatment plant since the roof of the operations building did not meet seismic standards. The BJTP has a capacity of 20 MGD and provides treat & wheel services of SWT supplies for Cities of Calistoga and American Canyon. The recently improved process includes pre- and intermediate ozone along with conventional treatment. The clear well is a 5 MG steel tank. The transmission line is 42-inch reinforced concrete cylinder pipe that transitions to 36-inch asbestos-cement pipe and 24-inch ductile iron pipe that conveys water north to the City where it meets the 36-inch steel Conn line.

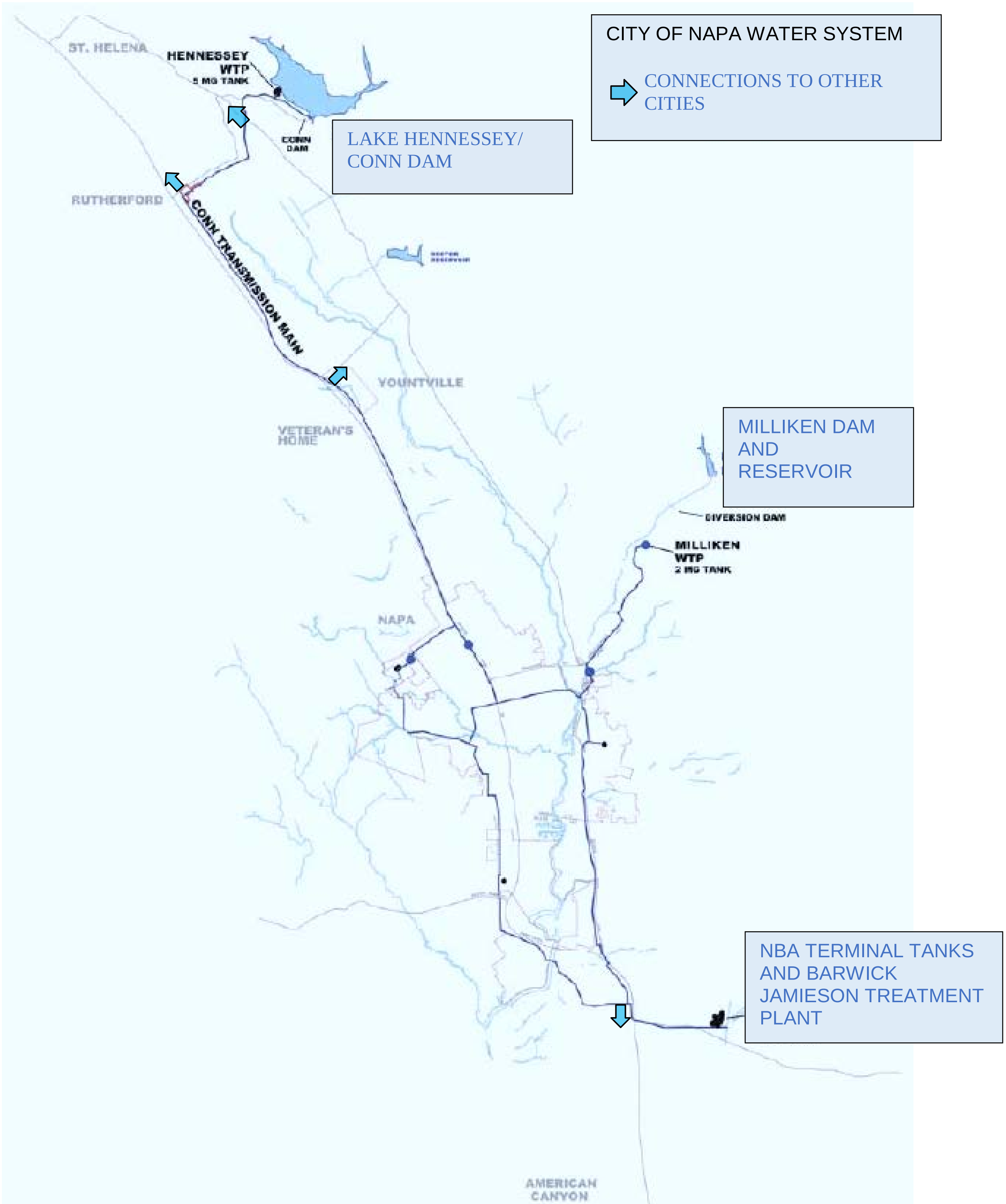

Figure 1. City of Napa Water Sources, Treatment Plants and Transmission Mains.

SEISMIC EVENT

At 0320, pacific time, on August 24, 2014, a 6.o magnitude earthquake occurred near the city Napa, California. The West Napa fault caused the earthquake and although the epicenter was 8 miles southwest of City of Napa, the shake maps indicate the energy radiated northwest along the fault and numerous surface faults were identified by staff and citizens alike to the west of downtown Napa as shown in Figure 2 [1]. As a result, the City of Napa's water system was most directly affected by the event when compared to utilities of neighboring systems.

SEISMIC EFFECTS ON CITY OF NAPA WATER SYSTEM

Water Treatment Operators on shift at the BJTP, located just 1 mile (1.6 km) from the reported epicenter felt the quake and made physical observations of the treatment plant. Typical demands in August range from 19 to 25 MGD depending on the temperature. Power was uninterrupted and the treatment plant showed no signs of damage. However, within the first three hours after the event system storage continued to decline as staff was deployed to physically inspect facilities to assess damage as best as possible with flashlights prior to daybreak. The treatment plant operator increased production from the BJTP. The two dams, Conn dam the earthen dam that retains Lake Hennessy and Milliken Dam, a concrete radial arch dam that holds back Milliken Reservoir both reported to show no impacts. All three treatment plants were reported to be in working order.

Water treatment staff were deployed to make physical inspections of water tanks that had no Supervisory Control and Data Acquisition (SCADA) communication with the treatment plant due to power outage or potential damage. Storage tanks levels were dropping rapidly and it was unknown whether the tank was leaking, the feed line was compromised, the outflow was compromised or the water level data was erroneous. Reports were received that all tanks, with the exception on one tank were in satisfactory condition. The 1 MG steel tank on the west side of town was empty and the field inspection reported that the corrugated metal roof was buckled, the roof framing was splintered and lay scattered on the ground around the tank and the valve to reduce flows from the tank was inoperable in automated and manual mode. The two pump stations that feed the tank continued to feed the tank while the level continued to drop as water flowed through the open valve to the system to feed the distribution leaks at lower elevations. Emergency generators were mobilized to these two pump stations to insure backup power in the event of an outage. The Hennessey Treatment Plant was started to increase higher pressure flows to the system in an effort to regain system storage.

Water management staff reported to the Water Administration office by 4:45 am to find the 1950's era former residential building chimney flue was shaken from the rooftop and lay in the front yard. The front door remained on its hinges but the door frame was cracked. There was no power at the facility. Inside the building shelves remained braced to the walls however binders and records were cleared from their places and were strewn across the floor as were whiteboards and wall mounted maps. All phones were off their hooks and computer monitors were on the floor.

City staff and emergency responders opened the Emergency Operations Center (EOC) and by 0500 the 911 dispatch call center was flooded with calls for assistance and reports of water outages and water line breaks in the streets. This report will focus on the response of the water system with reference to other services only as it related to water system operations and response.

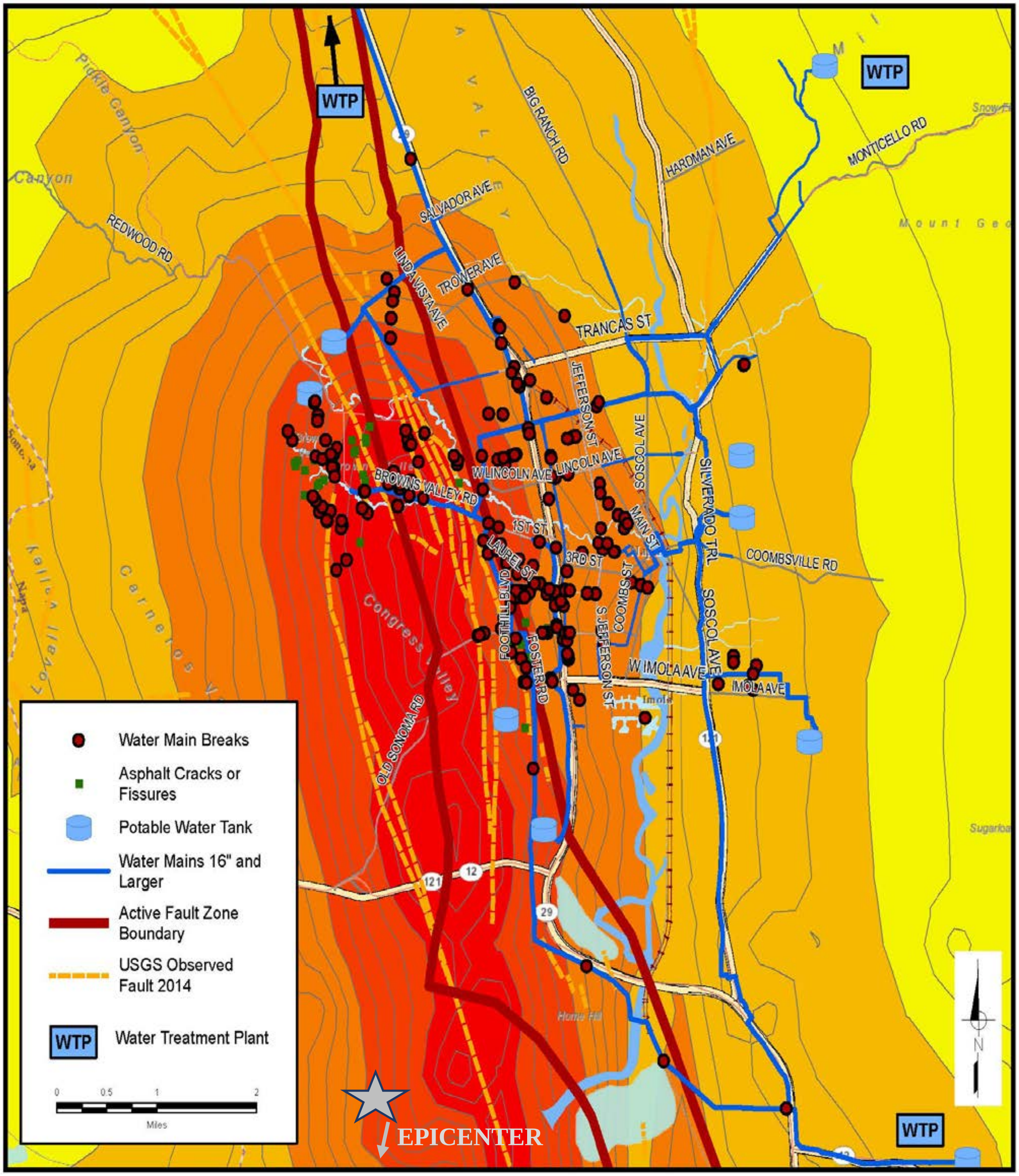

Figure 2. Epicenter of August 24, 2014 Event, Shake Intensity Map, West Napa Fault (Dashed) and Surface Faults (Green) and Water Storage Tanks (Blue)[1].

EMERGENCY RESPONSE

Day 1

Water management staff reported to the EOC and started a running list of water outages reported to the dispatch call center. Within hours, it was clear the water distribution system was experiencing many breaks. Water staff transferred to the corporation yard from where maintenance staff and heavy equipment are deployed. A Departmental Operations Center (DOC) was convened and a satellite dispatch center was created to receive calls for water system issues.

By 0900 there were over 60 water main leaks reported. Staff logged the locations, dispatched Napa water distribution crews and started to make repairs. The calls continued successively through the day. Field staff were divided into pre-determined emergency operation groupings of A and B shifts to prepare for 12-hour shifts and insure 24-hour operations. It should be noted that in a typical year Napa experiences between 70 and 110 leaks on its pipe network. For a system composed of 350 miles of pipe, 105 breaks are typical per annum of 3 breaks per 100 miles [2]. As the number of reported breaks topped 60 and the phone continued to ring indicating more reports of damage, local contractors were contacted to assist with the response. Four local contractors were contacted to assist with the response including three contractors under pre-existing contracts for assistance with emergency repairs. Leak repair crews were deployed and treatment plant flows were increased. Treated water production sustained 38 MGD or nearly twice the normal demands expected in the system. All efforts focused on maintaining system pressures and feeding the leaks to protect drinking water quality, avoid depressurization and potential backflow into the system.

Napa staff ordered fuel tanks for the Corporate Yard to avoid the need for refueling response vehicles at public gas stations. Other staff were assigned to build potable water stations and install them at hydrants in public parks for customers while repairs were made and service reinstated. Staff ordered hundreds of sets of repair kits including clamps, restraining joints, and pipe segments to increase inventory that would quickly be diminished.

CalWARN is the California Water/Wastewater Agency Response Network, a mutual aid and assistance agreement designed to help jurisdictions respond to incidents that require resources beyond the capability of the local utility [3]. The CalWARN Agreement identifies the administration of the program, describes how to request assistance, and describes response coordination and cost reimbursement. CalWARN members reached out to Napa water management staff within one hour of the event. Amongst prioritization of the initial response and upon receipt of damage assessment reports Napa requested five (5) Type III water distribution system repair teams that are fully equipped with heavy equipment, materials, and skilled labor to assist with the response. Napa prepared to receive and deploy the mutual aid teams including preparation of information packets including maps of staging and deployment locations, emergency incident (hospital) response centers, repair sites, as well as food, lodging, shuttles, fuel cards, and contact phone numbers. CalWARN crews were scheduled to arrive at 1100 on Day 2 after the incident, August 25, 2014. In addition to CalWARN, local municipalities within the County of Napa have pre-existing contracts to provide mutual aid services and after confirming their system status was normal, offered assistance.

Napa water management communicated with the State Division of Drinking Water (DDW) daily to discuss status. DDW was preparing to issue a systemwide boil water notice until staff assured them this was not necessary. Many regions and pressure zones of the system were unaffected by the event and system pressures remained high due to efforts to increase treatment plant production, maintain outward pressure on leaks, and make sure water quality was not compromised. Napa and DDW agreed that communication of a precautionary boil water notice to customers who live within an area that was depressurized to facilitate a water main repair. Napa staff hung individual door tags to notify customers when the 48-hour bacteriological analyses confirmed the water is safe.

Day 2

At the start of Day 2 of the event, 10 leaks were repaired, and 90 leaks were confirmed in need of repair. Organization and deployment of mutual aid is critical to an effective operation. Napa water managers quickly established that Napa crews would be most effective as facilitators of system locations, system operations including closing valves and insuring leaks are properly isolated, keeping a steady supply of repair parts as appropriate according to the existing pipe material and size, advising as to local knowledge of pipe alignment and depth, and documenting the number of customer services that were within the shutdown area so they can be notified of the end of the precautionary boil water notice.

Contractors were organized by existing staff to assist with traffic control, haul materials to the site for backfill, haul spoils from the site or haul trench plates to the site as a temporary measure to secure the roadway. Napa staff and local mutual aid crews were directed to perform flushing operations, take water quality samples to the water treatment plant laboratory for bacteriological testing. By organizing the outside assistance in concert with the knowledge of Napa staff, CalWARN repair crews were able to stay focused on excavating and repairing leaks while the forward team prepared the site prior to arrival and the follow-up teams completed the site restoration and sample confirmation. Figure 3 shows the workflow and responsibilities of the teams.

As is commonplace for all emergency response actions where reimbursement funding is sought, documentation of work performed is vital. All crews logged their time, job locations, materials and vehicles used in their efforts. Timesheets were set up at the start of each work day and secured at the end of each work day with each individual signing in and out with a timed log.

Day 3

At the start of the third day there were a total of 120 leaks confirmed and two additional CalWARN Type III water distribution repair teams were ordered to join the effort. By the end of Day 3 the treatment plant production had reduced from 38 MGD to 29 MGD and it was apparent that the distribution was starting to return to normal even though 14 additional new leaks were reported that day. In many locations one leak would be repaired, and nearly backfilled, only to identify another leak just fifteen to fifty feet away within the same segment of pipe that was depressurized to facilitate repairs. In one western area of town there were 17 breaks within just a few city blocks. Nonetheless
the goal was set to release CalWARN and Mutual Aid crews by Day 6, Friday, and the start of the Labor Day holiday weekend.

Days 4-6

Production of leak repairs continued in a coordinated manner and CalWARN and mutual aid crews were sent home on Friday. By the end of day six over 120 leaks were repaired with just a few additional distribution leaks continuing to show through the weekend. The on-call customer service workers were busy for several additional weeks responding to customer calls for shut-offs and turn-ons so customers could repair private service lines. The system returned to normal customer demands

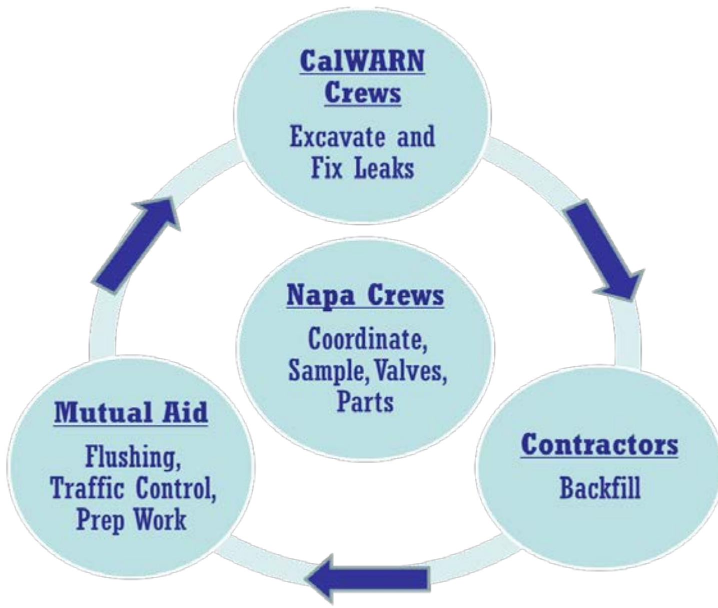

Figure 3. Sequence of Work and Responsibility of Napa Staff and Mutual Aid [1].

of 20 MGD. All samples proved safe and passed the bacteriological testing, proving the pre-cautionary notice was just that, pre-cautionary.

CONCLUSION

Throughout the response period several important lessons were learned. First and foremost, there is no substitute for preparedness. Each event will be unique in nature. Protocols in place for staff to report to work after securing their homes and families, and establishment of an Emergency Operations Center saves valuable time in the wake of uncertainty. Pre-existing contracts for mutual aid and the highly responsive network of CalWARN was very important to make the response as expedient as possible and reinstate water service to customers. Preparation to receive mutual assistance requires significant logistics to provide food, lodging and local transportation for the crews that have traveled to provide assistance. Administrative processes need to be in place to insure documentation of aid received including labor, materials, vehicles and all resources consumed, as well as photo documentation of the work performed.

Damage assessment in the initial hours after the event is critical to organizing the level of required response. Channeling customer calls to one appropriately sized call center, documenting the information in one central database, and gathering sufficient information from the customer is important to identify duplicate reports of leak locations. Documenting the address, logging the time the call was received, time repair crews dispatched to make the repair, identification of property damage, and time repair completed is critical to prioritize response efforts. Napa staff worked 24-hour shifts to receive calls and to field verify the information reported from customers. Assigning field verification staff to geographic regions is key to efficient reporting and confirmation of status.

Logistics of the production process was greatly assisted by mapping repair sites in order to identify staging areas for backfill material and dump locations for asphalt and trench spoils to reduce travel time and prioritize system repairs. Communication protocols are critical to every emergency situation. A central clearing house for reports from the field populated in databases and maps insure continuity across shift changes and accessible, reliable data to decision makers. Communication of accurate information to regulators and other emergency responders allow the proper identification of need and allocation of resources for an organized and effective response. Control of information released to the media and the public insure confidence. Napa established press conferences twice daily to report on work completed and outstanding.

This report focused on the immediate response to the South Napa Earthquake and the initial impacts to the water system. Fortunately, the damage was limited to the pipe network, predominantly on the west side of the system as well as one storage tank while the supply sources (dams) and treatment plants were not compromised by the seismic event. However, during the six months following the event, the water system experienced an additional 120 breaks through the period. Repairs were performed by Napa staff with no outside assistance. Approximately ten weeks after the initial event, the 36-inch asbestos cement transmission main developed three simultaneous leaks at concrete collars joining pipe segments compromising the flow of water to isolated regions where only local distribution pipes were available to convey reduced volumes to customers. The repairs were made with the assistance of local contractors to restore normal service.

In the end, customers were understanding of the event, appreciative of the coordinated response, and patient while they recovered from the event. Napa staff learned a lot through the event and found that the professional water network and community really comes together in time of need.

ACKNOWLEDGEMENTS

The City of Napa Water Division is grateful for the immediate responsiveness, support and assistance from the following groups: contractors - Atlas Peak, GD Nielson, Hess, Northern Pacific, Commercial Power Sweep, the Barricade Company and V. Dolan Trucking; CalWARN - leaders Steve Dennis and Ray Riordan, leaders, managers and hard-working crews from Alameda County and Contra Costa Water Districts, East Bay Municipal Water District and City of Fairfield; neighboring Cities of American Canyon, Benicia, Calistoga and St Helena, Town of Yountville, Napa County, Napa Sanitation District and North Marin Water District. It was a team effort and the resources available allowed for swift action and minimal downtime for water customers.

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Application of Road Excavation Management System for Seismic Disaster Preparedness

Chun-Cheng Chen and Tin-Lai Lee

ABSTRACT

Tainan City has 37 administrative districts and an area of 2,192 km^2, including 750,000 manhole, 49 pipeline authorities and total underground pipeline length of 36,000 km. To effectively integrate, manage the pipelines and prevent disasters from happening, Tainan City Government not only has installed public utility database and road excavation management system, but also has actively developed earthquake disaster prevention evaluation system and other surplus applicative functions. In response to the digital trend, the system has been transform from computer system management into mobile management and various mobile device application functions. It wielded actual effects on the February 6th earthquake of 2016, in which it provided disaster relief information within a short period of time so that underground pipeline problems can be handled precisely to prevent secondary disasters and enhance efficiency greatly.

Keywords: public utility database, mobility management, disaster prevention, earthquake.

1. Introduction

Tainan city with a size of about 2,192 $m^2$and has a population of 1.88 million. There is a total of 49 pipeline management agencies that maintain about 750,000 utility manholes and over 30,600 kilometers of pipelines that include a number of hazardous pipeline systems for high voltage electricity, natural gas, and oil within the city's jurisdiction. Maps and data for these utility pipelines were mostly independently established and maintained by the respective agencies. However, the power and responsibility of supervision and management of these pipelines were distributed amongst various agencies instead of being integrated under a single standard due to the requirements of Taiwan's laws and regulations, leading to tough management issues during integration, supervision, and disaster prevention.

Tainan city is also a high-risk compound disaster area and local residents have dealt with threats stemming from multiple natural and man-made disasters for a very long time. Utility pipelines also face similar threats from these disasters as well. A most recent example would be the February 6th, 2016 magnitude 6.3 earthquake (hereinafter referred to as the "0206 Earthquake"), which had a maximum intensity rating of VII. The damages resulted in power outages for over 170,000 households and water outages for over 400,000 households in the city, and showed that damages to utility pipelines would be unavoidable during earthquakes.

According to the survey of the Central Geological Bureau indicated that there were 6 active faults in Tainan, 3 of first-type fault and 3 of second-type, giving the city the highest number and density of faults for any county and city in Taiwan. We can foresee a very high earthquake hazard potential. Realizing that, Tainan City Government takes actions to manage public utilities pipelines with the concept for disaster prevention and began to study how to make public utilities pipeline information available for disaster relief applications. There are four topics for public utility database management system (Figure 1):

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Tin-Lai Lee, Director, Sixth Branch Office, Taiwan Water Corporation

Fig.1 Topics for public utility database management system in Tainan City

2. Development and applications of Public Utility Database Management System

In order to develop disaster prevention functions for its utility pipelines, Tainan City developed management system with following features:

2.1 Pipeline maps accessible anywhere

The cell phone APP could be used to quickly retrieve the maps and information of pipelines located within 200 meters of the cell phone location (Fig.2). During disaster prevention, frontline personnel could employ the APP to immediately acquire information and distribution of underground pipelines without flipping through printed maps or performing on-site excavation. During the 0206 Earthquake disaster rescue operations, rescue personnel were able to access and peruse pipeline layouts around disaster sites promptly to determine the location of hazardous pipelines and to notify relevant pipeline agencies to activate emergency responses and standby at the site. This solution not only improved disaster rescue efficiency, but also reduced the incidence of secondary disasters that may be caused by hazardous pipelines.

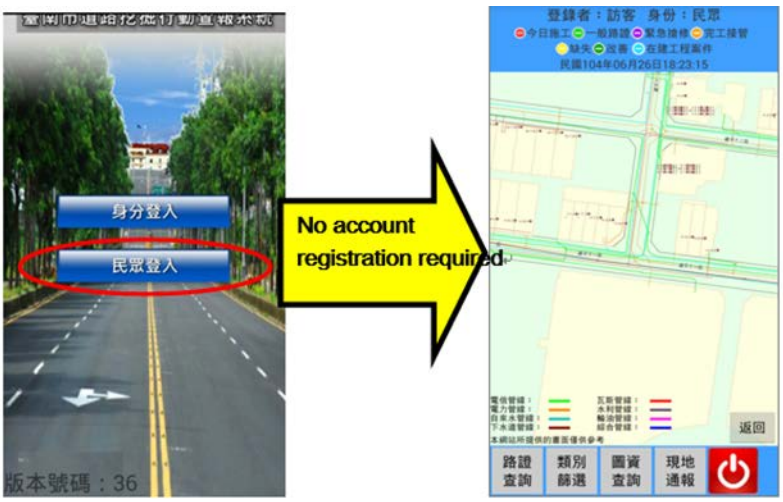

Fig.2 APP for Public Utility Database Management System

2.2 Preliminary review of disaster potential

Worked with the Disaster Prevention Research Center (DPRC) of National Cheng Kung University (NCKU) to develop the Earthquake and Disaster Prevention Evaluation System and established earthquake simulation data for the 6 fault zones in Tainan City. An example would be the analysis of the Houjia Village Fault (Fig. 3). Subsequent studies helped to demonstrate how pipelines of different materials, diameters and age would sustain the shock during earthquakes to identify areas that may be affected more severely during disasters. Taiwan Water Corporation would then be recommended to initiate preventive measures to improve the safety of water supply systems.

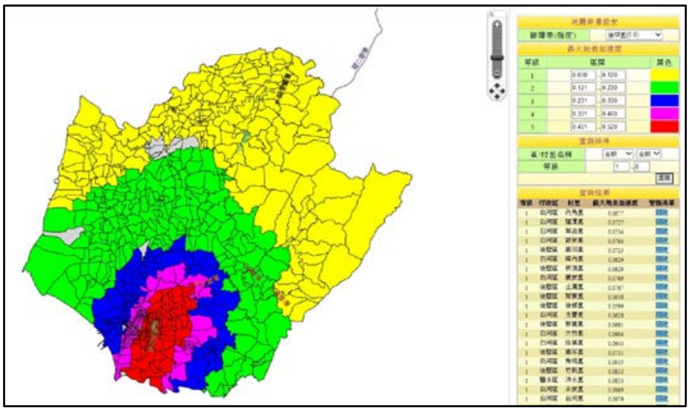

Fig. 3 Earthquake simulation of the Houjia Village Fault

2.3 Exposing all hazardous pipelines

When applying for road excavation works, the areas around the excavation site must be verified by the utilities to identify any hazardous pipelines. The road excavation management system was required to display the hazardous pipelines map layer so that these pipelines could be avoided during construction to prevent any dangers (Fig. 4). The system will also provide a reminder if the excavation area includes military pipelines.

Fig.4 Searching for hazardous pipelines close to the excavation site

2.4 Active reminders to prevent damaging excavation works

When public utilities carry out their construction and excavation works , the system will automatically overlay the zones with the hazardous pipeline map as shown in Fig. 5, allowing the utility easily to study their excavation area when overlapped with natural gas pipelines and reminds them to take special precautions during the actual excavation procedure.

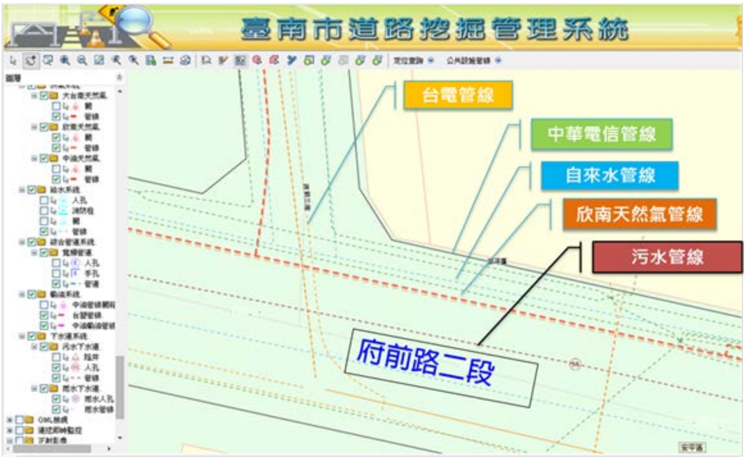

Fig.5 System overlaps the road excavation with different utilities pipeline

2.5 Establishing SOPs for emergency rescue and repairs of damaged pipelines

Disaster prevention and rescue processes have been defined using SOPs in order to ensure that every worker have general familiarity with the tasks they were supposed to handle during disaster prevention and rescue operations. Those who lack familiarity may reference workflows and guidelines to complete their tasks.

During the 0206 Earthquake, the collapse of the Weiguan building damaged a major water transmission line, cutting off water supply to more than half of the Tainan City. The rescuing process was handled according to the SOP shown in Fig.6.

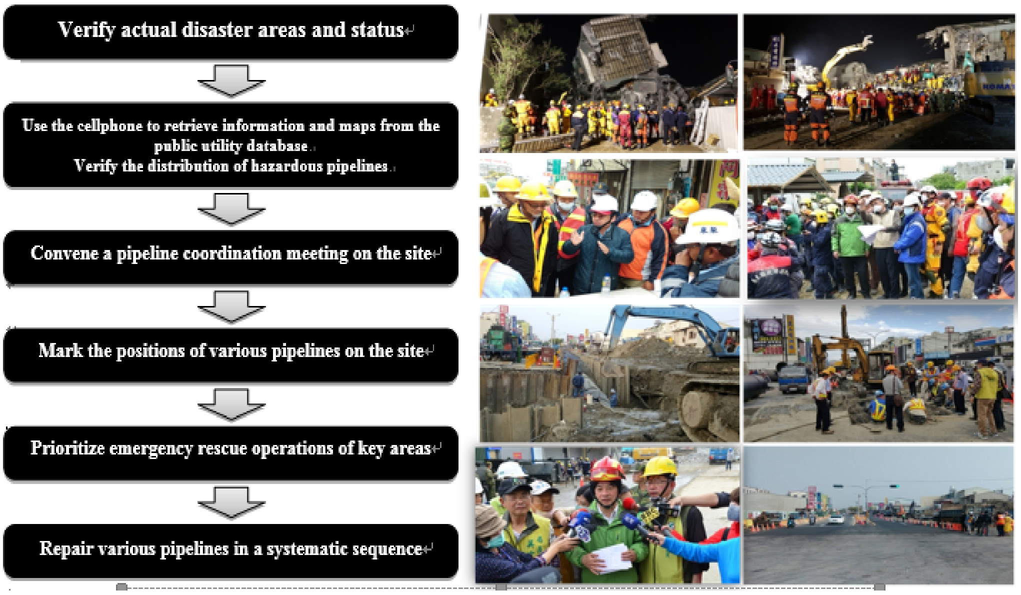

Fig6 SOP for the emergency rescue and repairs of damaged pipelines

3. Conclusion

The Tainan City Government has invested a great deal of effort in establishing the public utility database and developed many innovative and practical functions to improve the standards and safety of utilities' pipeline services.

After the 0206 Earthquake, Tainan City continued to uphold the principle of prevention is better than rescue, and avoidance is better than prevention and developed many of Taiwan's first innovative applications in these areas. The solution provided integrations with the aim of preventing disasters before they occur and mitigating the impact when they do. The database system and cell phone APP were used in actual frontline rescue operations of the 0206 Earthquake, and demonstrated their abilities in quickly providing information needed by disaster rescue operations, helping to mitigate the impact of the disaster and avoid the incidence of subsequent secondary disasters.

Tainan City Government shall continue to cooperate with public utilities to build upon this experience of success to maximize public benefits and welfare and establish Tainan City as a safe, livable, and healthy city for the people.

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Concept of Waterworks in Disaster Relief based on the 2016 Kumamoto Earthquake

Yosuke Uno, Hiroto Sano, Haruko Kakita

ABSTRACT

In the occurrence of the 2016 Kumamoto Earthquake , Osaka Municipal Waterworks Bureau had sent the cumulative total of 42 staff to the affected area in five cycles for one month in which the 1st batch was sent on 16th April, the day of receiving request from Relief Headquarter, until the final 5th batch returned Osaka on 14th May to implement three supporting activities, emergency water supply, emergency restoration and back up support. We reported our performance of supporting activities during the dispatch period and the background of completion of those activities. Based on the experience of the 2016 Kumamoto Earthquake, Osaka Municipal Waterworks Bureau has drawn up the guideline, serving as a road map of supporting activities in case that a large-scale disaster occurs at other cities. This guideline has intended to implement prompt and effective supporting activities when large-scale disaster occurs somewhere in Japan in the future. At the end of this report, we introduce the construction of accepting support plan from waterworks entities of other cities when disaster hits Osaka along with Business Continuity Plan of Osaka Municipal Waterworks Bureau (BCP) that we're currently revising.

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PREFACE

The 2016 Kumamoto earthquake recorded on the Japanese seven-stage seismic scale, which damaged not only human and property but also the waterworks system enormously. In Kumamoto City, located near the epicenter, all households underwent water suspension temporarily. Since The East Great Japan Earthquake, preparation is being re-assessed all over in Japan for anticipated heavy damage or widespread disaster, such as Nankai Trough earthquake and earthquake centered directly under the capital etc. The 2016 Kumamoto Earthquake reminds us that a large-scale earthquake can possibly occurs anywhere in Japan. In this paper, we report on three points; the concept of supporting activities of Osaka Municipal Waterworks Bureau at the affected area in the 2016 Kumamoto earthquake, construction of support system in preparation for large disaster based on the issues arising from the supporting activities this time and construction of system of accepting support in case that we suffer from a disaster and are in a position of accepting support.

OCCURRENCE OF KUMAMOTO EARTHQUAKE

On 14th and 16th April 2016, the inland earthquake, the epicenter of Kumamoto region with the intensity of 7 struck Kumamoto area. It caused enormous damage extensively in Kumamoto city and to its near areas. In Kumamoto City, out of 96 water sources (wells) in service, 69 was disrupted due to increase of the turbidity by foreshock on 14th April, resulting in water suspension for 85,000 households. Furthermore, all 96 water sources were disrupted, resulting in water suspension for all households, 326,000 approximately due to main shock in 16th April. In responding to the foreshock on 14th April, Relief Headquarter of Japan Waterworks Association (hereafter, referred as the Relief Headquarter) was established under the initiative of JWWA consisting of water suppliers and private companies across the nation. In the morning of main shock occurrence on 16th April, the Relief Headquarter requested Kansai regional chapter of JWWA for the support to Kumamoto city. (Figure 1) The flow of this support request is based on "Guideline for Response to Earthquakes and other Emergencies", revised in March 2013. In responding to the request, Osaka city, the head of Kansai regional chapter of JWWA, and six entities belonging to Kansai regional chapter dispatched support team.

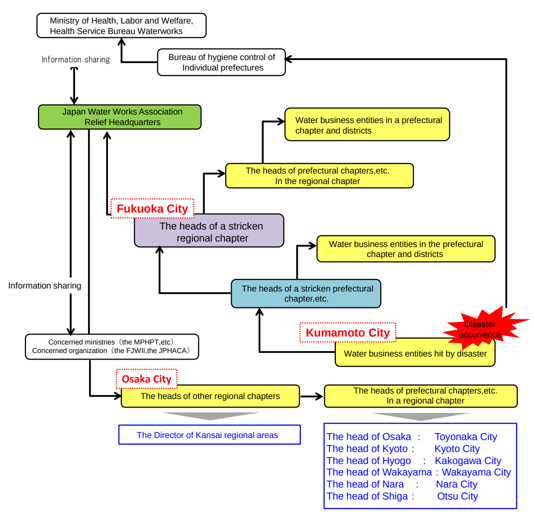

Figure 1.Flow of support request

OUTLINE OF SUPPORTER ACTIVITIES

Emergency Water Supply Team

(1) Role of Emergency Water Supply Team

Emergency water supply point was opened at 33 places maximum in five districts including, Higashi, Nishi, Minami, Kita and Chuo districts. Also the support team, cumulative total of 4,286 personnel from 97 water suppliers implemented supporting activities with the cumulative total of 1,027 water tank trucks. The 1st, 3rd and 4th batches of Osaka City implemented emergency water supporting activities, delivering water to 6 points in Higashi district and each emergency water service point with two water tank trucks (four tons each). Particularly, 4 ton of emergency water tank truck owned by Osaka City was larger than any trucks provided by other cities. It equipped with pressure function and served as supply vehicle, which contributing smooth emergency water supply implementation.

(2) Constituent of Emergency Water Supply Team

<Dispatch period>
16th April 2016 to 6th May 2016 (21 days)
Active period
17th April 2016 to 2nd May 2016 (16 days)

<Headcount>
1st batch: 7 persons
3rd batch: 6 persons
4th batch: 6 persons Total 19 persons

(3) Performance of Emergency water supply of Osaka City

The performance of supporting activities by Osaka Municipal Waterworks Bureau is as below

TABLE 1.PERFORMANCE OF EMERGENCY WATER SUUPLY

	1st batch	3rd batch	4th batch	Total
Cumulative total person	42	48	12	102
Emergency water supply (ton)	95	26	2	123
Cumulative total emergency water supply points	16	8	2	26

Emergency Water Restoration Team

(1) Role of Emergency Water Restoration Team

Emergency restoration activities were conducted from 17th April to 17th May. In Kengun and Akita water distribution areas, the main water distribution area, leak detection activities and leakages that had been found out by leak detection activities were restored.
Leak detection work was conducted by the support team consisting of the cumulative total of 313 staff from 19 waterworks suppliers across the country. In addition, leak restoration work was conducted by 75 construction companies as well as cumulative total of 5,216 personnel from 54 waterworks entities
The 2nd, 4th and 5th batches of Osaka City implemented emergency restoration activities. Kengun and Akita water distribution areas were divided into 17 blocks, Kansai regional branch was assigned for 4 out of 17 blocks. Among those, Osaka city was responsible for 1 block that covers Chuo and Higashi districts, conducting water leak detection, as well as leakage restoration work for distribution pipes and service pipes in collaboration with the construction companies

dispatched from Osaka city.

(2) Constituent of Emergency restoration team

<Dispatch term>
21st April 2016 to 14th May 2016 (24 days)
Action period
22nd April 2016 to 13th May 2016 (22 days)

<Headcount>
2nd batch: 3 persons
4th batch: 3 persons
5th batch: 3 persons Total 9 or persons

(3) Performance of emergency water supply activity

The performance of supporting activities by Osaka Municipal Waterworks Bureau is as below

TABLE 2. PERFORMANCE OF EMERGENCY RESTORATION ACTIVITIES

Leak detection	Road surface inspection (Visual inspection)	0.78km2	22nd to 24th April
	Door to door inspection	Total number of inspection ・2.231 Leak detected ・34	25th April to 13th May
Leak restoration	Direct management or construction company	35	28th to 13th May

On-site Headquarter

(1) Role of on-site Headquarter as Logistics Support of Emergency Water Supply

On-site Headquarter of Osaka City was stationed in Kumamoto Water and Sewage Bureau office. The leader attended a meeting held by Kumamoto Water and Sewage Bureau to learn the progress of emergency water supply activities and collect necessary information for implementing activities. In addition, Osaka City was assigned as the leader of Higashi district along with Nagoya City, comprehending the volume of emergency supply water, developing the deployment schedule of emergency water supply trucks and taking initiative for other support team in Higashi district.

(2) Role of the on-site Headquarter as Logistics Supporter of Emergency Water Restoration

Since it was difficult for Kumamoto Water and Sewerage Bureau to set up the system as affected area, they could not be involved in the overall instruction for the emergency restoration activities. Thus, in accordance with the agreement of time of disaster (Memorandum of mutual support for disaster by the waterworks bureaus of 19) signed by 19 government-designated cities in Japan, Emergency restoration headquarter was established by Fukuoka City, the primary city for aid, and JWWA. Beneath that, six sub-teams were established independently (Figure 2).

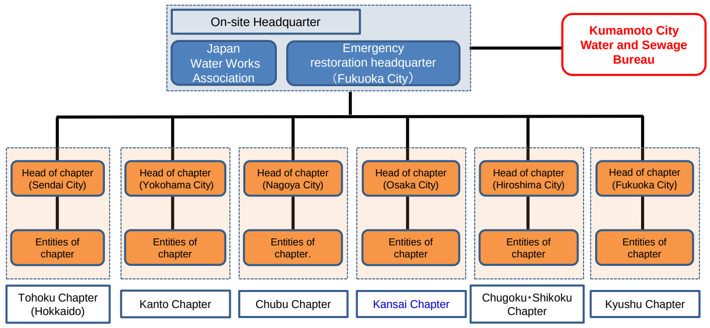

Figure 2 .On-site organization chart of emergency restoration

As the director of Kansai regional branch, on-site headquarter team of the Osaka City attended meeting every morning to comprehend the progress of emergency restoration activities and collect information and share the information within the branch. Also, in order to proceed with water leak detection and leak restoration activities in the assigned areas, we managed the leakage locations and restored areas by describing in a report and took initiative for other entities within the branch.

(3) Role of on-site Headquarter within the Support Team of Osaka City

On-site headquarter reported the activities performed by Osaka Municipal Waterworks Bureau and requested the commodities for implementing activities to Osaka Municipal Waterworks Bureau by 8 O'clock every morning. Also, payment control for procurement of requisite items, accommodation fee, petrol fee, etc., attendance management of staff were conducted by the headquarter.

Completion of Supporter Activities

(1) Withdrawal of Emergency Water Support Team

Since the occurrence of earthquake, the leak detection and leakage restoration effort was given by Kumamoto City and the support teams including Osaka City. As a result, leakage volume was decreased in two weeks and distribution amount was reduced. On the other hand, water pressure started increasing at the furthermost area from the water source, indicating improvement of water supply condition. (Figure 3)
In line with the trend, Kumamoto City had suggested reduction of support in the afternoon of 28th April, and then stated that water supply system had been restored in the entire of the city on 30th April.
In responding to the statement, Osaka City released emergency water supply team on 2nd May. After 2nd May, the work had been handled by Kumamoto Waterworks and Sewerage Bureau and Kyushu Branch of Japan Waterworks Association, and emergency water supply activities were finally completed on 6th May.

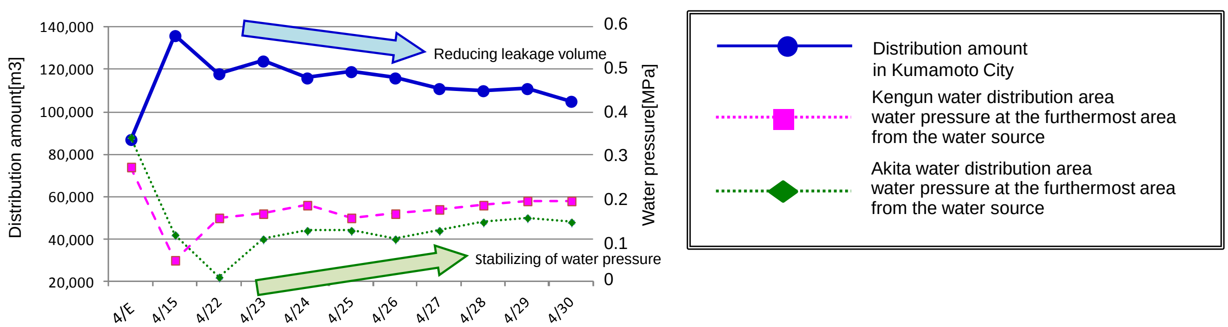

Figure 3. Distribution amount and water pressure at the furthermost area from the water source (Early April to 30th April)

(2) Withdrawal of Emergency Restoration Team and on-site Headquarter

After that, water supply volume has been decreased due to the effort of leak detection and leak restoration by Kumamoto City and support teams. The water pressure of the furthermost area from the water source indicated 0.20MPa. Kumamoto City suggested reduction of emergency restoration system because water supply condition had restored to the same level as before the disaster. Next day 6th May, Relief Headquarter officially announced reduction of support system. Each support team shifted to withdrawal. Then, the emergency restoration activities by support team were finally completed as of 17th May. For withdrawal, Osaka City was committed for completing the restoration service on the leakages detected at the area in charge as the director of Kansai regional branch and handing it over to Kumamoto City. On 13th May, we completed all restoration works and withdrew the support team next day, 14th May.

GUIDELINE OF SUPPORTER DISPATCH OF OSAKA MUNICIPLE WATERWORKS BUREAU

Background of Developing of Supporter Dispatch Guideline

At the time of large scale disaster, it is important to construct the system to confront danger under the coordination with relevant institutions. Although Osaka Municipal Waterworks Bureau had given support for the 2016 Kumamoto Earthquake and the Great East Japan Earthquake in 2011, the detailed support system for the city outside Osaka was not decided. For this, some confusion occurred to initial response from receiving support request directly after the outbreak of earthquake to dispatching support, which became the issue we had to improve. Based on the lesson and knowledge acquired through the experience of support implementation, we have drawn up "Guideline for dispatching supporter of Osaka Municipal Waterworks Bureau" (hereafter referred as the Guideline) that designates the standard behavior about supporter dispatch system and assignation of administration work for implementing supporter dispatch to the areas outside Osaka City.

Outline and Structure of the Supporter Dispatch Guideline

To develop the Guideline, we heard the opinion of our staff who had implemented on-site supporting activities. We considered that the opinion and knowledge based on on-site experience is the key for creating practical guideline. As a result of hearing, we found the points to be improved as below;

- Support system
  Clarify a flow from the occurrence of disaster to deciding support within in-house organization
- Document (Report formant for sharing information within the site)
- Preparation including equipment (Itemizing the equipments to be brought with supporter dispatch and staff in-charge of procurement for those items)

Based on those opinions, we summarized the details of support system, documents and list of equipment etc. in the guideline.

Collecting Disaster Information, Emergency Assembly, Contact and Coordination

As for disaster occurrence information, each action, from information gathering by each staff for the intensity, epicenter and initial damage status through radio or television, etc., to implementing supporter dispatch is extracted (Figure 4).

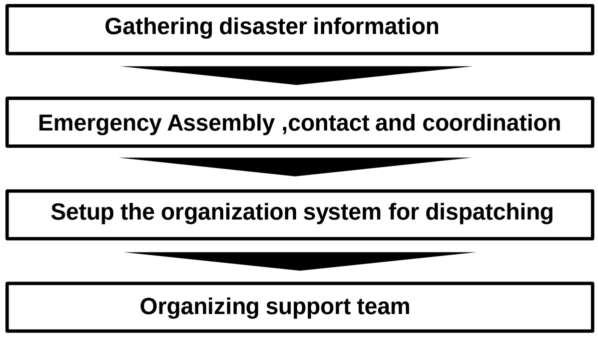

Figure 4.Flow of dispatch support of Osaka Municipal Waterworks Bureau

As a step for developing organization of dispatching support, it is necessary to collect information of damage of water systems at the affected entities, the condition of emergency assembly was added in case of the occurrence of disaster on holiday or off-duty time. (Table 3)

TABLE 3. NECESSARY CONDITIONS FOR ASSEMBLING
(HOLIDAY AND OFF-DUTY)

Place of occurrence	The necessary conditions for assembling
○Kansai region 6 prefectures (Osaka, Kyoto, Hyogo, Nara, Shiga, Wakayama) ※In case of Osaka City being affected, Kobe City Is included as the primary support city.	Intensity lower 5 or more
○Fukuoka City （Secondary support city in case of Osaka being affected)	
○ Other prefectures	Intensity upper 6 or more

Based on this condition, emergency assembly members (TABLE 4) gather in Osaka Municipal Waterworks Bureau office, they coordinate with the affected waterworks entity or other cities that back up the affected waterworks entity for confirming the damage status and support request as appropriate.

TABLE 4.ASSEMBLING MEMBERS IN EMERGENCY
(HOLIDAY AND OFF-DUTY)

assembling members in emergency
Manager for General Affairs Department Manager for Emergency Management Assistant manager for Emergency Management Administrative Staff for General Affairs Department Staff for Emergency Management

Developing Systems for Dispatching Support

In case of being requested for dispatching support, we set up the Aid Headquarter and decide operation method. Aid Headquarter is positioned as an in-house organization so as to determine the system of dispatching support. We have sorted out the constituent members including the director of Waterworks Bureau, as chief of Aid headquarter, and secretary office. Along with this, the work description of coordinator and logistics support is summarized and the responsibility of each related section is clarified, making it possible for smooth action when dispatching support. (TABLE 5, 6)

<Contact and coordination>
Coordination is implemented by General affairs Department, mainly collecting disaster information of affected waterworks entity and serving as a contact with the related institutions.

TABLE 5. IN CHARGE OF CONTACT AND COORDINATION

Work description（According to the timeline after the occurrence)
○ Collecting and integrating basic information about affected entity (Receiving support request from the affected entity)
○ Setting up and running Aid Headquarter
○ Providing information to General manager of Head Office, staff of Head Office
○ Providing information to the media
○ Reservation of accommodation and transportation for dispatching support
○ Itemizing the commodities and goods to be brought with support dispatch
○ Information sharing with support team members
○ Arrange the expense claim for dispatching support

<Back up support>
Each procurement team arranges the personnel and materials required for emergency water supply, emergency restoration activities and on-site headquarter activities.

TABLE 6. IN CHARGE OF BACK UP SUPPORT

In charge of procurement	Work description
Related Department	○ Arrangement of the personnel of support team
Water Distribution/ Water Service Installation department	○ Arrangement of the vendors for emergency restoration
Emergency management Section, General Affairs Department	○ Arrangement of uniform (disaster prevention cloth) ○ Arrangement of emblem for dispatch support vehicle (stickers, banners) ○ Arrangement of stationaries for on-site activities ○ Arrangement of requisite supplies for life and hygiene
ICT Promotion Department	○ Setting of information sharing tools (Google account) ○ Arrangement Personal Digital Assistance (Portable PC, Smart phone)
General Affairs/ Accounting Department	○ Arrangement of funds required for support activities
Personnel Department (Training/Welfare)	○ Arrangement of spare uniforms and rain gears for support team members ○ Arrangement of foods, etc. ○ Arrangement of medical supplies, first aid kit, etc.
Waterworks Maintenance Center	○ Arrangement of vehicles to dispatch (Chief car, Emergency water supply truck) ○ Arrangement of emergency water supply material (Emergency water supply bag, temporary water tap) ○ Arrangement of emergency restoration materials (leak detector, leak sound detection bar)

Organizing the support system

Next, we developed a basic framework of support team to be dispatched.

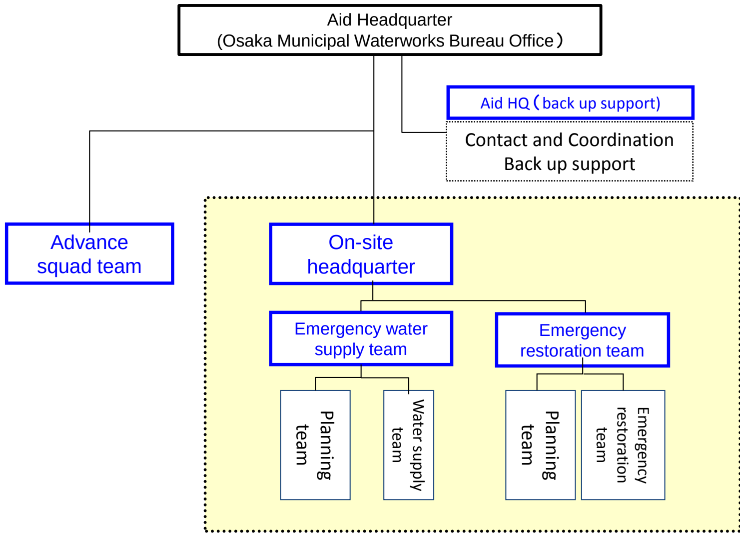

Figure 5. Standard organization of support team

Although Aid Headquarter will decide the scale of each team and its constituent members considering the detail of support request and damage status, etc., the guideline for each team is standardized based on the dispatch activities in the past. (TABLE 7)

TABLE 7.RESPONSIBILITY OF EACH TEAM AND CONSTITUENT MEMBERS

Formation of support team		Responsibilities	Head counts
Advance squad team		・Secure (select) the transportation route to the affected area ・Gather information of affected area （Disaster status, water suspension and restoration progress and prospect) ・Set up on-site operation headquarter ・Secure the operation site (including accommodation) ・Contact and coordination with affected area and comprehend the requisite support	Per team 2 or more members
On-site headquarter		・Comprehend the disaster situation ・Contact and coordination with Aid HQ (Osaka) and report the progress ・Contact and coordination with related institution on site ・Coordination with authoritative support team and integration of information ・Develop the emergency supply water plan and restoration plan ・Back up support of each team (select and procure the requisite goods) ・Contact and coordination as Director of Kansai regional area of JWWA	Per team Leader: 1 Member: 2 or more (including sub-leader)
Emergency water supply team		・Take command at site, Report the progress of emergency water supply team (early stage of support)	Per team (2 emergency water tank trucks) Member: 4 or more
	Planning team	・Take command at site, Report the progress of on-site operation status ・Develop the emergency water supply plan ・Gather necessary information for emergency water supply plan / contact and coordination ・Manage and integration of claim and request from the users	
	Emergency water supply team	・Emergency water supply activities and water supply activities at site	
Emergency restoration team		・Take command at site, Report the progress emergency restoration team (early stage of support）	Per team
	Planning team	・Planning of water suspension work	Leak detection: 3 or more
	Emergency restoration team	・Leak detection	
		・Supervise the contractors (Leak restoration work)	Supervise the contractor： 2 or more

Dispatch term

Furthermore, in case of large scale disaster, dispatch period is assumed to prolong, the idea of the term and rotation is sorted out based on the actual supporter dispatch.

Except the survey team dispatched immediately after the occurrence of disaster, the dispatch period of each team is short term (1 week to 10 days) as a rule, middle term (2 weeks approximately) at a maximum considering the on-site activities, accommodation status, and health condition of members.(TABLE8)

TABLE 8. DISPATCH PERIOD OF SUPPORT TEAM

Support team	Dispatch term
Advance	Several days
On-site headquarter	Short term (1 week to 10days) ～middle term (2 weeks approx.)
Emergency water supply	
Emergency restoration	

(1) The status in Kumamoto Earthquake in 2016

During one month of the support for the 2016 Kumamoto Earthquake, all members of support team were changed each time. In that case, when a handover took place in a day time, the advance team members could stay only for a short time as they had to go back to Osaka. As a result, only a short time could be spent on handover. On the other hand, in case of handover overnight, longer time could be spent, however as the number of people who stayed in accommodation became twice as much, reservation for accommodation was difficult.

(2) Solution

To solve this issue, the half of members are changed as a rule so that the members of newly-arrived batch can work on supporting activities while taking over from the advance team member, making it possible for smooth handover. In addition, sub-leader is assigned in each team so that he or she assists the leader of advance team while taking over from the leader, and in the late half period he or she takes over the position of leader at the timing of rotation, enabling smooth handover of operation of leader. Also, in order to exchange information effectively, it is important to arrange the rotation timing flexibly so as to avoid overlapping the rotation period with other waterworks entities as much as possible.

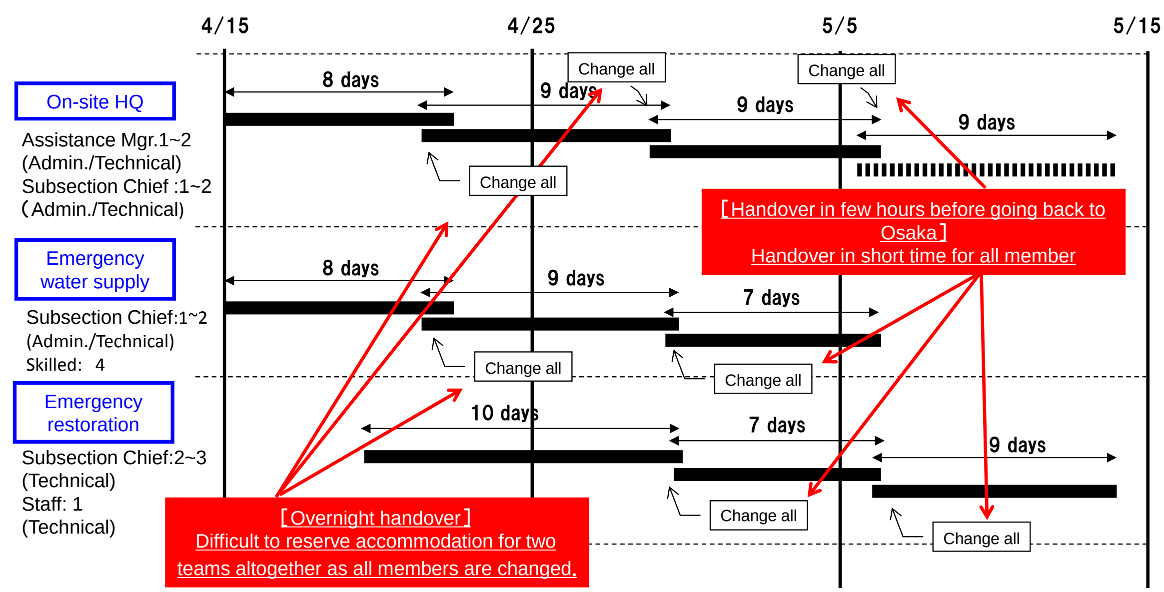

Figure 6. Supporter dispatch system for the 2016 Kumamoto Earthquake (change all members)

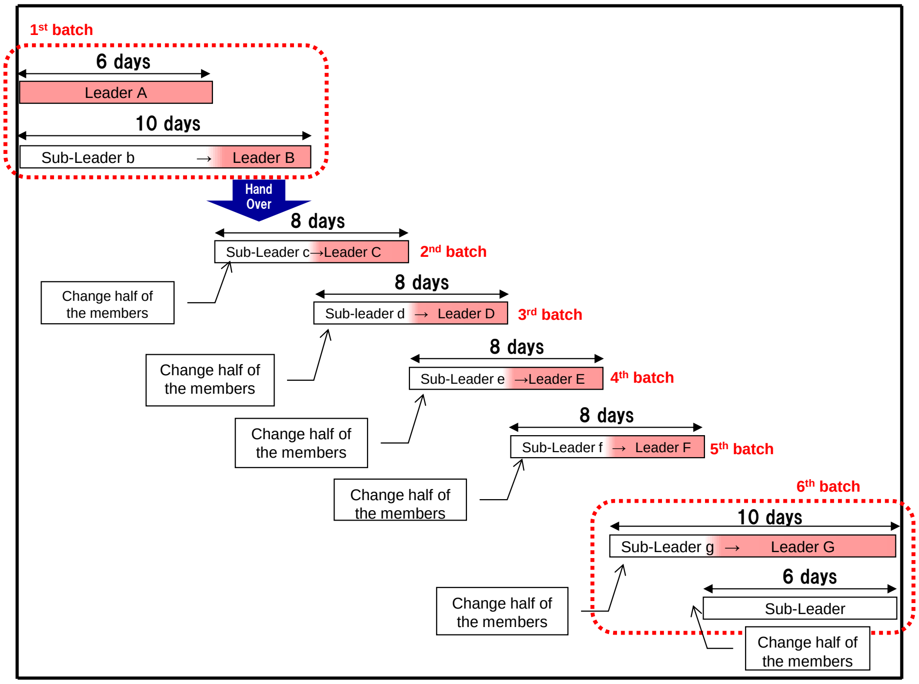

Figure 7. Image of changing half of the team members

CONCEPT OF ACCEPTING SUPPORT

With respect to the supporter dispatch, the guideline has been developed based on the experience in the past. On the other hand, the importance of accepting support is now being recognized in case that Osaka City suffers from disaster. In this chapter, we report on the Osaka Municipal Waterworks Bureau Business Continuity Plan (BCP).

Review of Business Continuity Plan (BCP) of Osaka Municipal Waterworks Bureau

(1) Circumstances of Osaka Municipal Waterworks Bureau Business Continuity Plan

Osaka Municipal Waterworks Bureau has determined the policy, system and procedure in Business Continuity Plan issued in 2010 in order to continue the key business or recover the business as quickly as possible even under the occurrence of large scale disaster such as earthquake. It has been developed based on the damage prediction for city-wide pipeline in 2005 to 2006 and the evaluation on influence of reducing water and water suspension in the city based on the prediction. However, it has been almost ten years since the prediction of city-wide pipeline damage and the survey on influence of reducing water or water suspension. Considering the fact that disaster beyond the prediction and complex disaster occurs in recent year, it is obvious that the data of 10 years behind does not keep up with the current situation.
The government has reviewed predicted immersion caused by river flood or tide in accordance with partial revision of Flood Control Act. In Osaka City, Nankai Trough earthquake was added for new anticipated earthquake, and possible disaster and damage is now being reviewed.
On the other hand, Osaka Municipal Waterworks Bureau has proceeding with enhancing the facilities such as earthquake resistance of water purification plants and pipelines, or expansion of main line network, development of service reservoir, etc. For constructing the system of accepting support of Osaka Municipal Waterworks Bureau in time of large-scale disaster, it is necessary to comprehend the possible damage upon re-evaluating the existing assumption of damage considering the change and progress of internal and external environments.

Estimation of Damage and Accepting Support System

(1) Estimation of the Volume of City-wide Pipelines Damage

First of all, it is planned to estimate the volume of damage of city-wide pipeline by predicting the ground motion and possibility of liquefaction considering the latest enhancement status such as earthquake resistance of pipelines and water purification plants. The number of damage of city-wide pipelines is estimated using a formula developed uniquely by Osaka Municipal Waterworks Bureau that can incorporate damage characteristics of both liquefied and non-liquefied grounds through the combined data of Great Hanshin and Awaji earthquake and the Great East Japan earthquake.

(2) Estimation of required team and instruments

Next, the number of team required for emergency restoration activities is estimated based on the assumed restoration progress considering the volume of damaged city-wide pipeline. To minimize the water suspension area, water supply plan is developed by calculating the number of team necessary for emergency water supply activities and the quantity of required instruments.
In times of great disaster, much manpower is required. Osaka Municipal Waterworks Bureau has signed thegreement of mutual anssistance with the waterworks entities of other cities, preparing for the shortage of human and material resources. For this, we have determined the number of teams and equipment which we can acquire by ourselves. Then, as for the shortage, we determine the number of team required for restoring normal water service within the restoration period defined for each predicted earthquake, provided that we accept the assistance such as personnel and instruments etc., under the agreement of mutual assistance with waterworks entities of other cities.

(3) Construction of Accepting Support System

As a preparation of accepting support team, we set up a single contact for accepting support, preparing message for support request (the scale of support, assembly place, etc.), facility for accepting support (hub for supporting activities after assembly, capacity of people as water facility, car parking, etc.), also for preparation of smooth emergency work activities after accepting, support accepting system (activities of support team, information providing for activities), record of support progress (develop a format for comprehending the restoration status),etc., which will be clarified as accepting support plan and reflected onto Business Continuity Plan.

CONCLUSION

The 2016Kumamoto Earthquake was the large-scale disaster that directly hits Kumamoto City, which is one of the government-designated cities in Japan.
After main shock, all households underwent water suspension and the city-wide pipelines were damaged. However, prompt restoration was conducted thanks to the numerous supports given from all over Japan, which showed the strong bond of waterworks industry. On the other hand, the supporting dispatch made us recognize the importance of setup of support system for the affected waterworks entity after the earthquake, in addition the importance of preparation for accepting support in case that we are in a position of being supported from waterworks entity of other cities. We consider it as our mission to make use of lesson and knowledge we learn from the dispatch supporting activities and construct the support and accepting support system.

Seismic Scenario Simulation of Water Supply Systems

Chin-Hsun Yeh[1], Gee-Yu Liu[2] and Hsiang-Yuan Hung[3]

ABSTRACT

Lack of water for a long time after disastrous earthquakes may cause severe inconvenience to the daily lives of people in the affected areas, not to mention fire-fighting, medical-care, sanitation, and so on. To reduce losses and disruption time, water companies and authorities may develop a seismic scenario simulation technology to assess various kinds of probable outcomes due to large earthquakes, such as the distribution of ground motion intensity, the extent of ground failures, the damage-state of facilities, the number of repairs in pipelines, the amount of water shortages, the number of households without potable water, the expected restoration time and losses due to damage of facilities and pipelines, etc. Countermeasures could be proposed and executed accordingly before earthquakes to enhance the preparedness or emergency response in an appropriate and timely manner. In this paper, a seismic scenario simulation technology developed by NCREE (the National Center for Research on Earthquake Engineering, Taiwan) was introduced. The ground motion intensity and the ground failure extent due to fault rupture or soil liquefaction were considered in the seismic hazard analysis model. The damage and loss assessment models of water facilities and pipelines have been proposed and used in the scenario simulation. The water outage in terms of reduction in daily supply and the number of households without potable water soon after the scenario earthquake were also output base on damage and loss-of-function assessment of facilities and pipelines. The coefficients of analysis models used in the scenario simulation technology were calibrated by the observations from the 1999 Chi-Chi earthquake; and they have been also verified by the 2016 Meinong earthquake.

OVERVIEW OF SEISMIC SCENARIO SIMULATIONS

Generally speaking, seismic scenario simulation technology is to estimate probable consequences given a set of seismic source parameters including earthquake magnitude, epicenter location, focal depth, rupture fault length, width, dip angle, and so on. Depending on the details of the seismic source characteristics, the energy release mechanism of an earthquake may be modeled as a point-source, a line-source or a plane-source. For large earthquakes with magnitude greater than 7.0, the geometry of rupture fault plane should be specified more carefully. The potential earth science hazards induced by a scenario earthquake can be estimated through empirical attenuation laws, site-modification factors, soil liquefaction assessment, and so on. Depending on the site-specific geologic conditions, hazard estimates and the structural seismic capacities, the damage-state probabilities of various kinds of civil infra-structures, such as buildings, bridges, water facilities and pipeline systems, can also be estimated [1].

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Starting from 1999, a GIS-based Windows application, named "Taiwan Earthquake Loss Estimation System (TELES)", was developed by the National Center for Research on Earthquake Engineering (NCREE) in Taiwan. It was later customized to estimate the damage and loss of potable water facilities and pipeline systems, such as water treatment plants, storage tanks, transmission and distribution pipelines, etc., during earthquakes. The customized software was called Twater. Integrating with Taiwan Rapid Earthquake Information Release System which is developed and maintained by the Central Weather Bureau, early seismic loss estimation (ESLE) technology was also developed to provide brief but reliable disaster estimates, such as identification of facilities which may exposed in hotspots, probable number of repairs in pipeline systems, etc, soon after earthquakes to assist in starting up emergency responses. This paper mainly explains several unique features of hazard analysis and damage assessment used in Twater.

ESTIMATION OF PERMANENT GROUND DEFORMATION

Permanent ground deformation induced by soil liquefaction and/or fault rupture is one of the major hazards caused by earthquakes. As shown in Figure 1, most of the damaged water facilities during Chi-Chi Taiwan earthquake in 1999 were located near the ruptured Chelongpu fault and on the hanging-wall side. If only peak ground acceleration (PGA) or any other ground shaking parameter is used to estimate the failure probability of facilities and pipeline systems, it often overestimates the damage-state-probability of facilities or the expected number of pipe repairs. To improve the accuracy, both ground shaking parameter (such as PGA and 1-second spectral acceleration) and permanent ground deformation should be taken into consideration in hazard, damage and loss estimations.

The permanent ground deformation due to soil liquefaction and the liquefaction probability may be estimated by empirical formulas proposed by Yeh, et al. [2]. The permanent ground deformation (PGD) due to fault rupture may be estimated by the following model,

$$\mathrm{PGD} = \begin{cases} D & \text{(within 10 m)} \\ (1/d_{sr}) \cdot f_H \cdot D \cdot \exp[-d/(d_{sr} \cdot f_H)] & \text{(hanging wall)} \\ (1/d_{sr}) \cdot f_F \cdot D \cdot \exp[-d/(d_{sr} \cdot f_F)] & \text{(footwall)} \end{cases} \tag{1}$$

where D is the mean slip (or dislocation) of the rupture fault, which can be estimated by the well-known empirical formulas proposed by Wells and Coppersmith (1994) [3] considering earthquake magnitude and different style of faulting; d_{sr} is the depth of seismogenic rupture top; d is the estimated minimum distance between the facility/pipeline and the rupture fault plane; f_H and f_F are coefficients reflecting different attenuation rates on the hanging wall and footwall side, respectively. The f_H and f_F are assumed to be functions of dip angle (α) of the rupture plane, i.e., $f_F = \mathrm{abs}(\alpha)/180$ and $f_H = 1 - f_F$.

It should be noted that the ground deformation induced by fault rupture is neither uniform nor continuous. Therefore, like liquefaction probability, the encounter rupture probability at fault distance d is assumed to be $p_{fault} = 0.7 \cdot \exp(-d/2)$, where d is expressed in km. In addition, for a large-size facility and/or a long transmission pipeline, if the size of facility/pipeline and the major orientation of it are known, the nearest fault distance (d_e) between the facility/pipeline and the rupture plane may be updated using the following model.

$$d_e = \begin{cases} \max\left(0,\quad d_c - 0.5 \cdot l \cdot \sin\left|\varphi - \theta\right| \cdot \sin\alpha\right) & \text{(hanging wall)} \\ \max\left(0,\quad d_c - 0.5 \cdot l \cdot \sin\left|\varphi - \theta\right|\right) & \text{(footwall)} \end{cases} \tag{2}$$

where d_c is the minimum fault distance between the centroid of facility/pipeline and the rupture plane; α is the dip angle of rupture plane; l represents the size of facility/pipe; φ and θ are the major orientations of the facility/pipeline and the rupture fault trace, respectively, as shown in Figure 2. The updated minimum fault distance (d_e) is then used in Eq. (1) to calculate PGD that may be occurred at the facility or pipeline. Use of Eq. (2), some large-size facilities, such as Fengyuan water treatment plant with daily total output 1,000,000 CMD, as shown in Figure 1, were identified to be very close to the Chelongpu fault and would suffer severe damage due to fault rupture in 1999 Chi-Chi earthquake.

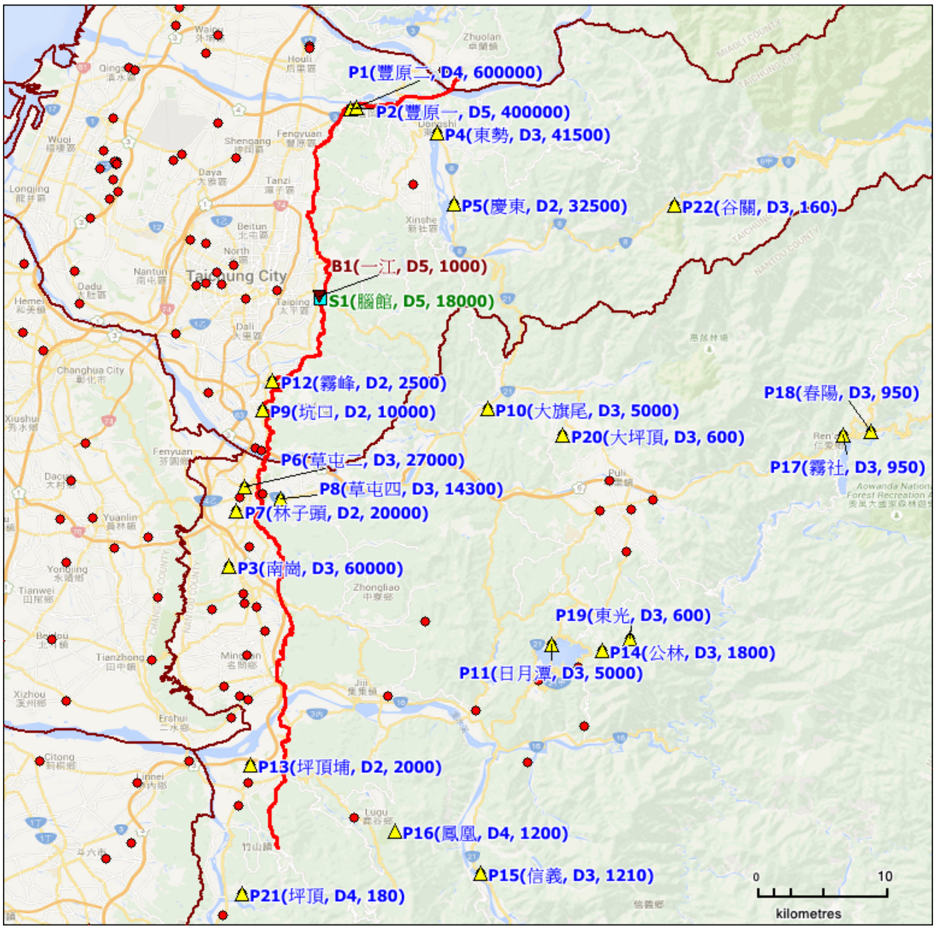

Figure 1 Observed distribution of damaged water facilities in 1999 Chi-Chi Taiwan earthquake. The thick red line is the ground surface trace of Chelongpu fault, which was ruptured in the Chi-Chi earthquake. The prefix of each ID: P stands for treatment plant, S stands for storage tank, and B stands for pipe bridge. Inside parentheses, the first item is the name of facility (in Chinese), the second item is the damage-state observed, and the third item indicates the capacity of facility. The small red dots show the locations of all treatment plants with or without damage.

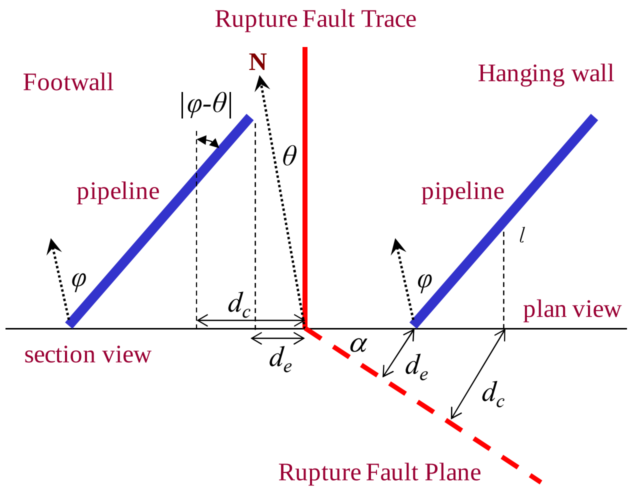

Figure 2 A schematic diagram explaining how to calculate minimum distance (d_e) between a long pipe with length l and the rupture plane, when d_c is known.

ESTIMATION OF POST-QUAKE SERVICEABILITY OF PIPELINES

Unlike damage assessment of facilities, the estimations of loss-of-function, repair cost and restoration time of pipelines are often expressed as functions of repair rate and/or repair number. The repair rate is defined as the number of repairs per unit length of pipeline. The three hazard estimates mentioned before, i.e., ground shaking intensity in terms of PGA, permanent ground deformation due to soil liquefaction and fault rupture, are all considered in the calculation of probable repair rate for any specific pipeline. The probable repair rate is expressed as

$$RR = \max\left(RR_{PGA},\quad p_{fault}\cdot RR_{PGD(fault)},\quad p_{lqf}\cdot RR_{PGD(lqf)}\right) \tag{3}$$

where RR_{PGA}, $RR_{PGD(fault)}$ and $RR_{PGD(lqf)}$ are the estimated repair rates using empirical formulas based on peak ground acceleration (PGA), and permanent ground deformation (PGD) due to fault rupture and soil liquefaction, respectively; p_{fault} and p_{lqf} are the encounter rupture probability and soil liquefaction probability, respectively. The RR_{PGA} and RR_{PGD} can be expressed as

$$RR_{PGA} = 4.501\cdot C_{S_i-PGA}\cdot C_{T_j}\cdot(\mathrm{PGA}-0.1)^{1.97} \tag{4}$$

$$RR_{PGD} = 0.04511\cdot C_{S_i-PGD}\cdot C_{T_j}\cdot \mathrm{PGD}^{0.728} \tag{5}$$

where C_{S_i-PGA}, C_{S_i-PGD} and C_{T_j} are correction coefficients for different pipe sizes (S_i) and material/joint types (T_j), as given in reference [4]. It is noted that C_{S_i-PGA} and C_{S_i-PGD} for any specific pipe size have been assigned different values to reflect different seismic capacity with respect to ground shaking and ground deformation.

Eqs. (3), (4) and (5), together with the encounter rupture probability and the soil liquefaction probability, may be used to estimate the probable number of repairs in the pipeline systems when a scenario earthquake occurs. In order to evaluate more accurately the post-quake serviceability in system level, it is desirable to differentiate the level of severity at the pipe repair. For simplicity, only two levels of severity are considered, i.e. leak and break. Since it is unlikely to have a pipe break when the pipeline is subjected to small shaking and/or ground deformation, the expected break ratio (BR_{PGA} and BR_{PGD}) of pipe repair rate is linearly adjusted within ranges of small ground shaking ($\mathrm{PGA} < 0.6g$) and ground deformation ($\mathrm{PGD} < 100$ cm), and can be modeled as follows

$$BR_{PGA} = \begin{cases} B_{S_iT_j-PGA} \cdot 2 \cdot (\mathrm{PGA} - 0.1) & 0.1g < \mathrm{PGA} < 0.6g \\ B_{S_iT_j-PGA} & \mathrm{PGA} \geq 0.6g \end{cases} \tag{6}$$

$$BR_{PGD} = \begin{cases} B_{S_iT_j-PGD} \cdot 0.01 \cdot \mathrm{PGD} & \mathrm{PGD} < 100 \text{ cm} \\ B_{S_iT_j-PGD} & \mathrm{PGD} \geq 100 \text{ cm} \end{cases} \tag{7}$$

where $B_{S_iT_j-PGA}$ and $B_{S_iT_j-PGD}$ are the upper limits of expected break ratio due to ground shaking and ground deformation, respectively. These upper limits should depend on the pipe sizes (S_i) and material/joint types (T_j), as indicated in the subscripts.

The pipes in a water supply system may be classified into transmission pipelines, distribution pipelines and service laterals. If there is no information about the role of each pipeline in the water supply system, it may be roughly classified by pipe size only. In this study, the main transmission pipelines refer to those with diameter greater than or equal to 800 mm. They play the most important role in water supply systems and often used to deliver huge amount of water (either treated or untreated) between two places separated by a long distance. Considering the level of severity and the uncertainty in repair-rate assessment, assuming the impact of two leaks in pipeline are equivalent to that of one break in pipeline, the post-quake serviceability (Ω) of transmission pipelines may be estimated by the following model

$$\begin{aligned} \Omega &= \exp[-1.582 \cdot (1 - e^{-(0.5n_l + n_b)})] \\ &= \exp[-1.582 \cdot (1 - e^{-0.5(n_r + n_b)})] \end{aligned} \tag{8}$$

where n_r, n_l and n_b are the expected number of repairs, leaks and breaks on the transmission pipeline, respectively, due to a scenario earthquake. The function form used in Eq. (8) is solely due to stability consideration. For example, if one break is expected (but in reality the break may not happen at all), the post-quake serviceability may expect to reduce to 0.368 comparing to normal times when $\Omega = 1$.

Pipelines with diameter greater than or equal to 500 mm but less than 800 mm are referred to as sub-transmission pipelines in this study. Since the sub-transmission pipelines may form a network-type, a tree-type or a simple line-type depending on the service area and the daily water usage ($\bar{D}$) of a system, the post-quake serviceability (θ) of sub-transmission pipelines inside a water supply system may be estimated by the following model

$$\theta = \begin{cases} \exp[-1.582 \cdot (1 - e^{-0.1(n_r + n_b)})], & \bar{D} \geq 100{,}000 \text{ CMD} \\ \exp[-1.582 \cdot (1 - e^{-0.2(n_r + n_b)})], & 10{,}000 \text{ CMD} \leq \bar{D} < 100{,}000 \text{ CMD} \\ \exp[-1.582 \cdot (1 - e^{-0.5(n_r + n_b)})], & \bar{D} < 10{,}000 \text{ CMD} \end{cases} \tag{9}$$

where n_r and n_b are the expected number of repairs and breaks on sub-transmission pipelines inside the water supply system, respectively, subjected to a scenario earthquake.

Pipelines with diameter greater than or equal to 100 mm and less than 500 mm are referred to as distribution pipelines in this study. The water loss ratio (L) due to damage of distribution pipelines after a scenario earthquake may be estimated by the following model

$$L = \begin{cases} 1/(1 + 0.667 \cdot RR^{-1.113}) & \bar{D} \geq 10{,}000 \text{ CMD} \\ 1/(1 + 1.5 \cdot RR^{-1.113}) & \bar{D} < 10{,}000 \text{ CMD} \end{cases} \tag{10}$$

where RR is the average repair rate of distribution pipelines inside the water supply system after the earthquake.

The coefficients in Eq. (10) had been calibrated in the previous study on deriving empirical formula, using the 1999 Chi-Chi earthquake data [5, 6, 7], to estimate water shortage ratio by repair rate of distribution pipelines in water supply systems, as shown in the schematic diagram (see Figure 3). Let the daily water demand by customers in normal times be denoted by $\bar{D}$ and the actual water supply in the i-th day after earthquake be denoted by $D_i^{'}$, then water shortage ratio (S_i) in the i-th day can be defined as

$$S_i = (\bar{D} - D_i^{'}) / \bar{D} \tag{11}$$

The average daily water usage ($\bar{D}$) in normal times could be calculated for each water supply system before and after the Chi-Chi earthquake; however, the actual amount of water delivered to customers during restoration period after the Chi-Chi earthquake were missing. It was not possible to obtain reliable value of $D_i^{'}$ in Eq. (11). Therefore, different sets of coefficients a and b, used in estimating the water loss ratio L, as shown in Figure 3, had been tested in regression analysis. In that study, the coefficients used in Eq. (10) seem reasonable; and the empirical formula for water shortage ratio immediately after earthquake (S_1) was expressed in terms of repair rate of distribution pipelines as follows

$$S_1 = 1/(1 + 1.008 \cdot RR_1^{-0.7085}) \tag{12}$$

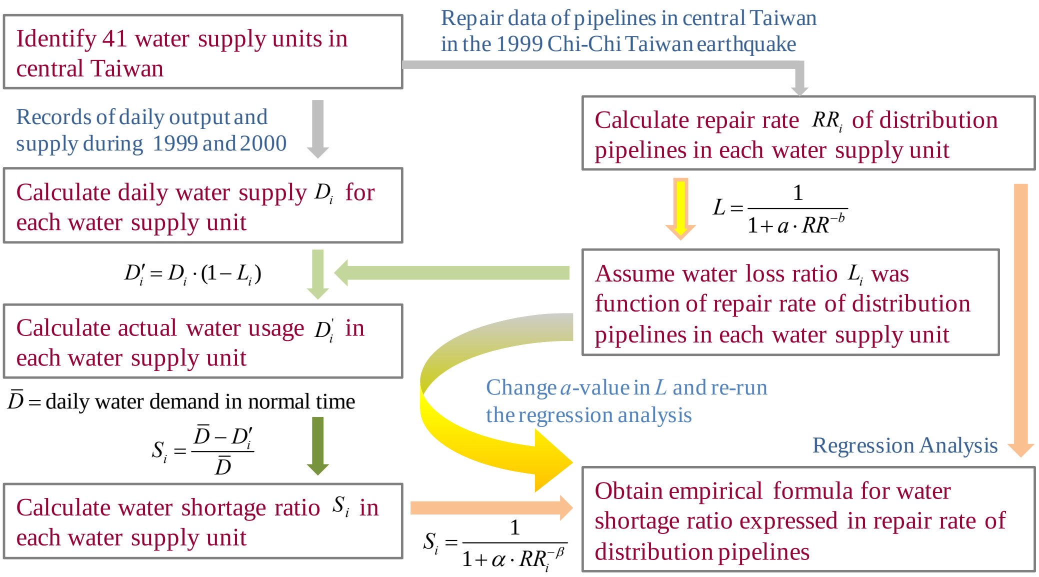

Figure 3 Schematic diagram of regression analysis using pipe repair data and water supply data before and after the 1999 Chi-Chi earthquake to obtain the empirical formula, which may estimate water shortage ratio by repair rate of distribution pipelines after earthquakes

ESTIMATION OF REMAINING CAPACITY OF WATER TREATMENT PLANTS

As observed in the 1999 Chi-Chi earthquake (Figure 1), the damage-state of water treatment plants due to earthquakes are highly correlated to both ground shaking and ground deformation. The parameters of shaking-related and deformation-related fragility curves may be properly calibrated using historical investigation data. The damage-state-probability of any specific water treatment plant may then be calculated as long as the ground shaking and the ground deformation estimates have been reasonably obtained in hazard analysis.

However, the predicted damage-state often represents the most severe part of the plant. In other words, the damage-state of individual facility inside the plant, such as pipelines, channels, storage tanks and pumping equipments, may not be the same. Depending on the amount of daily water demand, the plane size of water treatment plant may vary from several meters to several hundred meters. The plane size of water treatment plant should be taken into consideration in scenario simulations in order to improve the accuracy of estimation results.

For large water treatment plants, there may be more than one set of water treatment unit which may operate independently. These independent water treatment units are not likely to complete damage at the same time; and in most cases, only a small portion of a large water treatment plant may be completely damaged, the rest can be restored in short time. Therefore, the number of independent water treatment units in a large plant should be taken into consideration in estimating capacity after earthquakes.

In addition, most of the raw water required by large water treatment plants in Taiwan comes from distant reservoir through large-size raw water aqueducts and tunnels. If any one section of aqueduct or tunnel is severely damaged, the water treatment plant will lose its function, too.

ESTIMATION OF POST-QUAKE SERVICEABILITY IN SYSTEM LEVEL

Integrating all the estimation results on the serviceability of various kinds of pipelines and the remaining capacity of water treatment plants, the water shortage ratio in Eq. (11) may be calculated in another way. Let the daily water demand in a specific water supply system is supplied by N water treatment plants. The k-th water treatment plant contributes $\bar{D}_k$ daily before earthquake. Since some of water treatment plants locate far away from the system or population dense areas, the treated water must be delivered through main transmission pipelines. Assume there are M_k main transmission pipelines available to deliver treated water from k-th water treatment plant to the system. The j-th main transmission pipeline shares λ_j of $\bar{D}_k$. Before entering the trunks and distribution pipelines, the remaining amount of water (D) that the system may obtain from N water treatment plants after earthquake can be expressed as

$$D = \sum_{k=1}^{N} \left[\bar{D}_k \cdot O_k \cdot \sum_{j=1}^{M_k} (\lambda_j \cdot \Omega_j) \right] \tag{13}$$

where O_k is the remaining capacity ratio of the k-th water treatment plant; Ω_j is the post-quake serviceability of j-th main transmission pipeline, which may be estimated by Eq. (8)

In most cases, the trunks and distribution pipelines may also suffer damages after severe earthquakes. The actual amount of water available to customers (D') can be expressed as

$$\begin{aligned} D' &= \theta \cdot (1-L) \cdot D \\ &= \theta \cdot (1-L) \cdot \sum_{k=1}^{N} \left[\bar{D}_k \cdot O_k \cdot \sum_{j=1}^{M_k} (\lambda_j \cdot \Omega_j) \right] \end{aligned} \tag{14}$$

where θ is the post-quake serviceability of the trunks, as calculated by Eq. (9); L is the water loss ratio, as calculated by Eq. (10). The O_k, Ω_j, θ and L are functions of time. Complete restoration time depends on all of these four factors.

In summary, the water shortage ratio (S) can be expressed as

$$S = \frac{\bar{D} - D'}{\bar{D}} = 1 - \frac{\theta \cdot (1-L)}{\bar{D}} \cdot \sum_{k=1}^{N} \left[\bar{D}_k \cdot O_k \cdot \sum_{j=1}^{M_k} (\lambda_j \cdot \Omega_j) \right] \tag{15}$$

where $\bar{D}$ is the daily water demand by customers in normal times; D' is the actual amount of water available to customers; O_k, Ω_j, θ and L are defined as before. The number of households without potable water (V) may be then estimated by the following model

$$V = H \cdot \left[1 - \frac{1-S}{\gamma} \right] \tag{16}$$

where H is the total number of households in the water supply system; γ is the reduced ratio of daily water demand after earthquakes.

CONCLUSION

A seismic scenario simulation technology developed by NCREE was introduced. Both ground shaking intensity and permanent ground deformation due to fault rupture and/or soil liquefaction is considered in seismic damage and loss assessment. The damage and loss assessment models of water facilities and pipelines have been proposed and used in seismic scenario simulations. The water outage in terms of reduction in daily supply and the number of households without potable water soon after earthquake may also be estimated base on damage and loss-of-function assessment of water treatment plants, transmission and distribution pipelines. The coefficients used in the analysis models have been calibrated by the observations from the 1999 Chi-Chi earthquake; and they have been also verified by the 2016 Meinong earthquake.

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An Investigation of the Seismic Performance of Portland Water Bureau's Water System in an M 9.0 Earthquake

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ABSTRACT

The Oregon Resilience Plan (ORP) was developed in 2013 by the State of Oregon to reduce risk and improve recovery during and following a Magnitude (M) 9.0 earthquake and tsunami. The Portland Water Bureau (PWB) hired InfraTerra, Inc. to help them prepare a Water System Seismic Study (WSSS) of the PWB water system. PWB and InfraTerra determined the seismic performance of PWB's water system in an M 9.0 earthquake and developed mitigation actions to meet the target states of recovery (TSoR) provided in the ORP. The study findings highlighted the need to invest in mitigation projects and water system improvements. The study also identified resources needed for post-earthquake repair and areas where additional planning and policy change were needed.

INTRODUCTION

Background

The Oregon Resilience Plan (ORP) was developed by the Oregon Seismic Safety Policy Advisory Commission (OSSPAC) upon passage of House Resolution 3 by the Oregon House of Representatives. The purpose of the ORP is to reduce risk and improve recovery during and following a Magnitude (M) 9.0 Cascadia Subduction Zone earthquake and tsunami. The ORP addressed a number of concerns by developing Task Groups that looked at Business and Workforce Continuity, Critical and Essential Buildings, Transportation, Energy, Information and Communications, and Water and Wastewater. The ORP was finalized in 2013.

In 2016, the Portland Water Bureau (PWB) hired InfraTerra, Inc. to help prepare a Water System Seismic Study (WSSS) of the PWB water system. The performance goals developed by the OSSPAC Water and Wastewater Task Group of the ORP formed the basis for the WSSS. A key recommendation of the Task Group was to identify and strengthen a backbone water system that can provide water for critical needs following a M9 Cascadia Subduction Zone (CSZ) earthquake while damage to the remainder of the system is being repaired within a period of 6 months to a year. Table I shows ORP's target states of recovery (TSoR) for its water system.

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TABLE I. OREGON RESILIENCE PLAN WATER SYSTEM TARGET STATES OF RECOVERY

Event Occurs

Domestic Water Supply	0-24 hours	1-3 days	3-7 days	1-2 weeks	2 weeks - 1 month	1-3 months	3-6 months	6-months - 1 year	1-3 years	3+ years
Potable water available at supply source (WTP, wells, impoundment)	20%-30% operational	50%-60% operational		80%-90% operational			90% operational (current state)			
Main transmission facilities, pipes, pump stations, and reservoirs (backbone operational)	80%-90% operational					90% operational (current state)				
Water supply to critical facilities available	50%-60% operational	80%-90% operational				90% operational (current state)				
Water for fire suppression - at key supply points	80%-90% operational		90% operational (current state)							
Water for fire suppression - at fire hydrants			20%-30% operational	50%-60% operational	80%-90% operational			90% operational (current state)		
Water available at community distribution centers/points		50%-60% operational	80%-90% operational	90% operational (current state)						
Distribution system operational		20%-30% operational	50%-60% operational	80%-90% operational				90% operational (current state)		

Figure 1 shows the location of the CSZ in relation to PWB.

Figure 1. PWB seismic hazard from the Cascadia Subduction Zone

The WSSS scope included the following main tasks:

- Develop hazard maps for earthquake-induced liquefaction, lateral spreading, and landslides in the Portland area;
- Identify and assess the backbone system
- Assess the water distribution system;
- Develop mitigation measures to meet ORP's TSoR;
- Evaluate emergency preparedness for response and recovery.

Water System Description

The PWB water system is the largest water system in Oregon and serves a population of over 935,000, almost one-quarter of the state's population. Its service area covers approximately 225 square miles, including portions of Multnomah, Washington and Clackamas counties. PWB provides water to both wholesale and retail customers with the retail service area accounting for 64 percent (143.3 square miles) of PWB's service area. The Average Day Demand (ADD) for the water system is 86.9 million gallons per day (mgd) and the Winter or Minimal Day Demand (MinDD) is 76.4 mgd (approximately 88 percent of the ADD). The MinDD was chosen as the level of service (LOS) goal for the WSSS.

The Bull Run watershed is the primary source of water for the PWB system, and can supply up to 205 mgd. Water from the Bull Run Headworks comes into town via three large diameter supply pipelines (Conduit 2, Conduit 3 and Conduit 4), constructed in 1911, 1925, and 1952, respectively. Although the conduits are separated within the Bull Run watershed, transfer of water between the conduits is possible at the Larson's and Hudson Intertie facilities. In addition to the Bull Run supply, the Columbia South Shore Wellfield (CSSWF), with 27 production wells, serves as a secondary source of water supply for PWB and can provide up to 114 mgd of water supply.

The PWB distribution system consists of over 2,000 miles of pipelines that service 165 pressure zones. The distribution pipelines consist predominantly of concrete cylinder, cast iron, ductile iron, and steel. The cast iron pipelines are known to have high seismic vulnerability, and constitute more than 60 percent of the pipelines within the backbone and distribution system. Ductile iron is the other main pipeline type and constitutes more than 30 percent of the distribution system pipelines. The distribution system also includes 59 distribution system tanks, 5 terminal reservoirs, and 36 pump stations.

The WSSS project team, including key PWB stakeholders, InfraTerra staff, and PWB's outside expert, Don Ballantyne, participated in a workshop to identify critical components of the PWB's system that can serve as a backbone system. The identified backbone included terminal reservoirs, critical pump stations and 120 miles of major pipelines that can transport water across PWB's service area. The backbone also includes PWB's Bull Run and CSSWF supplies.

Seismic History

PWB has been upgrading its system to meet seismic requirements over the last twenty years. This work has included upgrades to several assets at PWB's Bull Run Headworks facility, new and improved interties between supply conduits, bridge and trestle improvements, and two tunnel projects. PWB also constructed three new terminal reservoirs, completed a pilot study using earthquake-resistant pipe, and has made improvements to several of its distribution storage tanks and pump stations.

IMPACTS FROM AN M9 CSZ EARTHQUAKE

Hazard Maps

The main seismic hazards to PWB's water system are soil liquefaction, seismically triggered landslides, and slope instability. The WSSS invested a great deal of resources into quantifying the liquefaction and landslide hazards by developing permanent ground deformation (PGD) maps for the study earthquake. Four maps were developed: liquefaction susceptibility, liquefaction-induced PGD (lateral spread), liquefaction-induced PGD (settlement) and earthquake triggered landslides. These GIS based maps will help PWB in future analyses and emergency response as well as providing key information for the WSSS hazard assessment.

Hazard Assessment

The seismic vulnerability assessment of PWB infrastructure included site reconnaissance and seismic analysis. The seismic analysis incorporated the potential for direct damage to the water system infrastructure from earthquake effects such as ground shaking, wave propagation, and permanent ground deformation. The assessment did not include potential collateral damage to the system resulting from failure of other infrastructure such as buildings and bridges.

Site reconnaissance of all storage and pumping facilities, groundwater production wells and groundwater pump station facilities was performed. The Bull Run 1 and Bull Run 2 dams, Headworks facilities, the Larson's and Hudson interties and the conduit bridge crossings were also reviewed. Geologic field reconnaissance included documentation of observed ground conditions and evidence of ground movement. Structural reconnaissance focused on as-built conditions and documentation of any visible signs of structural distress.

Seismic analysis ranged from simplified calculations to complex non-linear finite element analysis for critical pipelines. Probability of failures were developed using empirical as well as analytical methods and included Monte Carlo analyses to incorporate uncertainties in hazard quantification, structural response and structural capacities for pipelines, conduits, river crossings, tanks and pump stations.

The results of PWB's hazard assessment indicated that the backbone distribution system and wellfield pipelines would be most impacted by lateral spreading and that the supply conduits would be impacted by liquefaction-related lateral spreading and landslides.

Water System Performance

Seismic assessment of the PWB water system showed significant vulnerabilities in the current supply, the backbone, distribution, storage, and pumping systems. Hydraulic analysis of the backbone system showed that the existing system is unable to meet the MinDD or minimum level of service goal of 76.4 mgd following a M9 CSZ earthquake, and that the system could potentially drain within minutes following the earthquake due to the large number of predicted leaks and breaks. In addition, if it is assumed that a complete loss of pressure in the distribution system cannot be prevented (i.e. majority of system is allowed to drain, as a result of widespread damage), the time required to restore the system by post-earthquake repairs is significantly greater than the TSoRs identified in ORP.

Median estimates of the time required to perform necessary post-earthquake pipeline repairs showed that even with the most optimistic estimates of repair crew availability, the ORP's TSoRs for the restoration of backbone and distribution cannot currently be met. For example, PWB estimates that it would take a minimum of 5 days to complete backbone repairs, assuming 40 crews (which would require outside assistance such as mutual aid agreements) working one 12-hour shift or 20 crews working two 12-hour shifts per day. This restoration timeline is higher than ORP's TSoR for restoration, which is 80 to 90 percent of the backbone within 24 hours, as shown in Table I. Similarly, it would take a little over 5 weeks to complete the median estimates of repairs for the distribution system (assuming that the backbone and wellfield pipeline repairs would be performed first), whereas the ORP's TSoR for the restoration for 80 to 90 percent of the distribution system is 1 to 2 weeks. Furthermore, these estimates do not account for other demands on the repair crews, such as damage to the supply system, electrical/mechanical components in the pump stations, road clearing operations, and structural damage to the pump stations, tanks, and the production wells in the wellfield.

Consequently, it was determined that it is not possible to reliably meet the ORP goals for the backbone and distribution system without the implementation of improvement projects to reduce the number of post-earthquake repairs.

EFFORTS TO ASSESS AND MITGATE IMPACTS

Water System Mitigation

A comprehensive list of mitigation projects with planning-level costs was developed. These projects included replacement of sections of the supply conduits, significant upgrades to the Columbia South Shore Wellfield, tank and pump station retrofits, improvements to the backbone system, and additional studies that need to be completed. Projects were given an initial priority, and a plan to fund and phase these projects over the next 5 or 10 years (short-term) and over the next 50 years (long-term) is currently underway.

Emergency Response Improvements

The WSSS consultants reviewed several existing PWB emergency plans and provided recommendations for improving them. As part of the work, they provided insight into improving our pipe repair protocols, firefighting response, and emergency potable water strategies. This insight will help PWB strengthen their emergency planning and response efforts.

CONCLUSION

The Portland Water Bureau has completed its Water System Seismic Study and now has a list of improvements that will create a roadmap to reach the goals of the Oregon Resilience Plan over the next 50 years. Funding and prioritization of recommended water system improvements are now taking place. The Portland Water Bureau also has additional insight that will strengthen their emergency planning and response activities.

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Formation of Information Transfer Methods for Envisaged Disasters

Kazunori Iwamoto, Fujio Nagasawa, Hiroyuki Maeda

ABSTRACT

After the occurrence of the Great East Japan Earthquake on March 11th 2011, an unprecedented confusion occurred around the Tohoku region, because of the stoppage of communication infrastructure due to the interruption of network lines, power cuts, etc. In the City of Yokohama, too, it became difficult to transmit information due to connection restrictions of general and mobile phones. Because of this, Yokohama Waterworks Bureau had difficulty assembling staff, grasping the extent damage of its facilities, and sharing information amongst branch offices.

We consider that in order to carry out recovery activities of water supply swiftly in all the areas of the City of Yokohama at the time of similar disasters in the future, ensuring reliability of means of information communication across the headquarters of Yokohama Waterworks Bureau and its branch offices is important. Therefore, we have constructed a means of information communication to be used in the Waterworks Bureau with a consideration of economic factor about which we report here.

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Communication Status in the Affected Area

Figure 1 shows the initial status of communication in the affected Tohoku region.

In the disaster-stricken Tohoku region, buildings for transmission and facilities provided by a telecommunication carrier (NTT) were damaged, and also, the damage expanded to storage batteries, which are power sources in emergency, running out due to the prolonged period of commercial power failure. Because of this, with regard to landlines and optical lines, a maximum of 1.5 million lines were stopped, while for mobile phones, a maximum of 7,000 or a little less radio stations were suspended. Also, since the network was over capacity as a large number of people made calls using mobile phones, telecommunication companies implemented connection restrictions to protect circuit switching facilities. Then, about 10 days were required for the recovery of about 80% of facilities.

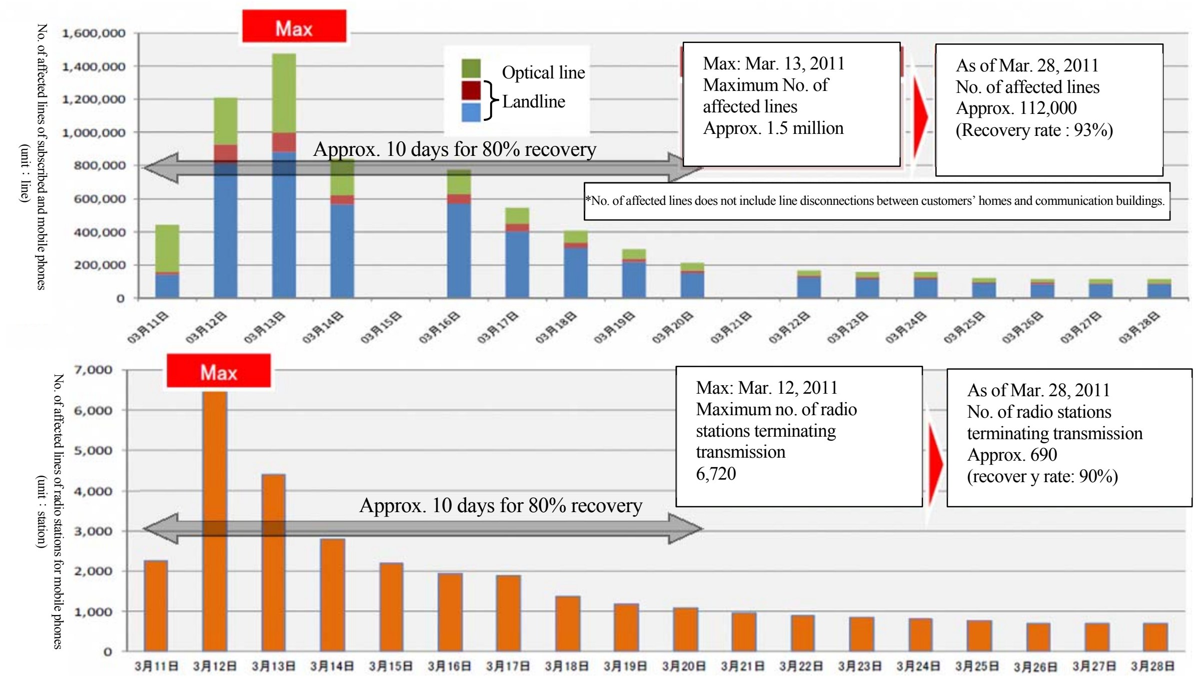

Figure 1. Communication status in the affected area due to the Great East Japan Earthquake (Source: data created by NTT)

Means of Information Transmission of Yokohama Waterworks Bureau

Table 1 shows an existing means of the Yokohama Waterworks Bureau. In order to convey information promptly even during a disaster, various communication facilities were developed and they were utilized according to their features. However, each of them had problems on their use. Especially, right after the occurrence of the disaster, the communication status became like that of the affected area, and swift information communication between branch offices could not take place sufficiently.

Table 1. Conventional means of communication

Equipment Image	  (Landline phones) (Mobile phones)	  (Portable) (Semi-fixed)	
Name	(1) Landline, mobile phones	(2) Disaster prevention administration wireless equipment	(3) Satellite mobile phones
Installed place	Placed multiple phones in each office	Placed them in each office and cars	Placed them in each government office building
Features	Owned not only by Waterworks Bureau, but also by other corporations and individuals, and have versatility.	210 units are possessed by Waterworks Bureau, and almost 1000 units are owned by the City of Yokohama.	Mobile phones that use artificial satellites, and have versatility.
Problems	Approximately 10 days are expected to be required for 80% recovery from disaster. It is all but impossible to use mobile phones right after the occurrence of a disaster due to connection restrictions. Reliability of communication depends on telecommunication carriers.	Since the whole Yokohama Bureau shares communication lines, if the network is over capacity, control regulations are exercised and Waterworks Bureau can use only 1 line.	One satellite mobile phone is placed in each office building of Waterworks Bureau. In a state of confusion, it is difficult to communicate a large amount of information.

Development of Waterworks Bureau's Original Wireless Communication Network

We have been developing a communication network that utilizes the 5GHz band wireless access system (hereinafter called 5GHz band FWA (Fixed Wireless Access)) as a new means of information communication since fiscal 2013, with a goal of constructing "a reliable lifeline that is resistant to disasters". Figure 2 shows its outline.

In fiscal 2013, the Head Office Building of Waterworks Bureau and Nishiya Purification Plant were connected using this 5GHz band FWA. Due to this, using extension telephones, fax, and data communication with computers for business use within the Waterworks Bureau were made possible without involving any telecommunication carrier.

Later in fiscal 2015, the Head Office Building, Nakamura Waterworks Office, Nishiya Purification Plant and Kikuna Waterworks Office were connected, and by coordinating with the existing Wireless Monitoring Network for Water Purification Plant (7.5GHz band micro wireless), a wireless communication network connecting 8 office buildings in Waterworks Bureau was developed. Figure 3 is a structure chart showing that, and figure 4 shows the positional relationships of offices.

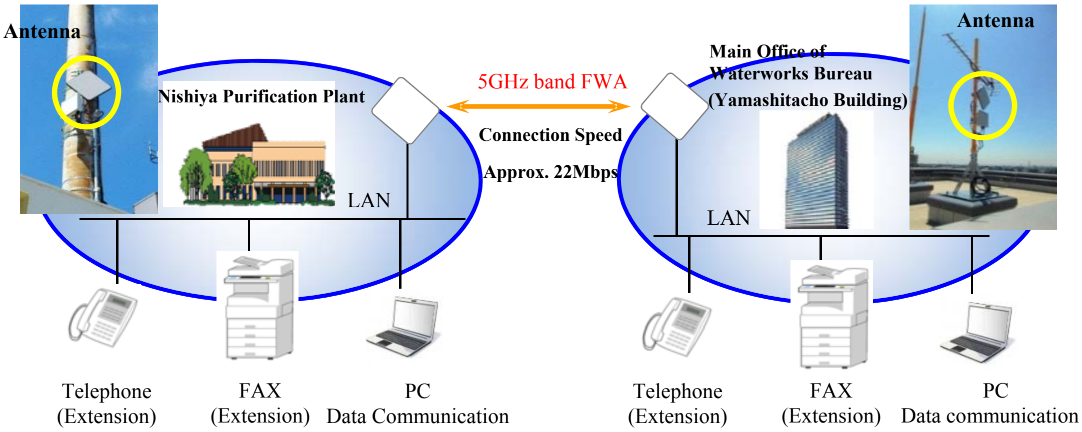

Figure 2. Outline of a communication network utilizing 5GHz band FWA

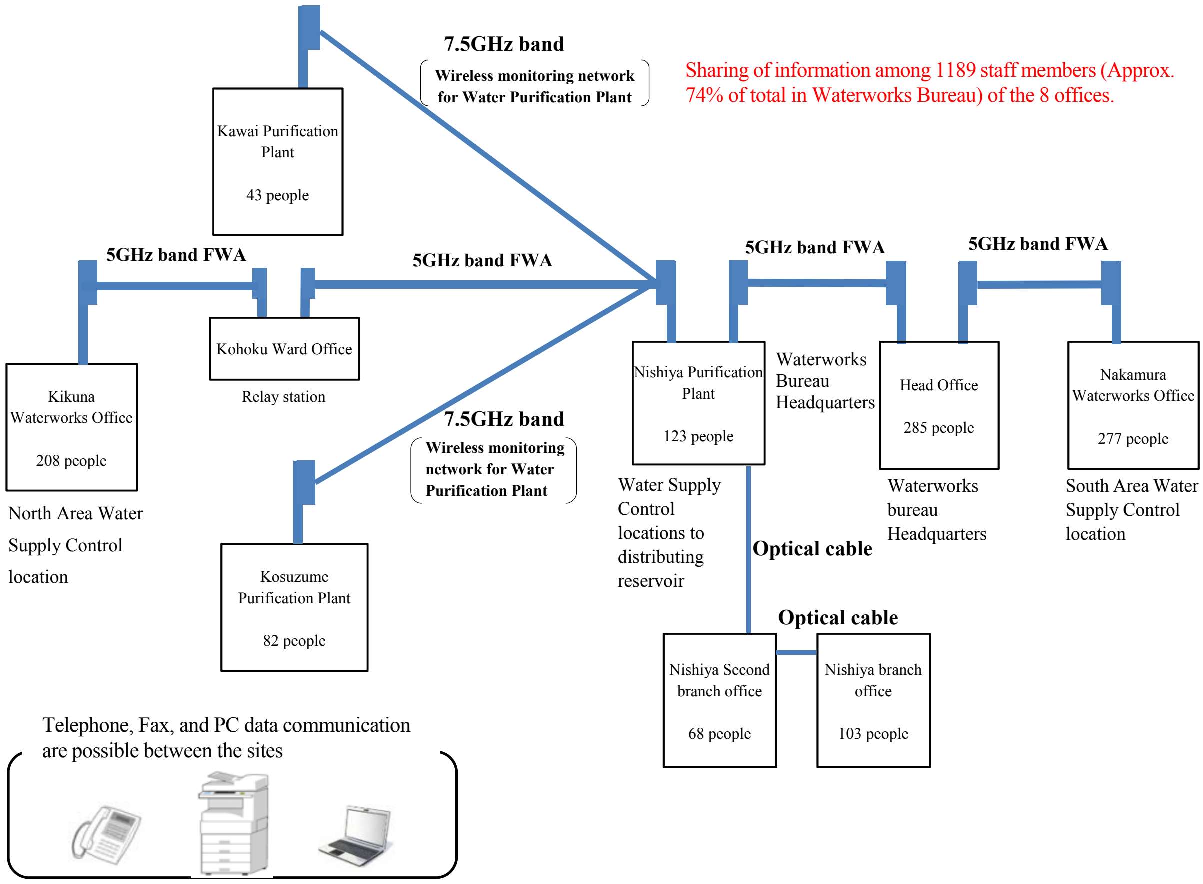

Figure 3. Structure Chart of Wireless Communication Network in Yokohama Waterworks Bureau

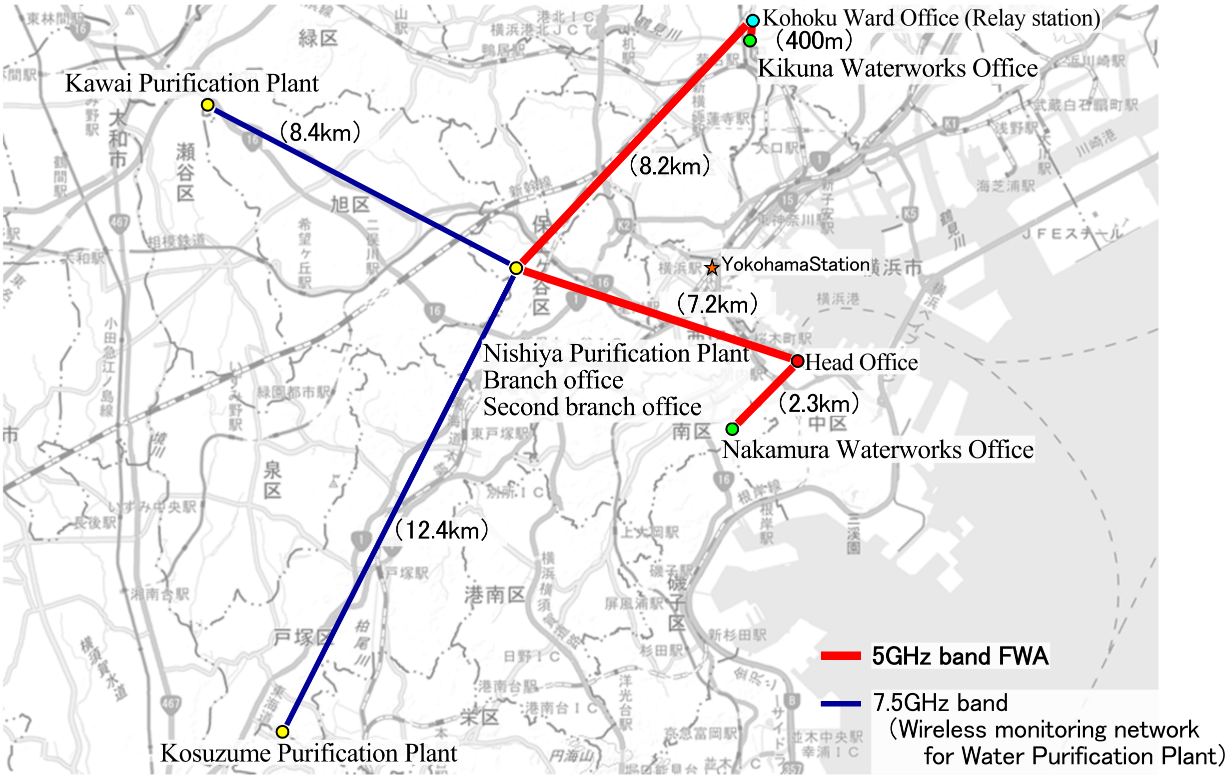

Figure 4. Positional Relationships of offices of Yokohama Waterworks Bureau

Device Configuration and Features of 5GHz Band FWA

Device Configuration

Figure 5 shows the device configuration of 5GHz band FWA. It is a simple device configuration with only a square shaped (about 36 cm) antenna and a transceiver body (about 25 cm). Router and HUB are connected to the LAN interface of the transceiver body, and communication terminals such as a private branch exchange and a PC are connected there.

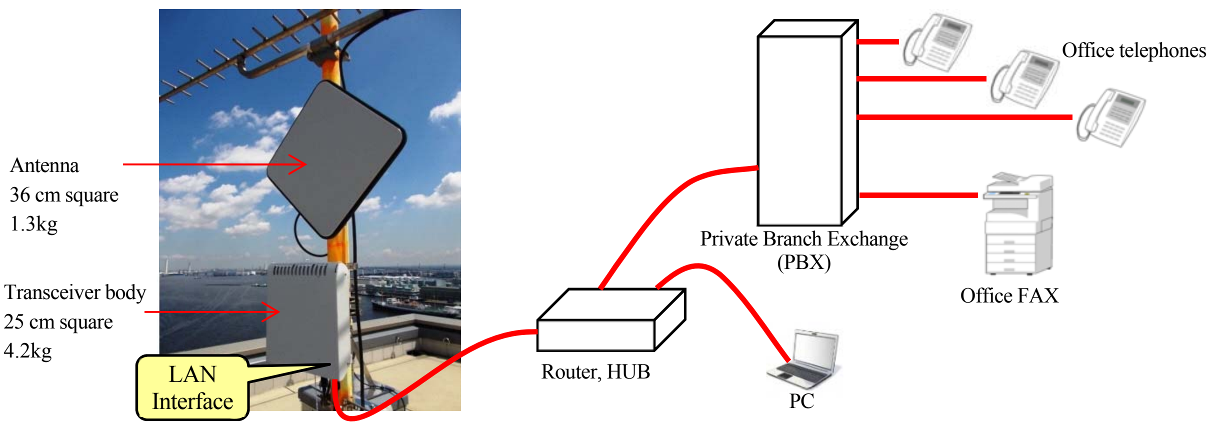

Figure 5. Device configuration and connection diagram of 5GHz band FWA

Features

The features of 5GHz band FWA are as follows.

- The transceiver body and the antenna are compact, and so they can be installed anywhere.
- Installation cost is low, about 1/5 of that for business use.
- Communication speed is so fast that the communication between the Head office of Waterworks Bureau and Nishiya Purification Plant (about 7.2 km) is possible at the speed of about 22 Mbps.
- Since it is a LAN connection, the exchange of data, audio, images, etc. is possible by connecting it with a PC, an IP-based private branch exchange, or a Web camera.
- Since it is an original communication line, it will not face network congestion as well as connection restrictions from any telecommunication carrier.
- Inside Japan, the screening for licensing has been simplified, therefore, it can be set up in about half a month after registration.
- As the signal is excellent in straightforward transmission, it is less affected by rain or fog, however, there's a need to install antennas in opposed directions in a range of one's view.

Effects of Installation

Secured a Communication System to be Used at the Time of Disasters

A communication network not dependent on a telecommunication carrier was constructed, and sharing of information among 1189 staff members of 8 offices (about 74% of total in Waterworks Bureau) was made possible.

Improvement in Easiness of Use

We developed a communication system that can function instantly at the time of a disaster by using regularly used telephones, FAX, or PC for business use without using a disaster prevention administrative radio or satellite mobile phone that is used in the time of emergency (Figure 6). In addition, when communicating among offices, intermediation is involved if an outside line is used, but an extension number can directly call a person, thus, its convenience has been improved (Figure 7).

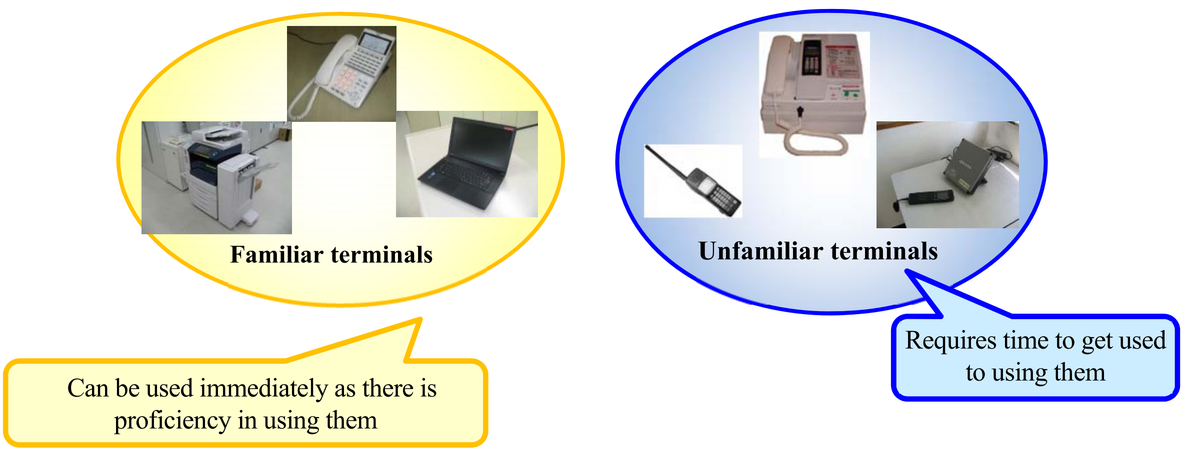

Figure 6. Impression of using terminals

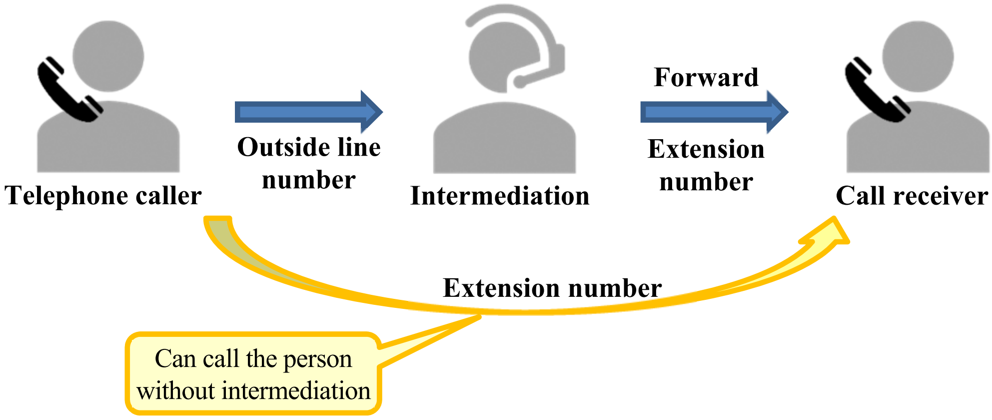

Figure 7. Image of call receiving

Reduction in Communication Cost

By using an extension line for business correspondence in place of outside line telephones that had been in use so far, communication cost was largely reduced. Approximately 16 years would be needed for full recovery of life cycle cost, which exceeds the 10-year service duration of the device, but the recovery of initial cost alone is possible in about 10 years. (Figure 8)

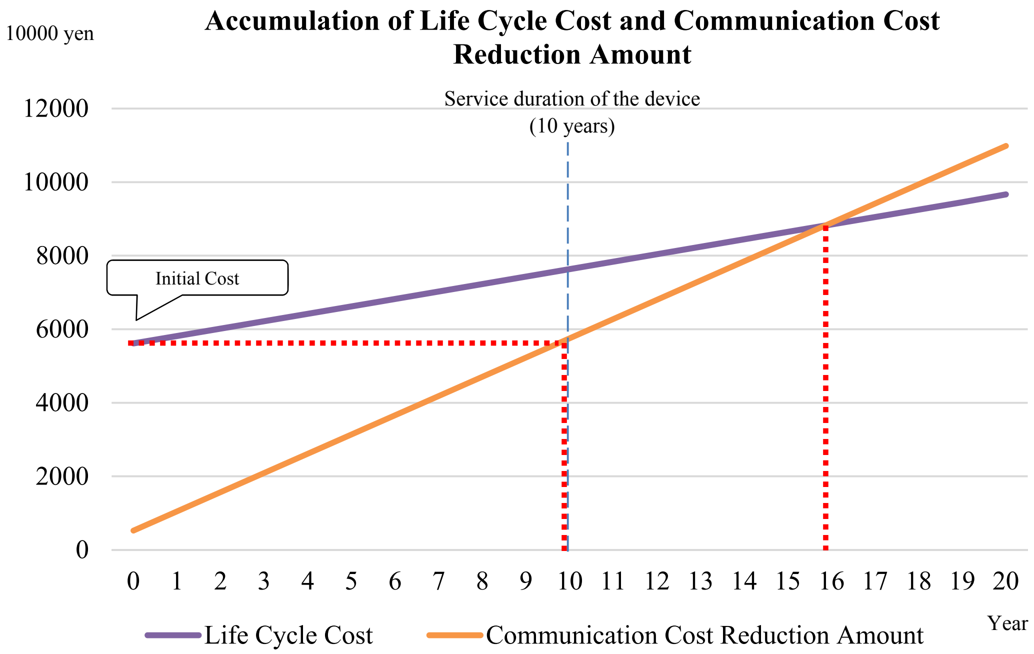

Figure 8. Accumulation of Life Cycle Cost and Communication Cost Reduction Amount

Conclusion

At the time of a disaster, the contribution to swift and definite activities for recovery of water supply facilities was made possible by effectively using this means of information communication. Also, further reduction in communication cost would be possible if each staff member actively uses extension lines for daily business correspondence.

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Application of a Mesh-based Earthquake Impact Assessment Tool for Water Supply System on Policy Support

Bing-Ru Wu and Siao-Syun Ke

ABSTRACT

A mesh-based earthquake impact assessment tool for water supply system, is developed in the Taiwan Earthquake Impact Information Platform (TERIA) with the collaboration of NCDR and academic institutions. The quantitative impact analysis in various levels of excitations, consisting of extreme and operational scenarios, can be applied to find the weak items and distribution for disaster preparedness. Two examples illustrate the application of impact analysis on disaster preparedness and policy support: (1) Scenario simulation for the National Earthquake Drill; (2) Impact analysis for policy suggestion on disaster management. The quantitative impact analysis in various levels of scenarios is helpful to disaster prevention planning.

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INTRODUCTION

Approximately 70% of the population is concentrated in 6 metropolitan cities in the western plain of Taiwan (Figure 1). Three catastrophic earthquakes (Meishan, Hsinchu-Taichung, and Chi-Chi) caused thousands of deaths in the past century. In recent decades, the disaster vulnerability has increased because of population concentration and complex infrastructures constructed in urban areas. If a large-scale earthquake like the Chi-Chi earthquake occurred in metropolitan cities, the induced casualty and loss may become several times of those in 1999. After the Chi-Chi earthquake, remarkable progress on disaster prevention has been achieved by central and local governments. However, the capability of disaster resilience against large-scale earthquakes should be examined under vulnerable environmental conditions. Detailed impact analysis for various levels of disaster scenarios is necessary for disaster prevention planning.

No.	Earthquake	Date	Magnitude (M_L)	Depth (km)	Casualty	
					Ceased	Injured
1	Douliou	1904/11/06	6.1	7.0	145	158
2	Meishan	1906/03/17	7.1	6.0	1,258	2,385
3	Nantou Series	1916/08/28	6.8	45.0	71	285
		1916/11/15	6.2	3.0		
		1917/01/05	6.2	0.0		
		1917/01/07	5.5	0.0		
4	Hsinchu-Taichung	1935/04/21	7.1	5.0	3,276	12,053
5	Chungpu	1941/12/17	7.1	12.0	358	766
6	Shinhua	1946/12/05	6.1	5.0	74	182
7	Longitudinal Valley Series	1951/10/22	7.3	4.0	>85	>1,000
		1951/10/22	7.1	1.0		
		1951/10/22	7.1	18.0		
		1951/11/25	6.1	16.0		
		1951/11/25	7.3	36.0		
8	Hengchun	1959/08/15	7.1	20.0	17	85
9	Paiho	1964/01/18	6.3	18.0	106	653
10	Hualien	1986/11/15	6.5	15.0	13	45
11	Chi-Chi	1999/09/21	7.3	8.0	2,405	11,305
12	Taoyuan	2010/03/04	6.4	5.0	0	96
13	Meinong	2016/02/06	6.6	14.6	117	551

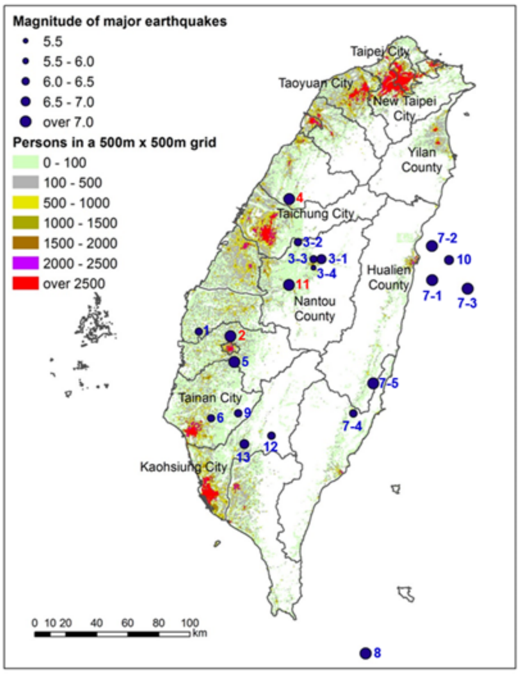


Figure 1. Location of disastrous earthquakes and population distribution in Taiwan

A MESH-BASED EARTHQUAKE IMPACT ASSESSMENT TOOL

Verity of analysis modules by means of the state-of-the-art techniques in conjunction with the inventory database were built in an open platform on the basis of mutual cooperation among the academic institutions, governmental agencies, and NCDR (Figure 2). Considerable efforts were devoted to construct the inventory database, including building, population, infrastructure, and lifeline system. The TERIA platform [1, 2] is capable of analyzing the response of ground motion, potential of liquefaction and landslide, casualty, damages of building, road, bridge, electricity, and portable water facility. With variety of inventory database constructed in this study, the analytical results in a 500 m × 500 m mesh at different layers can be integrated to interpret the disaster scenario in details.

Database of Portable Water System

The basic data of portable water system, including wells, treatment plants, pumping plants, and water pipeline, was obtained from the Taipei Water Department and Taiwan Water Corporation. The original files in various formats, such as SHP, UIF, DWG, were processed to retrieve the attribute to assemble a database covering the entire Taiwan (Figure 3). Table 1 shows the classification of brittle and ductile pipelines based on pipe materials.

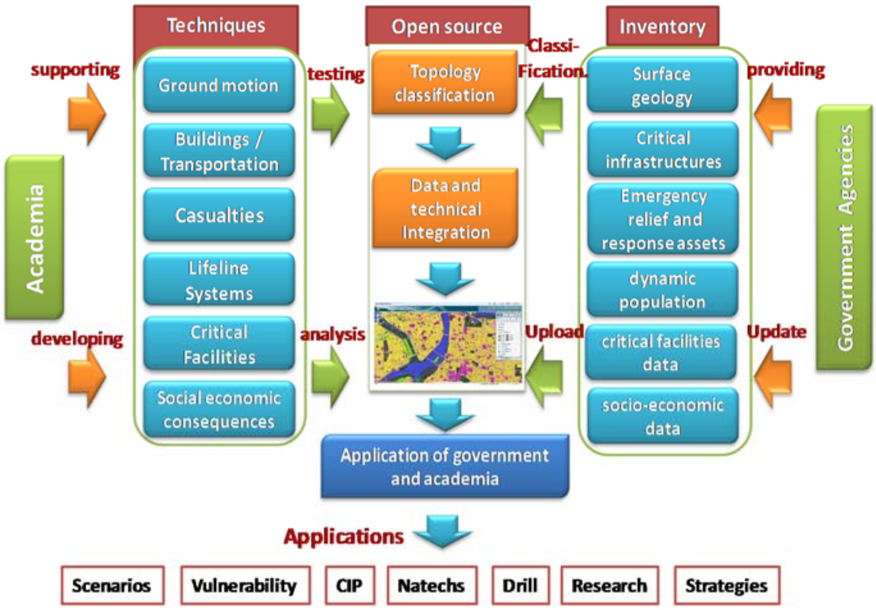


Figure 2. Framework of TERIA platform

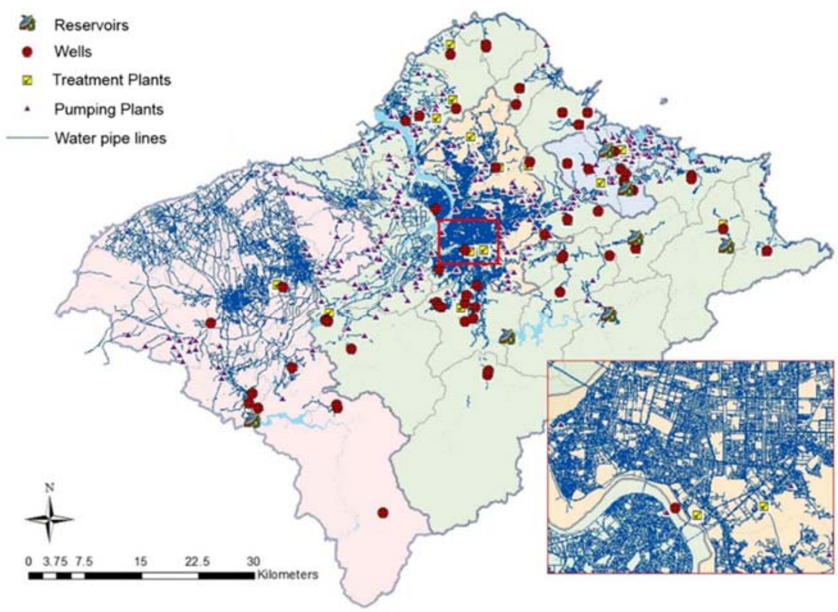


Figure 3. Database of portable water system

TABLE I. CLASSIFICATION OF PIPE MATERIAL [2]

Type	Material
Brittle pipeline	ACP, CIP, PCCP, PCV, PCVP, PCV/PE, PCVP+DIP, PCVPE. RCP
Ductile pipeline	Others

Damage Function for Portable Water Facility

The probability of damage (p) due to ground motion for portable water facility, including wells, treatment plants, pumping plants, and storage tanks, can be interpreted by the log-normal distribution in a cumulative distribution function [3]:

$$p = \frac{1}{2} + \frac{1}{2} erf\left(\frac{\ln PGA - m}{\sqrt{2}\beta}\right) \quad (1)$$

where m is the median, β is the standard deviation. Table II lists the median and standard deviation of damage function for portable water facilities.

TABLE II. PARAMETERS OF DAMAGE FUNCTIONS FOR PORTABLE WATER FACILITIES [3]

Facility	Capacity/Type	m	β
Water Treatment Plant	Small	0.38	0.50
	Medium	0.52	0.40
	Large	0.58	0.40
Pumping Plant	Small	0.36	0.65
	Medium/Large	0.36	0.65
Well	Small	0.36	0.65
On-Ground Anchored Storage Tank	Concrete	0.52	0.70
	Steel	0.70	0.60

Damage Functions for Buried Pipelines

The repair rate, *RR*, associated with peak ground velocity (PGV) and permanent ground deformation (PGD) which is induced by soil liquefaction can be calculated by the following equations [3]:

$$RR_{PGV}[\text{Repairs/km}] = 0.0001 \times (PGV)^{2.25} \quad (2)$$

$$RR_{PGD}[\text{Repairs/km}] = Prob[liq] \times (PGD)^{0.56} \quad (3)$$

where *PGV* is expressed in cm/sec, *PGD* is expressed in inches, *Prob*[*liq*] is the probability of liquefaction. The number of repairs in a grid for brittle and ductile pipelines is:

$$R_{brittle} = (RR_{PGV} \times 20\% + RR_{PGD} \times 80\%) \times L \text{ ; for brittle pipeline} \quad (4)$$

$$R_{ductile} = 30\% \times (RR_{PGV} \times 20\% + RR_{PGD} \times 80\%) \times L \text{ ; for ductile pipeline} \quad (5)$$

where *L* is the total length of pipeline in a grid. The damage rate in a grid is:

$$\alpha = (R_{brittle} + R_{ductile})/L \quad (6)$$

The probability of damage for pipelines can be expressed by a log-normal function:

$$p = \frac{1}{2} + \frac{1}{2} erf\left(\frac{\ln \alpha - m}{\sqrt{2}\beta}\right) \quad (7)$$

where m is the median, β is the standard deviation. Figure 4 illustrates the analysis steps for the portable water system. The distribution of ground motion, using an input source of either point, line, or user-defined distribution, can be predicted in a mesh of 500 m × 500 m. Accordingly, the seismic impact to the portable water system can be analyzed utilizing the database and damage functions for water facilities and pipelines.

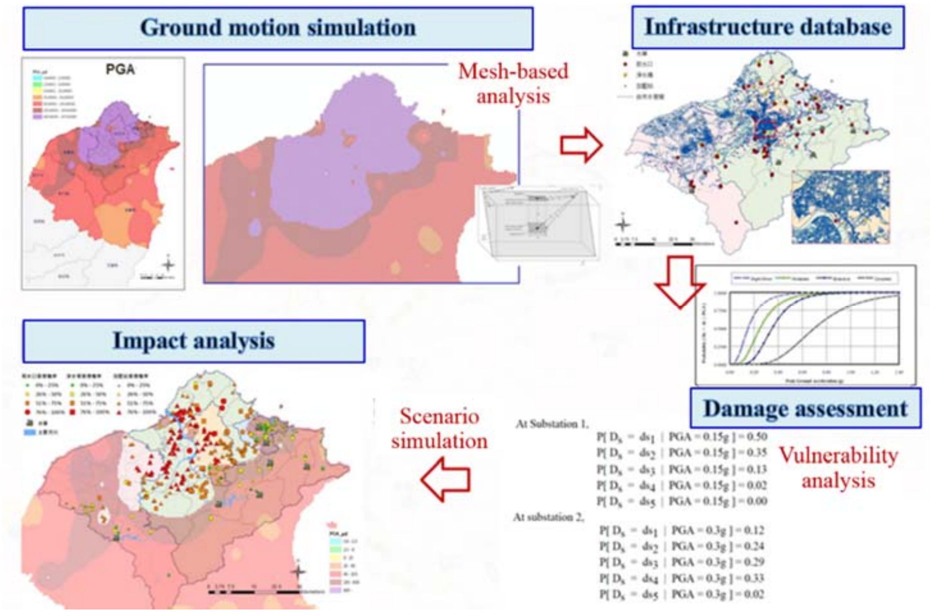
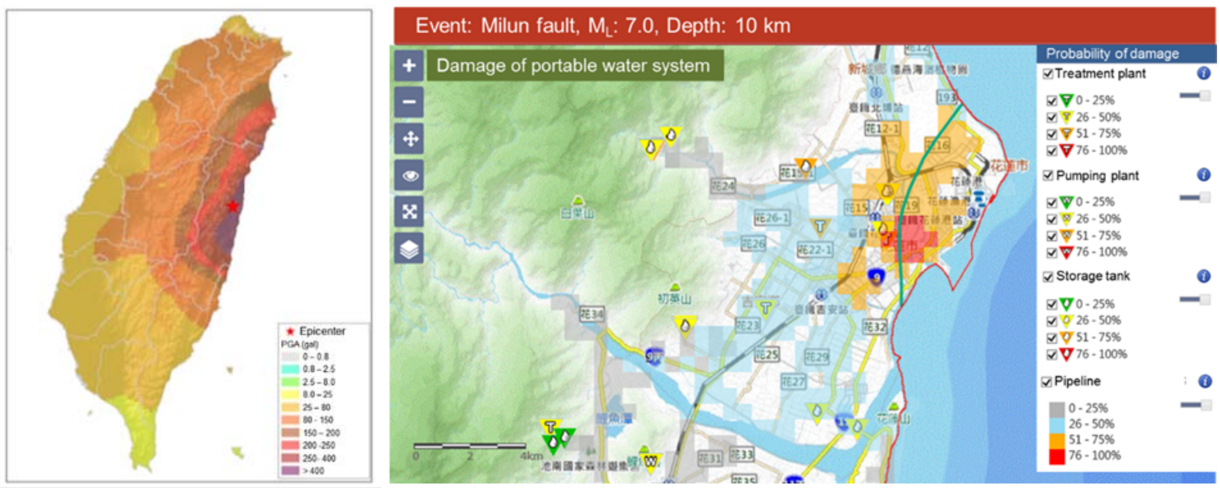


Figure 4. Analysis flow chart

SCENARIO SIMULATION FOR THE NATIONAL EARTHQUAKE DRILL

A major earthquake (M_L=7.0, depth=10 km) on the Milun Fault in Hualien county was assumed as the source of scenario simulation for the National Earthquake Drill on September 21, 2014. The Central Emergency Operation Center was operated by government officials from central ministries to provide assessments and suggestions to the commander. Figure 5 (a) shows the distribution of peak ground acceleration (PGA). The maximum PGA in areas close to the epicenter exceeds 400 gal. The damages of water facility and pipeline were evaluated by TERIA platform (Figure 5b). The probability of damage for pipeline is greater than 75% in downtown Hualien city which implies the portable water possibly cannot be transmitted to end users. The probability of damage for some pumping plants and storage tanks exceeds 50% where some damages may be found and need manual repairs.



(a) Distribution of PGA (b) Damage assessment of portable water system

Figure 5. Scenario simulation for the National Earthquake Drill in 2014

The evaluation results in a 500 m × 500 m mesh for casualty, buildings, roads, bridges, electricity, and portable water system can be integrated to interpret the disaster scenario in details (Figure 6). The building damage and casualty are serious in downtown Hualien city which need emergency rescue and medical care. However, many bridges have high possibility of damage (greater that 75%) which may influence the transportation of resources from the other counties. The probability of damage for portable water system is larger than 50% which implies some areas may be short of water supply. Some water tankers should be prepared for disabled welfare and nursing institutions in those areas.

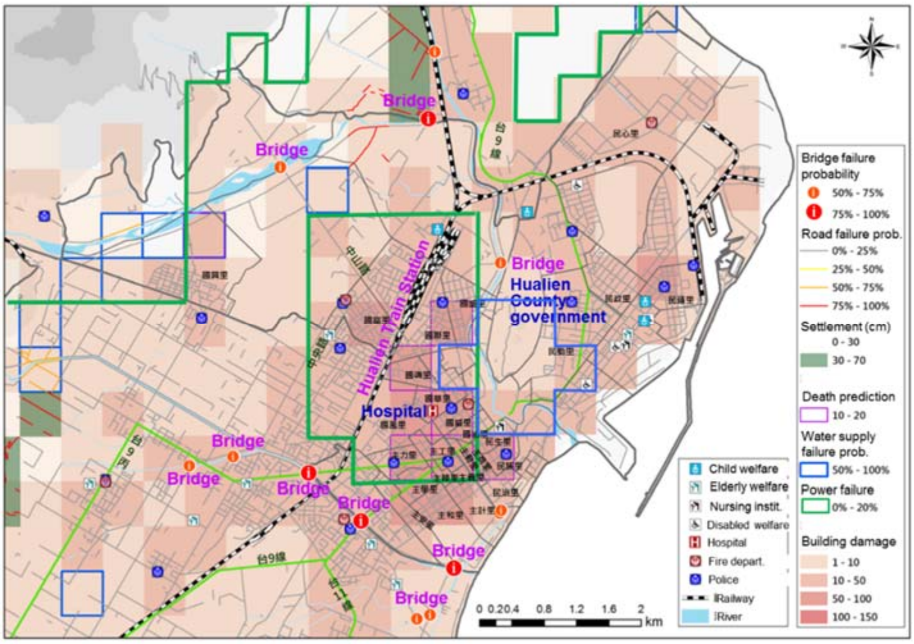


Figure 6. Summary of scenario simulation in Hualien city for the National Earthquake Drill in 2014

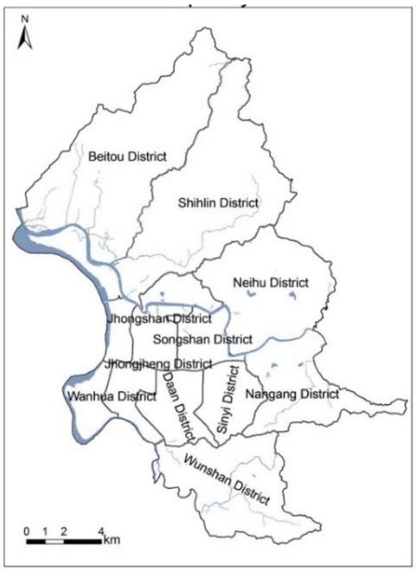
IMPACT ANALYSIS FOR POLICY SUGGESTION ON DISASTER MANAGEMENT

Scenario simulations in various levels of seismic excitations were applied to evaluate the disaster-resistant capability for disaster management. Three levels of input sources, including Intensity V (240 gal), Intensity VI (320 gal), and Intensity VIII (450 gal), were assumed as uniform acceleration distributed in Taipei city to check the weak points and their distributions (Figure 7).

Intensity level	Acceleration range	Scenario setting
V	80~250gal	240gal*
VI	250~400gal	320gal*
VII	>400gal	450gal**

* Based on the building code in return periods of 475 and 2500 years
**According to the average PGA measured in the central Taiwan for the Chi-Chi earthquake

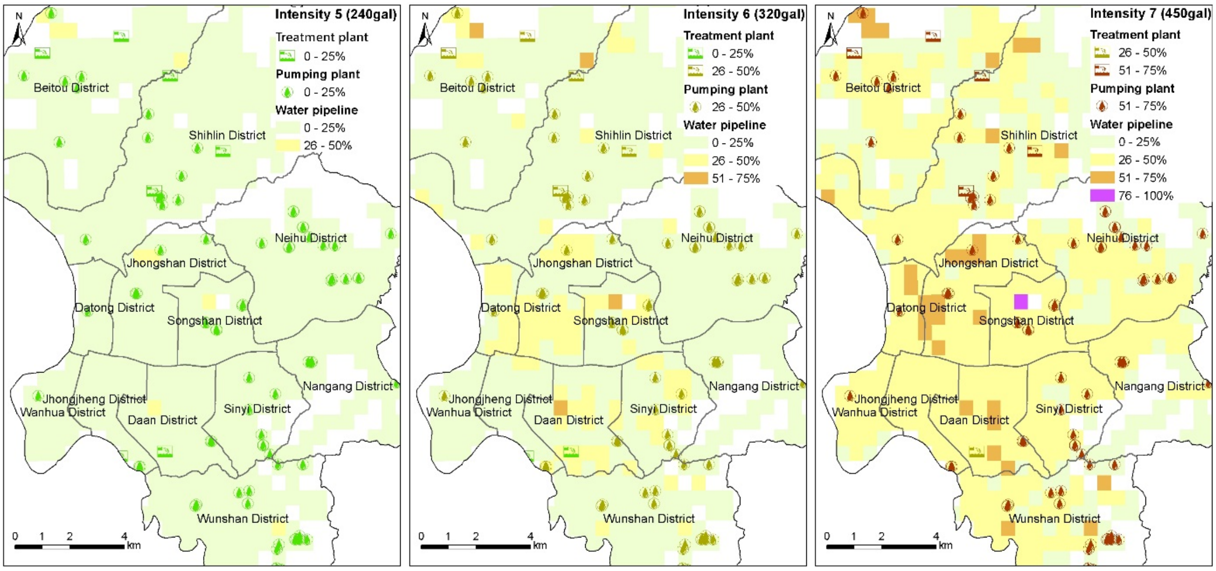
(a) Scenario setting



(b) Taipei city

Figure 7. Input sources of scenario simulations for Taipei city

From the simulation results in three levels for portable water system (Figure 8), the probabilities of damages and the extents of influence areas for treatment plants, pumping plants and water pipelines all increase as the PGAs increase. For the scenario of Intensity VII, the probability of damage is high as more than 75% and most of the treatment plants and pumping plants have probability of damage greater than 50%. Shortage of portable water supply could be expected in some districts such as Songshan and Jhongshan.



(a)Intensity 5 (PGA=240 gal) (b)Intensity 6 (PGA=320 gal) (c)Intensity 7 (PGA=450 gal)

Figure 8. Damage assessment for 3 intensity levels

In summary of simulation results for Intensity VII (Figure 9), there are more than 5,000 building seriously damaged and approximately 6,000 injury and death. The demand of medical care is larger than 4,000 which needs 2,000 to balance. The sheltering demand is more than 190,000 which is overloaded and need 30,000 to balance. Most of the cross-river bridges may be failed to transportation of resources. Power failure in the whole city could interrupt the communication and emergency operation of government. Based on the simulation results, some policy suggestions were proposed by the Disaster Prevention and Protection Expert Consultation Committee to the Executive Yuan to improve the framework of disaster management: (1) Launch a task force for configuration and promotion; (2) Inter-ministry coordination and administrative mechanism; (3) Enhance the resilience and continuity operation of infrastructure; (4) Promote the application of scenario simulation on disaster management.

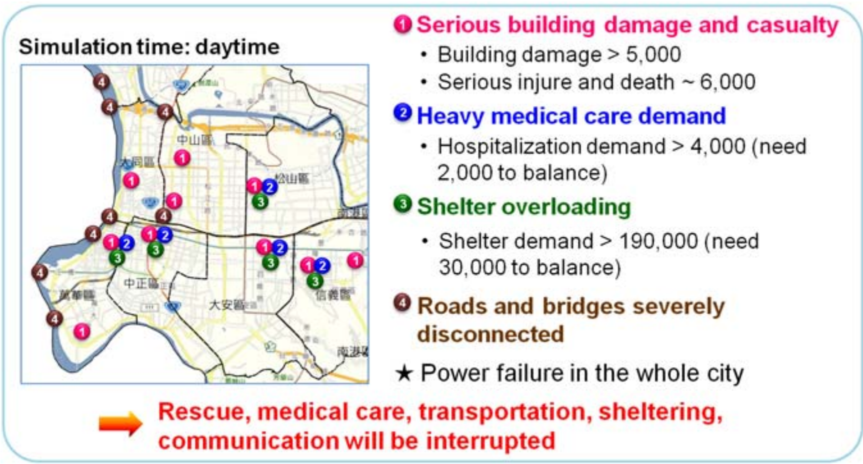


Figure 9. Summary of disaster scenarios for Intensity VII

CONCLUSIONS

The TERIA platform is capable of analyzing the response of ground motion, potential of liquefaction and landslide, casualty, damages of building, road, bridge, electricity, and portable water system. The scenario simulations for various levels of excitations interpreted in a mesh of 500 m × 500 m are helpful to disclose the possible disaster scenarios in details. Those accomplishments have been applied to the operation of the National Earthquake Drill and the policy suggestions for disaster management. The practical applications may enable a thorough planning for enhancing the disaster resilience against future major earthquakes.

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Study report of priority evaluation of earthquake resistance on water supply facilities focused on the restoration process of water supply

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1. INTRODUCTION

The priority evaluation of earthquake resistance is determined by the earthquake performance, the role as water supply base of an emergency, the presence of water supply to hospitals and shelters, and a degree of difficulty of recovering.

On the other hand, it is common to be shown the effect of earthquake resistance as using the indices of an earthquake resistance rate of water distribution stations, water purification plants and water pipes. These indices are effective to manage the progress of earthquake resistance on water facilities for water supply utilities, but it is difficult to understand the effect of earthquake resistance for water users. It is important for water users to know when we can be supplied water and water facilities get recovered, so it is considered that it would be more understandable for water users to put "the number of recovering days" and "suppliable water amount" into the indices of an effect earthquake resistance.

Therefore, we carried out a priority evaluation as indices of an effect of earthquake resistance focused on the restoration process of water supply with the aim of clarifying the effect of earthquake resistance from water user's point of view.

2. STUDY CONDITIONS

Evaluation Method

The estimation method is shown in Figure 1.

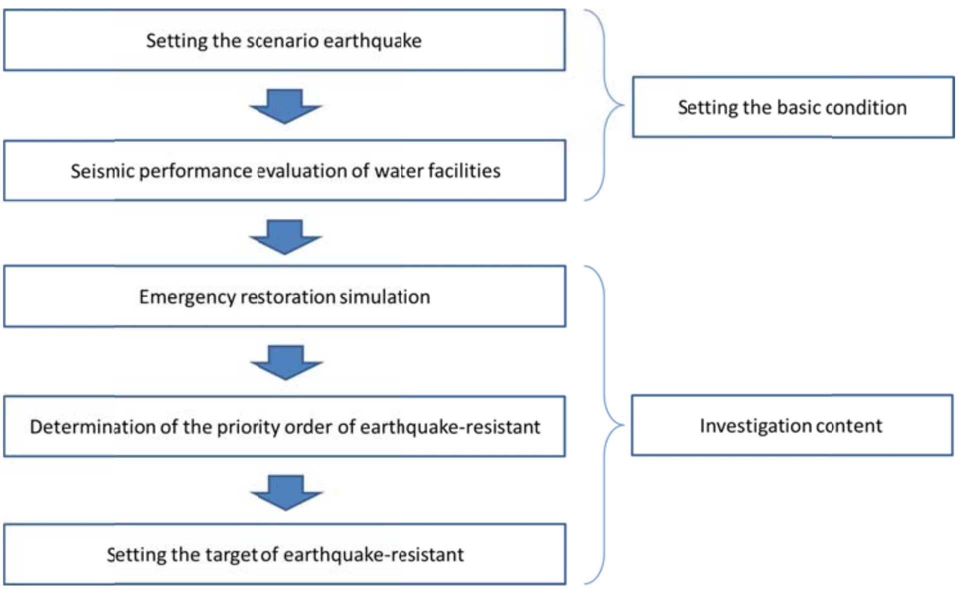

Figure 1 Evaluation method of the investigation

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Target Area

The target area on this report is located in Tokai area and has 700,000 people designated. It is located nearby the coast Pacific Ocean and it is consisted of a plain mainly for residents and northern mountainous areas.

Severe Earthquake Fault Model and Hypocentral Distribution

We selected Nankai Trough Earthquake as a scenario earthquake which is used in earthquake-resistant plan. Nankai Trough is about 4000m deep trench which is located in south of coast of Shikoku and regarded as large-scale earthquake occurrence area. The focal area of a scenario earthquake is between Suruga Bay in east part and Palau Oceanic Ridges in south west part. In deep direction, the range is regarded as about 40km which is from the trough axis to low frequency earthquake occurrence area which is a little bit deeper from the border of the plate.

The distribution of seismic intensity of Nankai Trough Earthquake is shown in Figure 2[1). It is assumed that strong quakes would be taken place in wide area of southern part of Japan.

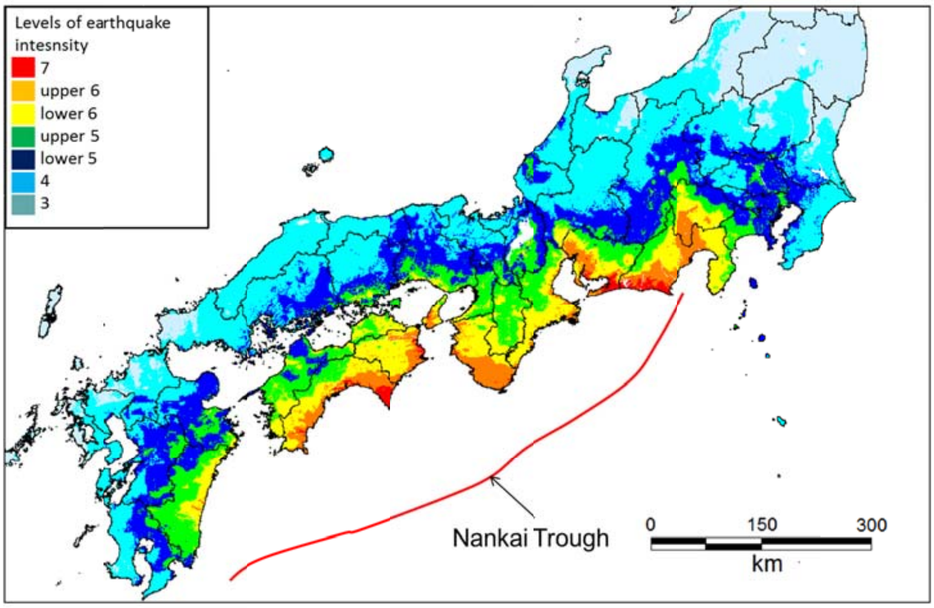

Figure 2 The maximum seismic intensity distribution[1)

We determine 4 areas where the strong earthquake would occur by strong wave calculation based on the characteristics of Pacific Coast of Tohoku Earthquake and magnetic earthquakes occurred in the world, and predict the degree of seismic intensity in each area.

There are 4 cases of seismic distribution data and we determined the case that would get damaged at the most. Figure 3 shows the distribution of seismic intensity of the subject area.

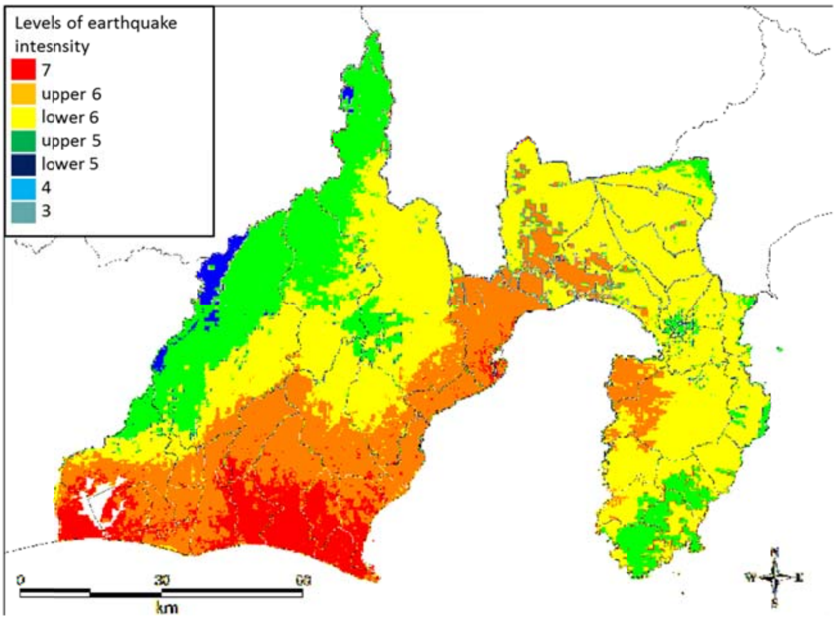

Figure 3 Seismic intensity distribution of the subject area

3. SEISMIC PERFORMANCE EVALUATION OF WATER FACILITIES

Civil Structures

Seismic performance evaluation of civil structures is that we reflect seismic detailed diagnosis that is conducted between 2013 and 2015, and we evaluate civil structures based on the established year and ground conditions. Then, we determine seismic properties in each level of earthquake. Figure 4 shows the flow chart of the evaluation for civil structures.

According to the diagnostics result, if the structures are diagnosed with not securing seismic performance of level 2, we evaluate them again based on the seismic intensity distribution of Nankai Trough earthquake. If the structures haven't diagnosed yet, we reflect the information of the scenario earthquake in each region and evaluate whether the structures get damaged or not based on the established year, construction method, ground conditions and base method.

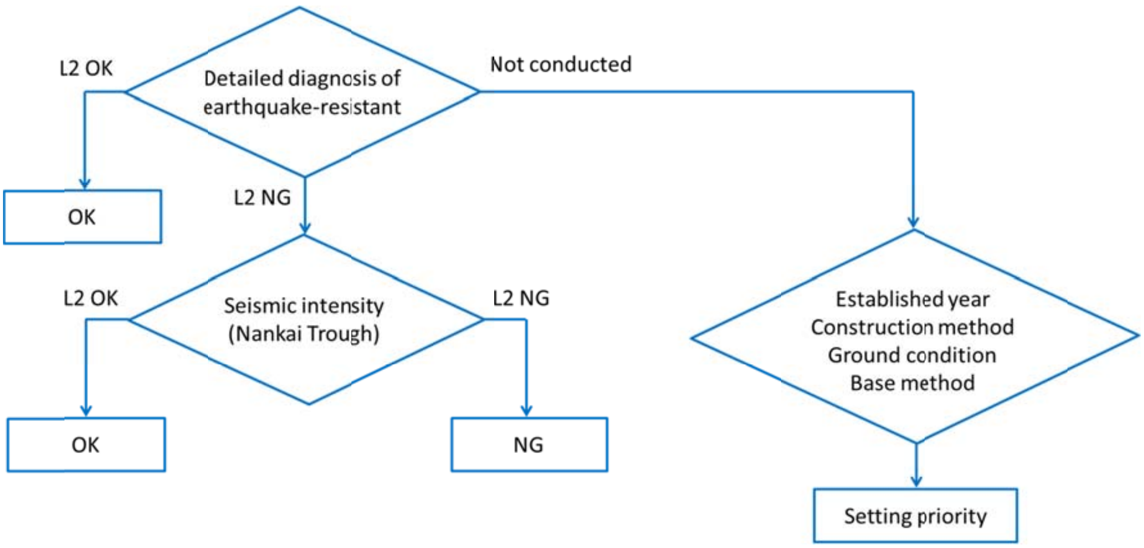

Figure 4 Flow chart of the evaluation for civil structures

Table 1　Estimation of earthquake-resistant

Category	Seismic Performance	Content	Estimation Standard
1	OK	Securing seismic performance of level 2	・OK by seismic detailed diagnosis ・“Ⅰ”structures or “Ⅲ”structures with great ground condition
2	Not necessary	Securing seismic performance of level 1	・“Ⅱ” and Rank B structures
3	Not good	Securing seismic performance of level 1	・“Ⅱ” structures with great ground condition ・“Ⅲ”structures without great ground condition
4	Bad	There is a possibility getting damaged	・NG by seismic detailed diagnosis ・“Ⅱ” structures without great ground condition ・Neither “Ⅰ”“Ⅱ” “Ⅲ”

Ⅰ：Structures built after 1997（made of RC,PC or Steel）
Ⅱ：Structures built after 1979（made of RC） or built after 1985（made of Steel）
Ⅲ：Structures with spread foundation built after 1980（made of PC and its capacity is less than 10,000 ㎥）
Current seismic standard : seismic performance in “The ordinance of technical standards on water facilities”[2)]

According to the result of the seismic performance evaluation, 80% of the water intake stations could not secure the seismic performance and 40% of purification stations could not secure the seismic performance, either. 50 % or more of the water supply facilities are not securing seismic performance due to the established year, and it may severely damage a lot of water facilities.

Water Pipes

Seismic performance evaluation of water pipes is that we predict the damage by earthquakes using pipeline damage prediction equation[3)].

$$R_m(v)\ (\text{spot/km}) = C_p \times C_d \times C_g \times C_l \times R(v) \qquad \text{(Eq.1)}$$

$$R_m\ (\text{spot}) = R_m(v) \times L \qquad \text{(Eq.2)}$$

（※（Japan Water Works Association)）

- Breakage rate : $R_m(v)$
- correction factor for type of pipe : C_p
- correction factor for pipe diameter : C_d
- Correction factor for terrain and soil : C_g
- Correction factor for liquefaction : C_l
- Maximum acceleration of seismic motion : v
- Breakage ratio（spot/km） : R（v）
- The number of breakage in mesh : R_m
- Length of pipes in mesh（km） : L

As a result of the seismic damage prediction, we get damaged on water pipes in 1566 places and the breakage ratio is 0585 spot/km. This breakage ratio is between Kobe and Nishinomiya when Hyougoken-Nambu Earthquake occurred and it would take a lot of time to restore.

We calculate the supply interruption rate from the breakage ratio in each region. The supply interruption rate is calculated by the relation between available water supply ratio and breakage ratio[3]. As a result, the total the supply interruption rate is 71.2% and it resulted that it influences water supply in wide range area.

Table 2 Breakage ratio in each region

Region	Ratio of water outage (%)	Length (km)	Number of the breakage	Breakage ratio (spot /km)	Restoration term (day / squad)
A	45.24%	1192	597	0.318	1543
B	64.15%	338	172	0.488	362
C	55.03%	808	683	0.455	1315
D	25.20%	206	63	0.174	207
E	44.00%	77	23	0.294	49
F	66.80%	56	29	0.507	56
Total	73.50%	2677	1566	0.585	3532

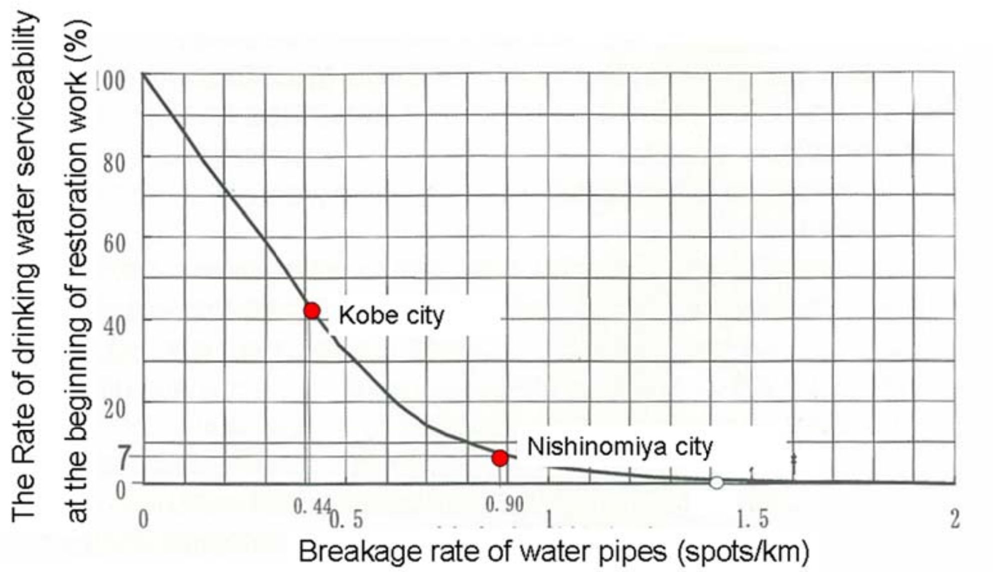

Figure 5 Rate of drinking-water serviceability at the beginning of restoration work[4]

4. EMERGENCY RESTORATION SIMULATION

Basic Policy

We predict emergency restoration term based on the result of estimating disaster on water facilities. The supply interruption term tends to be subject to the emergency restoration of water pipes so it is assumed that the restoration term should be calculated by the damage of water pipes[4], but we obtained the result that main facilities could get a lot of damages due to the damage prediction of civil and architect structures, too. Therefore, it would be adequate to consider the emergency restoration of water facilities in purification stations as well.

Restoration Speed of the Structures

We determine the emergency restoration term of each water facilities from the past big earthquake disasters. Table 3 shows the emergency restoration term of water facilities. These values show emergency restoration and we don't estimate the repairing and reinforcement.

Table 3 Emergency restoration term of water facilities

Name of water failities		Restoration term (day)
Purification stations	Rapid filtration (not securing sesmic performance)	30
	Slow filtration (not securing sesmic performance)	30
	Rapid filtration (securing sesmic performance)	15
	Slow filtration (securing sesmic performance)	15
	Membrane filtration	3
Water sources		3
Distribution stations		3
Pumping stations		3

Restoration Speed of the Water Pipes

Table 4 shows the restoration speed of water pipes of each diameter. We calculate the emergency restoration term of water pipes based on the restoration speed[4) and the restoration speed of its diameter of 700mm or more is calculated by "Earthquakes Countermeasure Manual Guidance"[3)

Table 4 Restoration speed of water pipes[4)5)

Diameter(mm)	Restoration speed (spot/squad・day)
φ700～	0.20
φ500～600	0.25
φ300～450	0.50
φ200～250	1.00
φ150	1.00
φ100	2.00
～φ75	2.00

Setting the Restoration Process

On this investigation, we set that 70 emergency restoration squads would be sent to the damaged portions in the subject area for one day, and they are supposed to restore water facilities stepwise. The number of squads is calculated by population served and the scale of the earthquake[6). The number of restoration squads in each area is determined by the ratio of the restoration term in each area to the total of restoration term. We multiple this ratio by 70 squad/day and set the number of restoration squads in each area. In terms of the restoration, we can't send water to the residents when purification stations got damaged even if feeder pipes are restored perfectly. Therefore, we restore water facilities from water intake stations in order. Figure 6 shows the restoration step of water facilities.

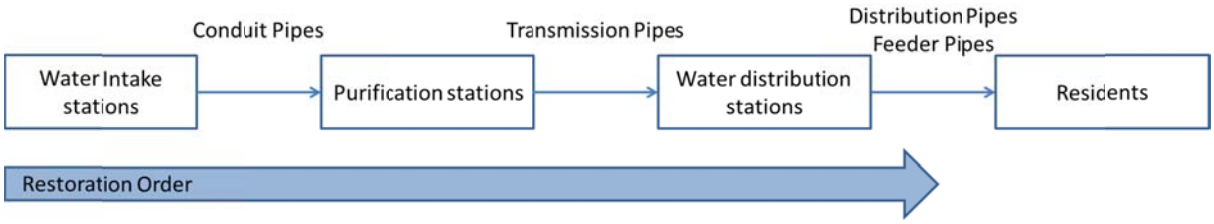

Figure 6 Restoration step on water facilities

Result

We found out the available water supply and target water supply from the restoration speed and restoration process, and available water supply is calculated from the restoration status of distribution pipes and feeder pipes when it is restored by the method. Target water supply is determined by the earthquake countermeasures of waterworks of the subject area. Then, we calculate the deficient term of emergency water supply in each area and we assume that water facilities started to be restored from the area that has longer deficient term. Further, we defined that the deficient term of emergency water supply is between the occurrence of the earthquake and the time that available water supply exceeds target water supply. Figure 7 shows deficient term of emergency water supply and restoration process. According to the figure, the water facilities are restoring in the order of water intake stations, conduit pipes, purification stations, and water supply starts increasing when feeder pipes are restored. Then, available water supply starts increasing at the same time that water distribution stations and distribute pipes are restored, and water supply would be stable when the end of the feeder pipes are restored.

On the investigation, we state the calculation method of a priority order using 4 areas of the deficient term. Figure 8 shows the transition of target water supply and available water supply in each area, and Table 5 shows the restoration term and priority order in each area.

As you can see the Table 5, area “d” has the longest term of the restoration of feeder pipes and distribution pipes, and it would get damaged at the most. In area “c”, it takes a lot of time to recover conduit pipes and transmission pipes, but distribution pipes and feeder pipes are restored in 2 weeks and necessary water supply are secured and the deficient term is shortest.

In this way, we focus on the deficient term of emergency water supply and promote the earthquake resistance countermeasure from the longest deficient term.

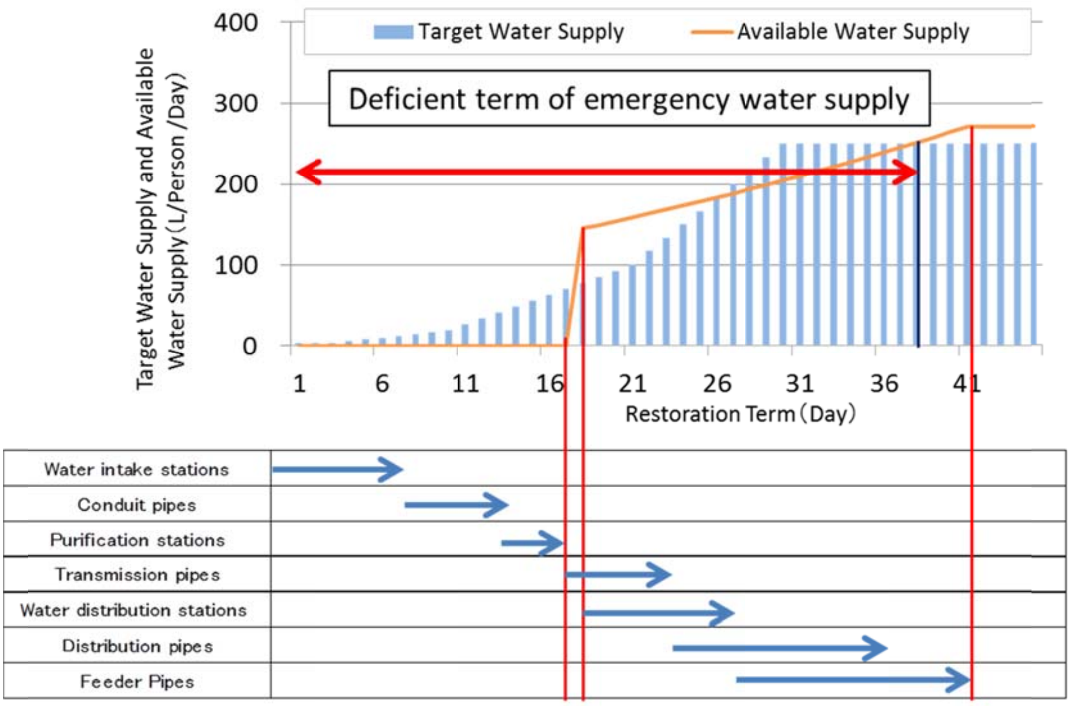

Figure 7　Deficient term of emergency water supply and restoration process

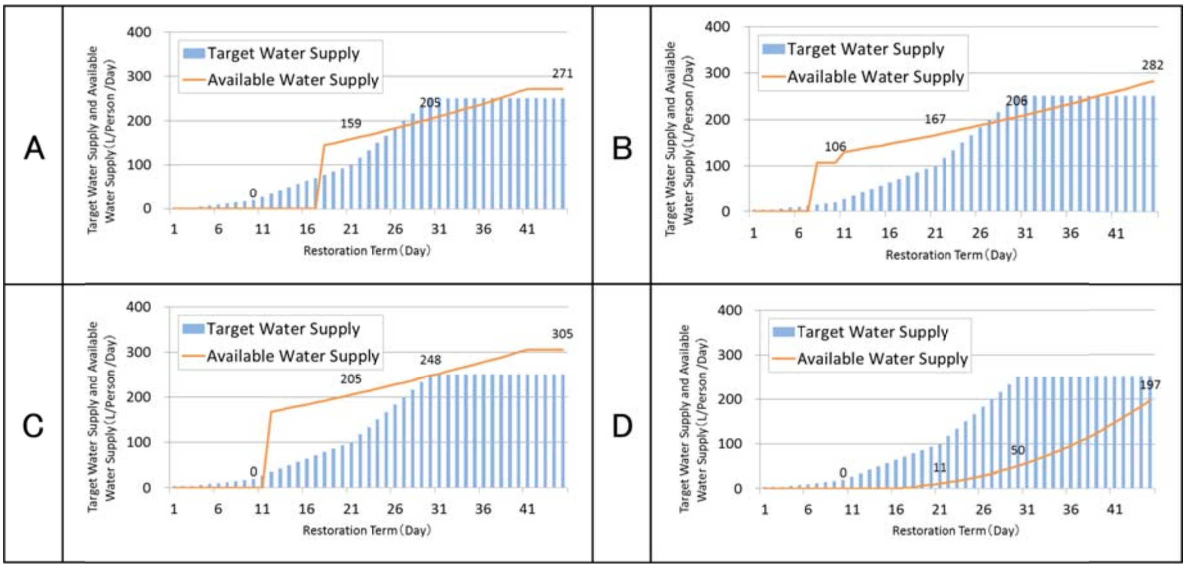

Figure 8　The transition of target water supply and available water supply in each area

Table 5　Setting priority order in each area

Area	Restoration term (day)			Restoration group (squad/day)	Priority order
	Conduit pipes and transmission pipes	Purification station	Distribution pipes and feeder pipes		
A	17	19	38	3	2
B	8	–	37	8	3
C	12	–	12	7	4
D	14	33※	45以上	28	1

※ It is restoring in stages.

5. SETTING THE TARGET OF EARTHQUAKE-RESISTANT

We mentioned how we set the order in each area in preceding paragraph, but the deficit of water flow would be different depending on the order of restoring water facilities.

Figure 9 shows restoration simulation before earthquake resistance in area “A”. As you can see the figure, from the occurrence of the earthquake to the 16th day, it would hardly supply water when conduit and transmission pipes are damaged even if feeder pipes are restored completely, so we need to restore conduit and transmission pipes to secure water supply. Therefore, it is considered that we reduce the damage of conduit and transmission pipes and we secure the available water supply right after the earthquake occurred.

The amount of available water supply started to be restored when conduit and transmission pipes recovered, but emergency water supply get to be deficient between 28th day and 33rd day. During this time, it is considered distribution and feeder pipes are not restored completely and they can’t afford enough water supply. Therefore, we need to take countermeasures of distribution and feeder pipes to afford enough water supplies during this period.

Figure 10 shows restoration simulation after earthquake resistance in area “A”. We assume that we reinforce 15% of conduit and transmission pipes and 10% of distribution and feeder pipes, and the reinforced pipes are not supposed to get damaged when the earthquake occurred. As you can see the graph, the available water supply exceeds the target water supply and it is considered that water supply is secured in this area even if Nankai Trough Earthquake occurred.

Thus, we set the target of earthquake resistance to secure necessary amount of water and make the effect of earthquake resistance visible. It is considered that we can show the earthquake resistance plan which is understandable for water users.

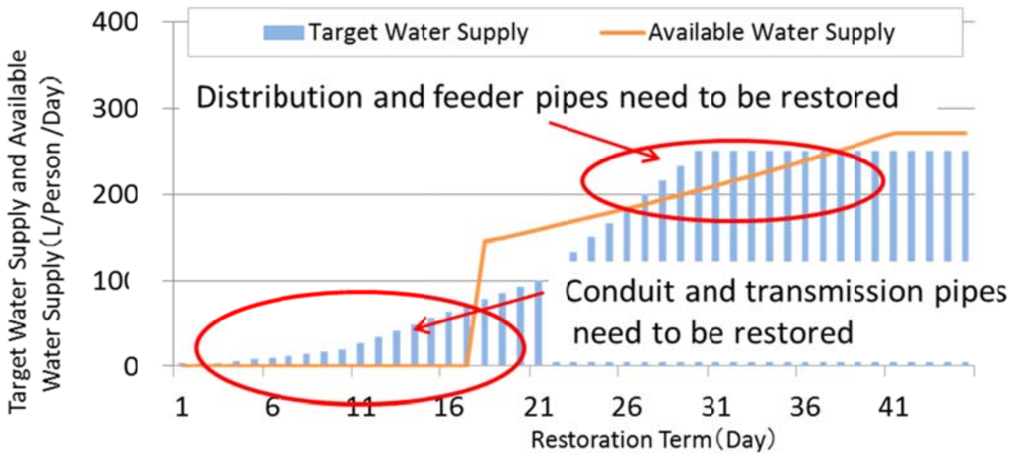

Figure 9 Restoration simulation before earthquake resistance in area “A”

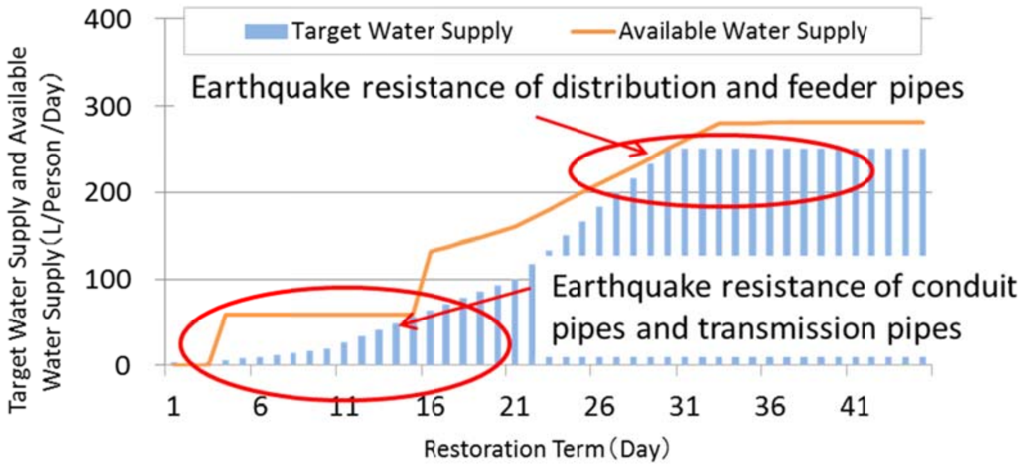

Figure 10　Restoration simulation after earthquake resistance in area “A”

6. CONCLUSION

On this investigation, we focused on the restoration process of water flow and carried out the priority evaluation of earthquake-resistance. We could show the understandable effect of earthquake-resistance for water users. We chose an examination target as a main city on this report, but if it is a small city, the number of restoration groups would be restricted and it is expected that there will be many water facilities that are not securing seismic performance. Therefore, we intend to carry out the restoration simulation on small cities and we will investigate the difference of restoration process between big cities and small cities.

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The Prioritized Pipeline Maps for Emergency Restoration

Keita Katae, Haruka Utada

ABSTRACT

In previous earthquake disasters, the water supply facilities suffered serious damage. It required considerable time for them to be restored, which impacted citizens of the area greatly. The 2016 Kumamoto Earthquake also caused a lot of water pipeline damage especially on service pipes and harmed the water supply. Water utilities from all over Japan, including the Yokohama Waterworks Bureau, helped emergency restoration of the water supply in the disaster area. The damage restoration efforts must share their experiences, which will allow effective measures to be taken in order to prepare for earthquakes in the future.

Meanwhile, in Yokohama, we have been replacing aged pipes with earthquake-resistant pipes, establishing emergency water supply stations, encouraging stocking of drinking water, and implementing citizen-participation in emergency water supply drills as earthquake measures.

Moreover, we have learned much through the assistance efforts in Kumamoto. As such, we have created prioritized pipeline maps for emergency restoration in case of earthquake disaster in Yokohama. When receiving external assistance/relief from other water utilities, the maps will serve as effective explanation material. Furthermore, we will consider the idea of emergency restoration of the water supply and sewage facilities in cooperation with offices that manage sewage works in Yokohama City.

In this paper, we report on the contents of the maps, the way of thinking, and future prospects.

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DETAILS

Outline of Water Supply in Yokohama City

Yokohama City has a population of about 3.73 million and about 1.67 million households (July 1, 2017) [1]. The area is about 437.49 km^2. Due to many hills and valleys, there are areas where water is supplied by gravity flow and pump systems. The Yokohama water distribution block system is made up of a total of 41 blocks including 24 pump systems and 17 gravity flow systems in order to provide a stable water supply to the entire city (Figure 1).

In order to grasp the flow rate, water pressure, water quality, etc. from the intake weir to the water distribution facility, measurement facilities were installed at 248 major points along the distribution reservoirs, the main distribution pipes, and the distribution pipes, and constant measurements are carried out. We can acquire the data at the information terminal at each office and an alarm is issued when an abnormal value is indicated.

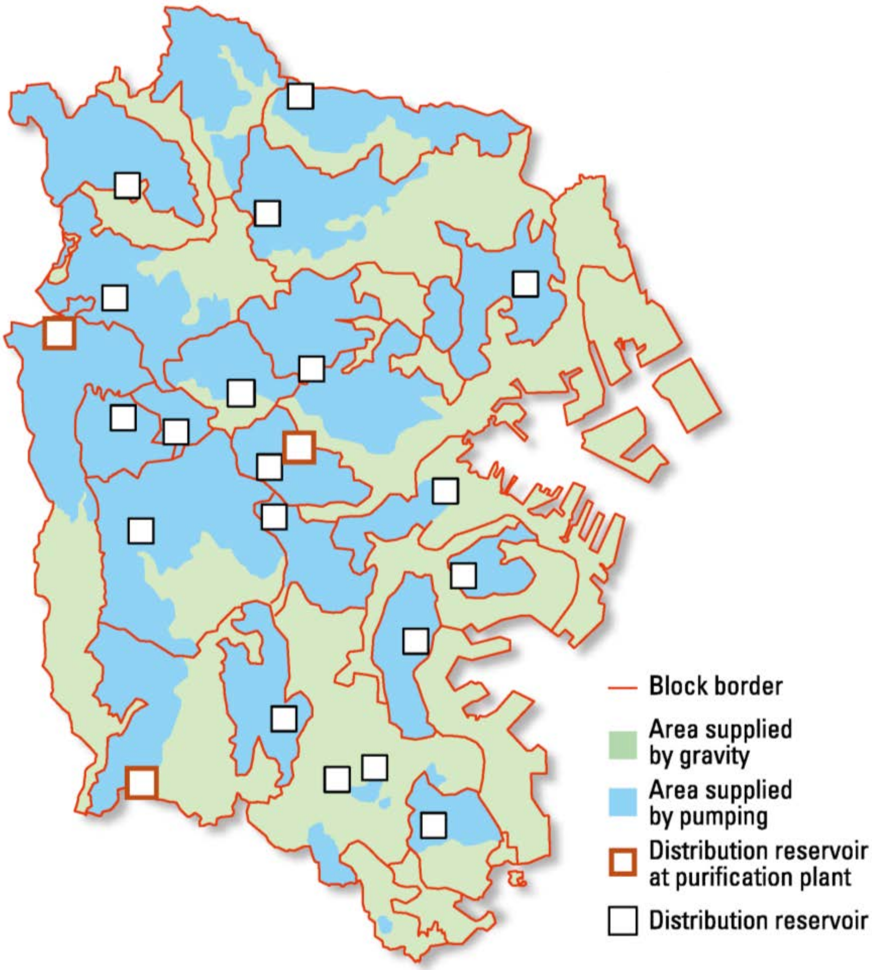


Figure 1. Yokohama water distribution block system

Earthquake Countermeasure of the Water Supply in Yokohama City

Japan is one of the countries where earthquakes occur most frequently. During the Great Kanto Earthquake that occurred in 1923, a maximum seismic intensity of 6 on the Mercalli intensity scale was recorded in Yokohama City, and severe damage occurred across the city. According to the Headquarters for Earthquake Research Promotion in 2017 report, the probability of ground motion equal to or larger than seismic intensity 6 Lower on the Japan Meteorological Agency seismic intensity scale, occurring within 30 years from the present, is estimated at 81% in Yokohama [2]. In order to maintain an essential lifeline for daily living, it is urgently necessary to take effective measures against any future earthquakes.

In Yokohama, we have taken earthquake measures as follows. From FY1996, we have been replacing aged pipes with earthquake-resistant pipes. In a Middle-term management plan from FY2016 to FY2019, we plan to replace 110 km of aged pipes annually and our target rate for earthquake-resistant water transmission and distribution pipes is 28%, and the rate for the main water pipes is 68% by FY2019 [3]. Moreover, we have begun establishing 358 emergency water tap stations and 134 underground water supply tanks for emergencies at important facilities in disasters, such as local disaster prevention centers. The taps and tanks are directly connected by earthquake-resistant pipes from the water distribution pipes of 400 mm or more. The underground water supply tanks contain 118 tanks with a capacity of 60 m^3, 11 tanks with a capacity of 100 m^3, and five tanks with a capacity of 700 to 1,500 m^3. Furthermore, we have been promoting the stocking of drinking water and implementing citizen-participation in emergency water supply drills. In this way, we aim to have a disaster-resistant water supply, which involves people protecting themselves on an individual basis (self-help), communities and companies assisting each other (mutual help), and official help via the Waterworks Bureau (public help).

Issues Revealed by the Emergency Restoration after the 2016 Kumamoto Earthquake

In April 2016, the 7.3-magnitude earthquake with maximum seismic intensity 7 occurred in Kumamoto. Up to 446 thousand houses were without water because a lot of service pipes were damaged.

As a part of the relief effort, 35 employees of the Yokohama Waterworks Bureau provided transportation, leakage investigation, emergency restoration, and contact adjustment for the disaster area. From these experiences, when receiving external assistance/relief from other water utilities, the following issues were revealed [4].

(1) In order to prevent confusion of other water utilities, it is necessary to give appropriate directions according to a pre-planned restoration procedure.

(2) In order to carry out the emergency restoration work smoothly, we have to prepare suitable maps in advance and promptly provide them to other water utilities.

(3) The sewage system also suffered great damage, and it was not possible to supply water even when the water supply system was restored. Therefore, we have to make plans for restoration in cooperation with offices that manage sewage works.

Solving these issues, we prepared explanatory materials as emergency restoration workflows assuming a disaster has occurred when requesting emergency restoration to other water utilities.

Concepts of Emergency Restoration for Important Facilities

The main concepts of emergency restoration are the followings. A lot of service pipes will be damaged in case of great earthquake disaster. Therefore, we close valves of the distribution pipes branching off from the main distribution pipes in order to prevent leakage of service pipes. Then, we restore pipelines in order from important facilities close to the distribution reservoir and secure water supply to important facilities.

We decided the restoration order in consideration of the following steps and priorities. Important facilities prioritized for water supply restoration are the following. There are 358 emergency water taps, 13 disaster base hospitals, 48 designated emergency medical centers and 254 local disaster prevention centers. We decided the priority of restoration for these total of 673 facilities.

In Step I, we established the restoration order for important facilities based on the following four criteria. Priority (1) is medical institutions: disaster base hospitals and designated emergency medical centers, priority (2) is disaster bases: local disaster prevention centers and emergency water tap stations, priority (3) is emergency restoration bases: City hall and Ward Administration Offices, etc. and priority (4) is transport hubs: Yokohama Station and Shin-Yokohama Station. Then, in Step II, we restore the main distribution pipes of 400 mm diameter or larger and major pipes of 300 mm diameter or less which were not restored in step I. Details of the procedure for restoration of the pipeline are as shown in the workflow of Table I.

Based on the above approach, we created prioritized pipeline maps for emergency restoration of 41 water distribution blocks. In this paper, we introduce the map of a Miho gravity flow block.

How to Create a Prioritized Pipeline Map

We introduce how to create a prioritized pipeline map of a Miho gravity flow block in Figure 2. The Miho gravity flow block supplies water to approximately 28,000 houses from the Miho water distribution reservoir via a gravity flow system. There are one designated emergency medical center, seven local disaster prevention centers, and four emergency water taps in this block. Three of the emergency water taps overlap the local disaster prevention centers, so there are nine important facilities in total.

In Step I, we prioritize nine important facilities. Kamoi Hospital is priority (1) and is the designated emergency medical center. Upstream of the pipe to Kamoi Hospital, there are Miho

Elementary School, Midori Ward Administration Office, Nakayama Elementary School, Kamoi Junior High School, and Midori Elementary School as priority (2), which act as local disaster prevention centers and emergency water tap stations. First, we restore pipelines (A) and (B) close to the distribution reservoir and supply water to Miho Elementary School and Midori Ward Administration Office. Second, we restore pipeline (C) and supply water to Kamoi Hospital and Nakayama Elementary School.

Up to this point, restoration of priority (1), the designated emergency medical center is completed and all remaining facilities are priority (2) local disaster prevention center and emergency water tap stations. Considering the efficiency of emergency restoration, we restore from facilities with a short pipe extension. Third, we restore pipeline (D) branching from pipeline (C) where restoration is completed and supply water to Kamoi Junior High School and Midori elementary School. Fourth, we restore pipeline (E) close to the distribution reservoir and supply water to Niharu Elementary School. At last, we restore pipeline (F) and (G) and supply water to Tsudanishi Elementary School and Kawawa Elementary School. Thus, restoration of the pipeline to all nine important facilities is completed.

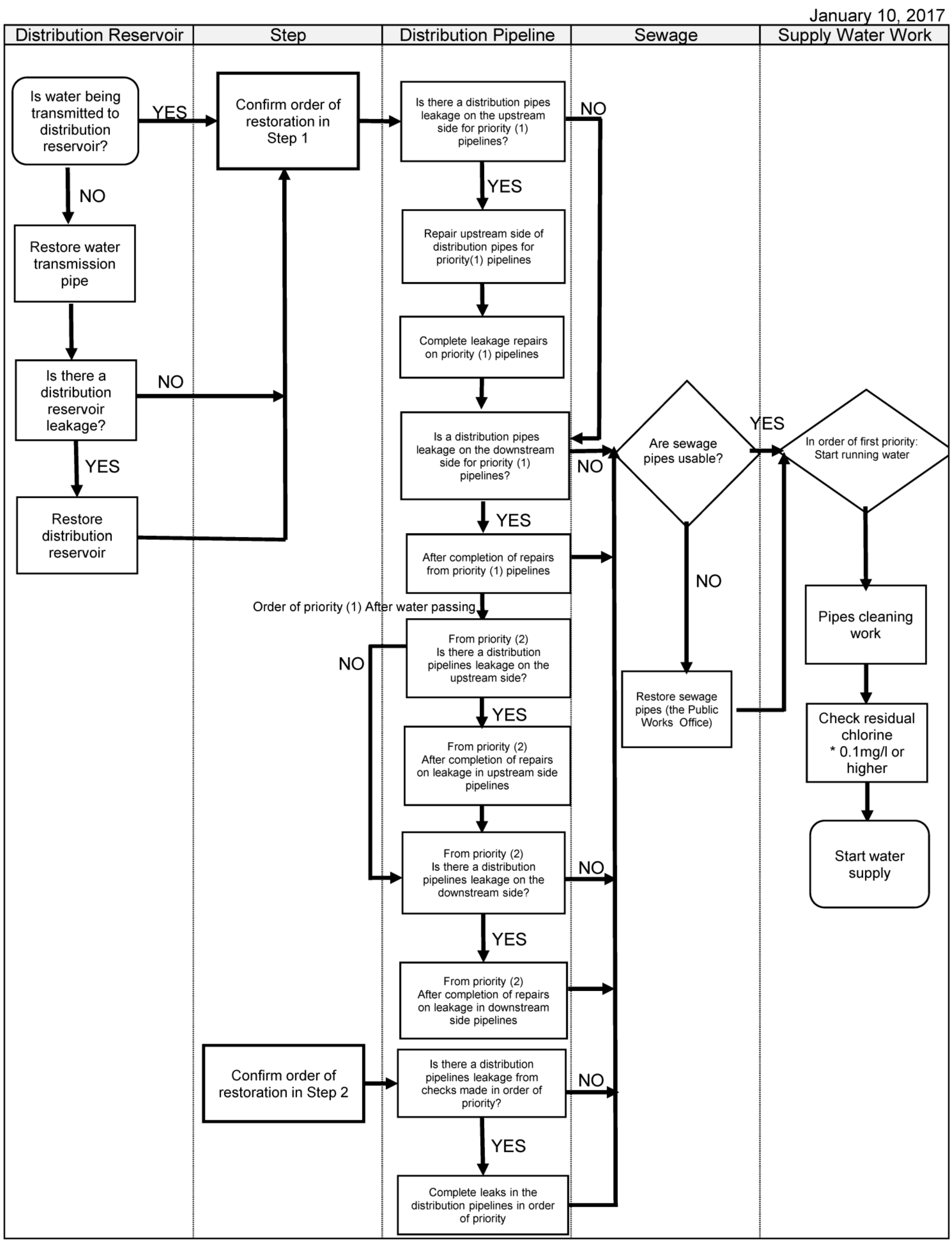
In Step II, we restore three pipes of 400 mm diameter or larger and four major pipes of 300 mm diameter that were not restored in step I. In order to preferentially loop the main pipeline, we restore Miho pipeline with a 600 mm diameter, Aoto pipeline with a 500 mm diameter, and Nakayama pipeline with a 500 mm diameter in order. Finally, we restore four pipelines with a 300 mm diameter important for water supply.

Actions for the Future

Although we created the prioritized pipeline maps this time, in order to restore in case of disaster, we must calculate the number of people needed and the time for restoration work. Also, in order to help other water utilities to provide support when receiving external assistance/relief, we have to prepare detailed drawings and information on routes. We plan to keep the maps in each Waterworks Office as a disaster prevention base for emergency restoration so that information can be promptly provided to other water utilities. Although we have carried out disaster drills in anticipation of an earthquake, by utilizing these maps, it is possible to conduct drills in the assumption of situations when receiving external assistance/relief.

In previous earthquake disasters, there were cases where the water supply was interrupted because the sewage system was not restored. Based on the priority for emergency restoration of the water supply, we plan to prepare plans for restoration of sewage in cooperation with offices that manage sewage works. As a result, efficient restoration aiming for a swift restoration of the water supply and sewage system will be possible.

TABLE I. EMERGENCY RESTORATION WORKFLOW



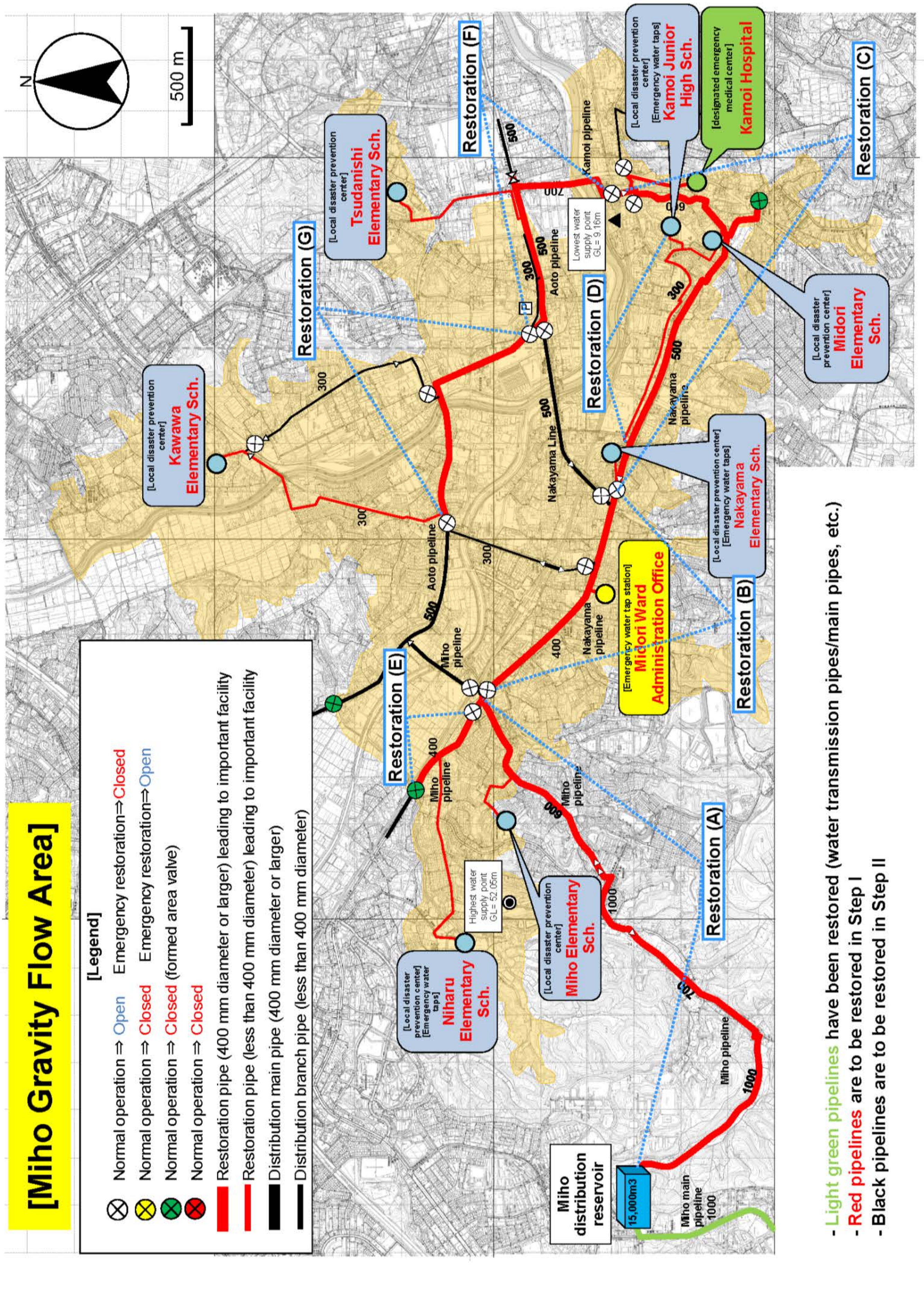


Figure 2. The prioritized pipeline map

CONCLUSION

During the disaster relief operation for the 2016 Kumamoto Earthquake, we reaffirmed the importance of earthquake measures. In order to smooth restoration works when receiving assistance/relief, we created prioritized pipeline maps for emergency restoration. By utilizing the maps, we can early establish place where citizens receive water in case of disaster, and we don't have to send water trucks to some important facilities. The information of facilities equipped for disaster countermeasures has not been in a state where other utilities can utilize it quickly or easily. Maps and workflows that collect this information will be important material for emergency restoration. However, since these materials alone are inadequate for restoration when receiving external assistance/relief, we must organize detailed maps and procedures for restoration efforts. In addition, by creating an emergency restoration plan of the water supply and sewage systems in cooperation with offices that manage sewage works, it is possible to perform more efficient emergency restoration.

What water utilities have to do for future earthquakes is to provide safe water to citizens as soon as possible. To this end, we have to anticipate the possible damage to the facilities, plan restoration in advance, and restore suffered facilities in the most efficient way.

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Emergency Activity during a Disaster by the Public–Private Cooperation in Nagoya City

Minoru Sakaguchi

ABSTRACT

A water supplier is required to supply safe water after a large earthquake. Nagoya City is predicted to suffer extensive damage in the upcoming Nankai Trough Earthquake. Therefore, we are promoting ways to develop seismic resistance of water facilities.

However, facing a severe financial situation due to decreasing water supply revenues, it will take a long time to make all water facilities earthquake resistant. Furthermore, in case of serious damages due to a large earthquake, there remains concern regarding whether the personnel necessary for disaster response can be secured quickly. Therefore, to construct a rapid post-disaster response system, we have been promoting the expansion of a cooperative system with Meisuikyo, an organization consist of Nagoya City designated company for water supply equipment work, during a disaster.

We report on this public and private partnership system, which we have been promoting between the city authorities and Meisuikyo, that operates during a disaster.

We concluded an agreement on emergency water supply in 2000 with Meisuikyo. In 2012, considering the situation during the Great East Japan Earthquake that occurred in March 2011, we revised the agreement and included emergency water supply, emergency restoration, and emergency waterproofing in it. Thus, we have prepared the foundation for a cooperation system that can be implemented during a disaster. Moreover, in 2016, we entrusted temporary water faucets, which are equipment for opening emergency water supply facilities, to Meisuikyo, who is working closely with local communities on a daily basis, and requested them to open 105 of 207 emergency water supply facilities after the earthquake occurred. We have thus established a system that can rapidly develop emergency water supply activities. Furthermore, we incorporate cooperative drills with Meisuikyo in our disaster reduction drills, which we conduct annually, and are trying to maintain and strengthen the collaboration structure between them.

From now on, we will continue to build the earthquake resistance of water facilities with limited personnel and financial resources. Furthermore, to implement emergency activities more effectively, we will strengthen our cooperation with various collaborators such as Meisuikyo and develop a town that can respond strongly during a disaster.

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INTORODUCTION

In recent years, large earthquakes have occurred around the world. Japan has also frequently witnessed large earthquakes, such as the Great East Japan Earthquake in 2011 and the 2016 Kumamoto Earthquake, which have caused extensive damage to various places.

As shown in Figure 1, Nagoya City is located near the center of Japan. The outline of the city's water supply works is as indicated in TABLE I. In recent years, there are concerns over the occurrence of a Nankai Trough megathrust earthquake with an epicenter at the Nankai Trough located in coastal waters, which is also expected to cause severe damage to Nagoya City [1].

Nagoya City Waterworks & Sewerage Bureau, aiming to continue the stable supply of safe and secure drinking water even after the occurrence of a large earthquake, such as a Nankai Trough megathrust earthquake, has made daily efforts to ensure the earthquake resistance of water supply facilities. As of the end of March 2017, the percentage of earthquake-resistant pipes out of all of the approximately 8,400 km of distributing pipes owned by the Bureau is approximately 28%.

In recent years, however, Nagoya City's revenue from water supply has decreased year by year. In such severe financial conditions, it would still take a long time to make all the water supply facilities earthquake-resistant with only a few annual construction works to improve the resistance to earthquakes of water supply facilities, which requires a large amount of funding. In the case of severe damage due to a large earthquake, with an expectation that many of our staff members will sustain damage, there remain concerns over whether we can quickly secure the personnel required to respond to such a disaster.

As such, our Bureau has improved and strengthened its emergency activity system in cooperation with private companies. Among such efforts, aiming to establish a quick response system at the time of disaster, we have improved and expanded our cooperative framework for the time of disaster with Nagoya City Designated Water Service Installers' Association (hereinafter "Meisuikyo"), one of the union organizations of the city's designated water supply device installers. Since the member water service installers of Meisuikyo have skilled techniques and daily interactions with local residents as the water service installer for the town, they can serve as reliable and encouraging entities for local residents at the time of disaster.

Figure 1. Location of Nagoya

TABLE I. Outline of Nagoya City's water service

Start of water supply	1914
Population served	Approx. 2.4 million people (2016)
Water supply ratio	100.0 % (2016)
Daily average water supply volume	Approx. 760,000 m^3/day (2016)
No. of staff members	Approx. 2,300 people (2016)
Managed by	Local governments

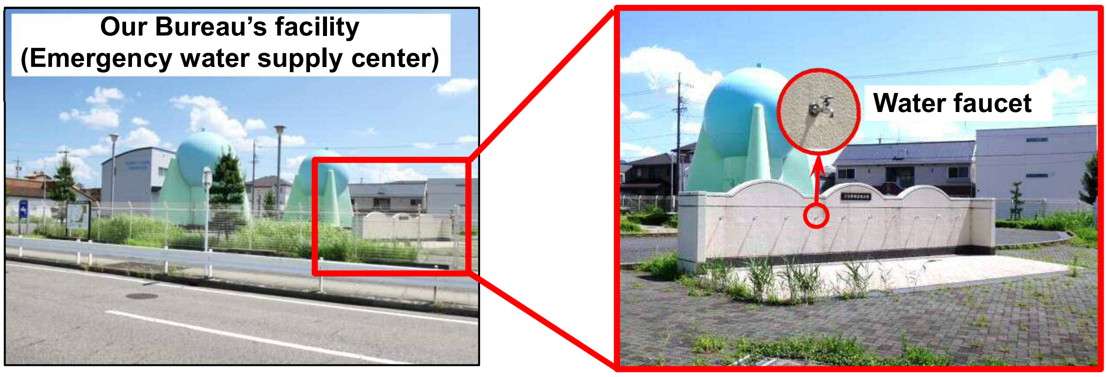
We will herein summarize and report on the public-private sector cooperative framework regarding emergency activities at the time of disaster, which has been advanced between our Bureau and Meisuikyo.

EMERGENCY WATER SUPPLY ACTIVITY SYSTEM

Our Bureau formulated Nagoya City Waterworks & Sewerage Bureau's Business Continuity Plan (earthquake countermeasure version) aiming for the quick recovery of water supply and sewerage functions and a quick response to disaster, and has made the emergency activity system and details of our emergency activities widely known to our staff by setting them in a manual.

Also, emergency water supply facilities are set in the water supply areas at approximately 2 km intervals, so that local residents can easily secure water at the time of disaster. There are some 207 such facilities. Emergency water supply facilities are roughly classified by their shapes into permanent types and temporary types. Permanent facilities are established inside our Bureau's facilities, such as water purifying plants, water distribution stations and emergency water supply center. Equipped with faucets even in normal times, our Bureau's permanent water supply facilities are open to the public as an emergency water supply (see Figure 2 (a)). Meanwhile, temporary facilities are installed in facilities such as safety evacuation area and designated evacuation shelters, in which the Bureau's staff members temporarily set water faucets as an emergency water supply after carrying in and assembling temporary water faucets, which consist of exclusive equipment for the time of disaster (see Figure 2 (b)).

According to the Bureau's arrangement, with the occurrence of an earthquake intensity of



(a) Permanent type

(b) Temporary type

Figure 2. Our Bureau's emergency water supply facilities

lower 6 or stronger on the Japanese scale of seven in Nagoya, we should establish an emergency water supply system by quickly opening all of our emergency water supply facilities.

After a disaster occurs, using these emergency water supply facilities and water supply vehicles, we will supply safe and secure drinking water to all local residents and evacuees.

COOPERATIVE FRAMEWORK BETWEEN THE BUREAU AND MEISUIKYO

Conclusion of the Disaster Mutual Aid Agreement

In April 2000, our Bureau and Meisuikyo concluded an agreement regarding emergency restoration works for water supply equipment with the aim of restoring water supply equipment quickly if these equipment are damaged due to the occurrence of an earthquake or other natural phenomenon. However, the Great East Japan Earthquake, which occurred on March 11, 2011, made us recognize that cooperation with private companies is absolutely essential in emergency water supply activities at the time of disaster, not to mention emergency restoration activities.

Thereafter in December 2012, we reviewed the content of the conventional agreement, and concluded a new Disaster Mutual Aid Agreement. The new agreement clearly stipulates that in an effort to improve conventional agreement details, we shall carry out not only “emergency restoration works” but also “emergency water supply activities” and “emergency water stopping operations” in cooperation with Meisuikyo.

Thanks to the conclusion of this new agreement, in addition to emergency restoration works, we have also become able to make a dispatch request to Meisuikyo for necessary personnel and vehicles in terms of emergency water supply activities and emergency water stopping operations. This has allowed Meisuikyo to expand the scope of its emergency activities, which in turn has led to improving the cooperative framework between our Bureau and Meisuikyo at the time of a disaster.

Cooperative implementation of disaster reduction drills

Our Bureau holds a disaster reduction drill in September every year. The emergency water supply activity training is also one of the implementation items. Since 2012, when we concluded the new Disaster Mutual Aid Agreement, with the purpose of strengthening our cooperation with Meisuikyo at the time of a disaster, we have held cooperative emergency water supply activity training with Meisuikyo. In this emergency water supply activity training, our Bureau and Meisuikyo jointly conduct training on loading a vehicle with a 1 m^3 water supply tank, training on

(a) Training on loading a vehicle with a water supply tank (1 m^3)

(b) Training on installing temporary water faucets

Figure 3. Our Bureau’s disaster reduction drills attended by Meisuikyo

installing temporary water faucets, information transmission training, and so on (see Figure 3).

Implementation of large-scale disaster reduction drills

Although we have improved the cooperative framework between our Bureau and Meisuikyo through such efforts as the conclusion of the agreement, there are concerns that many designated member water service installers of Meisuikyo have little experience of disaster response at the time of a large earthquake, and little accumulation of technologies and skills related to emergency activities. That is why we were expected to hold disaster reduction drills specializing in practical operations at the time of a disaster. As such, a large-scale disaster reduction drill, hosted by Meisuikyo and co-hosted by our Bureau, was held in 2013 at the Bureau's training facility. In this disaster reduction drill, which was attended by at least 300 people from member water service installers of Meisuikyo, some practical training was held, such as training on installing temporary water faucets, training on loading and transporting a vehicle with a water supply tank (1 m^3), training on operating gate valves and water stop valves, emergency training on operating gate valves and water stop valves, and emergency training on stopping water (see Figure 4).

In 2017, the second large-scale disaster reduction drill was similarly held. We will maintain and strengthen Meisuikyo's designated member water service installers' capacity to respond to disasters by periodically holding practical disaster reduction drills like this one again in the future.

Joint participation in disaster reduction drills which are held in the local community

Previously, our Bureau had participated alone in disaster reduction drills held in the local community, such as voluntary disaster reduction drills held by neighborhood association in

(a) Training venue

(b) Training on emergency stopping water

(c) Training on operating a gate valve

(d) Training on installing temporary water faucets

Figure 4. A large-scale disaster reduction drill

response to requests from the organizers of the drills. Currently, however, our Bureau and Meisuikyo are jointly participating in these drills. In disaster reduction drills held in local communities, we explain about our emergency activity system and emergency water supply facilities, and hold emergency water supply activity training with the participation of local residents. As such, our Bureau is strengthening the cooperation between the Bureau and Meisuikyo, and is making efforts to realize quicker and more effective emergency activities at the time of disaster by strengthening our ties with Meisuikyo and with local residents.

Entrustment of temporary water faucets

In 2016, for the quicker securement of an emergency water supply system after the occurrence of a large earthquake, our Bureau and Meisuikyo concluded an agreement concerning the installation of temporary water faucets (see Figure 5) and related matters at the time of disaster. The main points of this agreement will be shown in TABLE II.

The conclusion of this agreement has allowed our Bureau to entrust the temporary water faucets to be installed in emergency water supply facilities to Meisuikyo, and, at the time of disaster, to have a system in which designated member water service installers of Meisuikyo, on behalf of our Bureau, can install temporary water faucets after going into action at emergency water supply facilities.

Figure 5. Temporary water faucet

TABLE II. Main points of agreement concerning the installation of temporary water faucets and related matters at the time of disaster

[Main point 1] Entrustment of temporary water taps to Meisuikyo.
Our Bureau entrusts our temporary water taps to Meisuikyo free of charge.
[Main point 2] Designation of emergency water supply facilities for which Meisuikyo will install temporary water faucets, and of responsible water service installers
Specify beforehand emergency water supply facilities in which the entrusted temporary water taps will be installed, and Meisuikyo's designated member water service installers who are responsible for the operation of opening the facilities.
[Main point 3] Specification of actions based on observed seismic intensity
Specify actions to be taken by Meisuikyo's designated member water service installers depending on the maximum seismic intensity observed in Nagoya. **In the case of an earthquake measuring upper 5 or less on the seismic intensity scale** Install temporary water taps in previously specified emergency water supply facilities in response to a request from the Bureau. **In the case of an earthquake measuring lower 6 or more on the seismic intensity scale** Install temporary water taps in previously specified emergency water supply facilities, assuming that the Bureau has requested them.

Since designated member water service installers of Meisuikyo always engage in community-based activities, and many of them live in their shops, after the occurrence of a large earthquake, we can expect a more rapid emergency water supply system in which these installers can go into action at the emergency water supply facilities more quickly than the Bureau's staff members to install temporary water faucets. In the case of an emergency on holidays or at nighttime, in particular, since our Bureau's staff members need to come from far away to assemble at the Bureau's office and are then dispatched to the emergency water supply facilities, the installers would be able to open emergency water supply facilities more quickly.

Currently, based on this agreement, we have selected 105 out of all our Bureau's 207 emergency water supply facilities for Meisuikyo to take charge of the operation of opening the facilities, with 112 temporary water faucets entrusted by our Bureau to Meisuikyo stored by each designated water service installer in charge of the operation of opening emergency water supply facilities. The agreement stipulates that the number of responsible service installers for these emergency water supply facilities and the number of entrusted temporary water faucets can be increased or decreased through discussion between the two parties as required.

Furthermore, with training on installing temporary water faucets in cooperation between our Bureau and Meisuikyo added to disaster reduction drills as a training item, we are striving to secure Meisuikyo's technical skills and to maintain and strengthen the cooperative framework between the two parties.

IN CONCLUSION

Through the efforts explained above, our Bureau has established a system for quicker and more ensured emergency activities at the time of disaster. To make our emergency activities more effective, even after the highly likely occurrence of large earthquake in the near future, we must aim to establish a system with which we can make our facilities earthquake-resistant within our limited financial and human resources, and continuously supply safe and secure drinking water even after the occurrence of a large earthquake in an effort to create a disaster resilient city by strengthening and maintaining our public-private cooperative framework with private companies including Meisuikyo.

[1] "*Estimation of Damage by a Nankai Trough Megathrust Earthquake*" published by Nagoya City in 2014

Seismic Preparedness and Emergency Response of Water Systems — Visions and Experiences

Lap-Loi Chung[1], Chin-Hsun Yeh[2], Lee-Hui Huang[3] and Kuo-Liang Wang[4]

ABSTRACT

In this paper, the tasks related to seismic preparedness and emergency response of water systems were reviewed and discussed. The first task is to identify the water facilities and pipelines at risk. The inventory database containing geographical information and seismic attributes of water facilities and pipelines should have been collected and checked. Various kinds of seismic hazard maps, such as the hazard maps of earthquake ground motion, known active faults, soil liquefaction potential due to earthquakes, and so on, should have been studied carefully. The second task is to propose a feasible and efficient disaster reduction plan, which is based on seismic scenario simulation technology. Based on the scenario simulation of disastrous earthquakes, the probable damage-state of critical water facilities, the serviceability of transmission/distribution pipeline systems, the amount of water available for emergency usage such as medical-care and fire-fighting, the number of households without potable water, the expected interruption/restoration time, and so on, should be evaluated quantitatively. In addition, various kinds of resource needs after devastating earthquakes and comparison with the existing capacity, such as man-power, material and equipment, should be reviewed. The third task is to develop an early seismic loss estimation and notification system, which may provide brief but valuable information about probable disaster scale and damage distribution. The system should automatically notify emergency response sectors soon after earthquake occurrences. The immediate notification may assist starting-up and decision-making in emergency responses. With the help of early seismic loss estimation, it is expected to reduce casualties, losses and secondary disasters.

INTRODUCTION

Taiwan is located in high seismicity circum-pacific belt. According to the historical records in Taiwan, a devastating earthquake causing more than 100 deaths had been occurred in every 15~20 years. So far, it is still impossible by using the current technologies to eliminate earthquake occurrence or disaster in Taiwan. However, it might be possible to reduce or to minimize the influence, inconvenience, loss and disaster, as long as each strategy of preparedness and emergency response has been carefully reviewed and put into action.

There are many subsystems of water supplies, such as raw water supply system, treatment system, transmission/storage system and distribution system. The water facilities and pipelines are almost all over the place. It is not practical to entirely avoid passing through

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active faults or soil liquefaction susceptible regions. If an existing water facility or pipeline is identified to locate at soil liquefaction susceptible region or close to known active faults, it does not matter as long as the preparedness and/or emergency response strategy, such as conducting seismic retrofit, installing valves and bypass pipes, etc., has been carefully reviewed and put into action. On the other hand, if we overlook the problem or do not know the fact, then it is dangerous.

Early warning of earthquake occurrence may help to prevent losses or casualties. For example, with a few seconds of warning, high speed train may slow down gradually to avoid derailment; high-tech fabrication plants may stop immediately the manufacturing process to reduce damage and loss. However, the warning time is usually too short to take any effective action on water facilities and pipeline systems. The most effective way to reduce damage and loss of water facility and pipeline system is to develop/improve the seismic design for new constructions and to evaluate/retrofit the existing aged facility/pipeline. Since there are a lot of existing old-constructed water facilities and pipelines, seismic evaluation and retrofit are urgent; development and enhancement on seismic evaluation and retrofit technology are very important topic.

Devastating earthquakes, which may cause damage, loss and casualty, do not occur every year. Sufficient historical damage and loss investigation data could not be obtained; the statistical analysis could not be used to reasonably predict the consequences due to future earthquakes. Moreover, the seismic capacity of infra-structures, the migration pattern of populations, and other environment variables are changing all the time. Historical observations should not be used directly in prediction of future risk. Nonetheless, with the help of the limited information about the amount of damage/loss and its distribution, it is possible to develop seismic damage and loss assessment models, which may provide various kinds of quantitative estimation results to use in disaster reduction plans.

Unlike typhoons and floods, the location and magnitude of earthquakes cannot be predicted in advance without uncertainty; the duration of strong ground shaking is often less than a few minutes; but the devastating disasters may happen during these few minutes and spread in wide range. Immediate after earthquakes, emergency response personnel should be informed. However, without information of disaster assessment or reports, it is difficult to deploy rescue/fire-fighting/medical resources and to plan emergency responses.

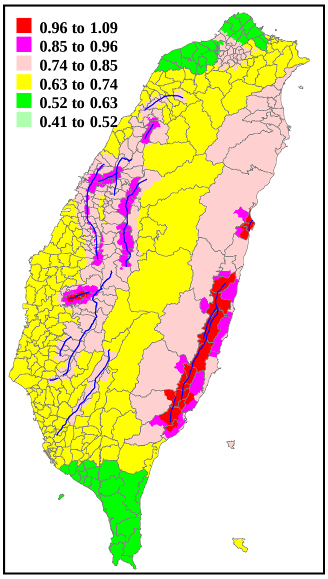
MULTIDISCIPLINARY DATABASES OF INVENTORY AND SEISMIC HAZARDS

There are two water utilities in Taiwan, i.e. Taipei Water Department and Taiwan Water Corporation. The two utilities have been established for many years. Part of existing water facilities and pipeline systems had been constructed long time ago, when the seismic technology and design codes were not so advanced as the current standards. It is desirable to seismic retrofit the old facilities and to upgrade the old pipes to meet the modern seismic standards gradually. However, as shown in Table 1, the total length of pipelines is too large; it may take very long time and cost very much to upgrade all the pipelines. In view of the importance of transmission pipelines, it may have the first priority to conduct seismic evaluation and retrofit for those transmission pipelines that are vulnerable and located at soil liquefaction susceptible region or near known active faults.

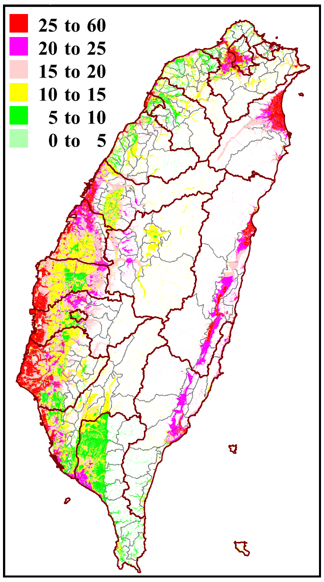
Since the total length of transmission pipelines with diameter greater than or equal to 800 mm is still very large, the two water utilities are encouraged to cooperate with academic or research organizations in order to develop a systematic and effective way to prioritize the seismic evaluation and retrofit sequence of the critical transmission pipelines, which may not have any backup or redundant pipeline. One of the important tasks in this concern is to establish inventory database of facilities and pipelines in GIS (geographic information system) format and record their attributes including location, service capacity, seismic ability, buried depth, pipe size, material-joint type, construction year, and so on. Once the seismic hazard maps, as shown in Figure 1, are available, the map of facilities and pipelines may overlap with seismic hazard maps and to identify the pipelines in hazardous areas.

Table 1 Total length statistics of pipeline systems

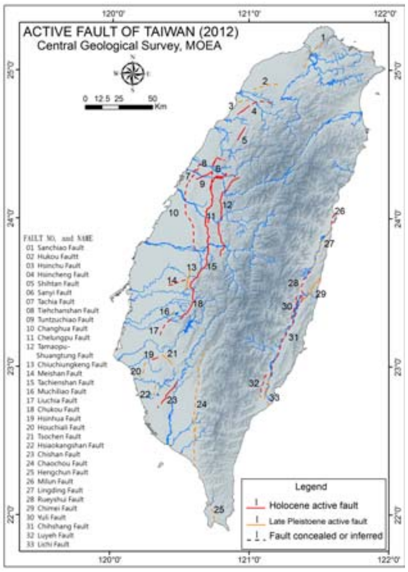
Class		Range of pipe diameter	Total length
Raw water	Transmission pipelines	$d \geq 700$ mm	335 km
Treated water	Transmission pipelines	$d \geq 800$ mm	2,163 km
	Sub-transmission pipelines	500 mm $\leq d <$ 800 mm	2,535 km
	Distribution pipelines	100 mm $\leq d <$ 500 mm	53,493 km



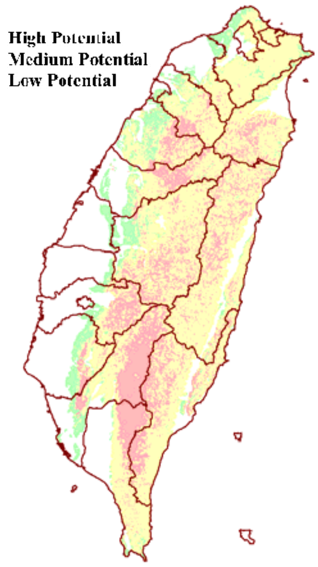
(a) Peak ground velocity hazard



(b) Soil liquefaction potential



(c) Active faults



(d) Landslide potential

Figure 1 Seismic Hazard Maps in Taiwan

COMPREHENSIVE SCENARIO-BASED DISASTER REDUCTION PLAN

An earthquake loss estimation methodology, HAZUS, was introduced to Taiwan in 1998 through a project called HAZ-Taiwan. The analysis framework of HAZUS and HAZ-Taiwan were very similar, as shown in Figure 1. Given any scenario earthquake, which has been properly described by earthquake magnitude, epicenter location, focal depth, rupture fault geometry, etc, the potential earth science hazards, the direct physical damages, the indirect physical damages and the socio-economic losses can be estimated by various state-of-the-art analysis models. Since all of the analysis models require localized database and site-dependent parameters in order to obtain reliable results, various kinds of nation-wide database such as seismic source characteristics, geologic site conditions and inventory databases were collected and calibrated. The analysis models and associated parameters, such as ground-motion prediction, soil liquefaction assessment, building damage assessment, casualty assessment, and so on, were also studied and calibrated accordingly to meet observations in the 1999 Chi-Chi Taiwan earthquake. Furthermore, to enhance the functionality and to improve the graphical user interface, the original software HAZ-Taiwan was totally revised and renamed as Taiwan Earthquake Loss Estimation System (TELES) [1].

The analysis models for different types of infrastructures, such as buildings, bridges, water facilities and pipelines, are all distinct; the characteristics for different lifeline systems and the main issues concerned by different users and authorities are not the same. Therefore, TELES was decomposed into several sub-systems, which may be run independently, to meet various kinds of user needs and to facilitate the maintenance of software. For example, sub-systems Tgbs, Twater and Thighway were customized to estimate the damage and loss of general building stocks, potable water systems and highway systems, respectively, as shown in Figure 1.

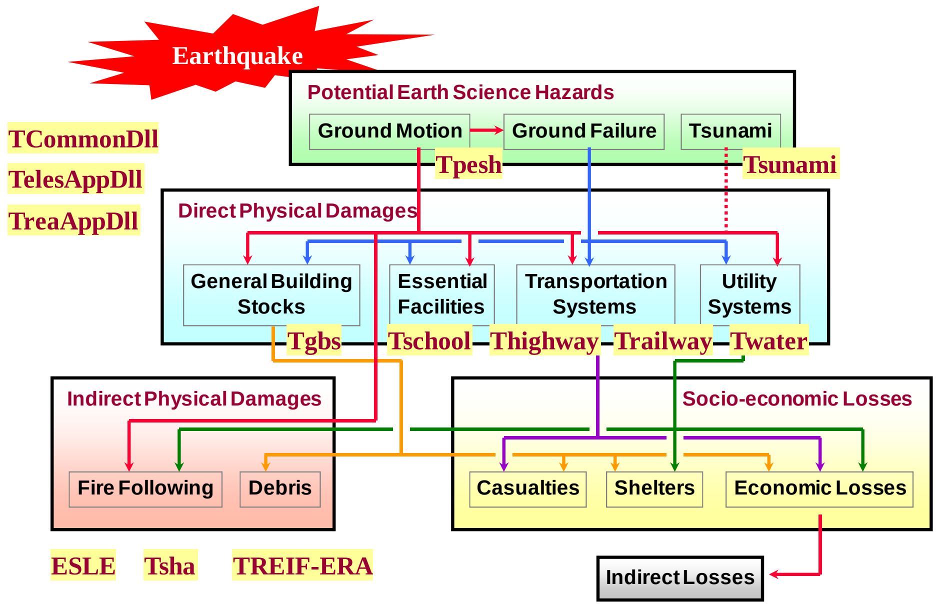


Figure 2 Analysis framework of HAZUS, HAZ-Taiwan and the family of TELES-related subsystems

Different transportation and utility systems may have interactions with each other, especially after devastating earthquakes. For example, efficient fire-fighting to extinguish a lot of post-quake fires at the same time needs uninterrupted highway system to transport fire-fighters and equipments; it also needs sufficient water supply. However, the highway system may be blocked due to damage bridges or collapse buildings; the water treatment plants and pumping stations may need electric power to function normally, not to mention transmission and distribution pipelines for emergency water supply may be damaged after earthquakes. In order to propose a feasible and efficient seismic disaster reduction plan, it is required to run comprehensively many kinds of scenario simulations on different essential facilities, transportation and utility systems, taking into consideration that some of the dependent systems may have lost of their functions.

EARLY SEISMIC LOSS ESTIMATION, NOTIFICATION AND JUDGEMENT

In case a strong earthquake occurs, the emergency response sectors of government or enterprise should be notified and have reliable information to decide whether or not to initiate Emergency Operation Center (EOC) in order to shorten response time and to reduce casualties and losses. Once the EOC initiated, it is also necessary to predict probable disaster distribution in order to dispatch efficiently the rescue, medical and livelihood resources. In addition, probable isolated hotspots may exist due to disruption of electricity, communication and/or transportation after strong earthquakes. These isolated hotspots should be identified as soon as possible to prevent delay of rescue operations.

Traditionally, there are two approaches to estimate disasters soon after strong earthquakes. The first approach uses the monitored peak ground acceleration (PGA) at each real-time station of the Central Weather Bureau (CWB) and conducts interpolation of the PGA to obtain site-dependent ground-motion intensity. Based on the PGA estimates, structural damage, human casualty and other disaster assessments are then conducted to obtain rough results. The second approach applies the seismic scenario simulation technology, but inputs point-source parameters which are provided by the CWB immediately after earthquakes. However, the rupture fault geometries such as fault trace, dip angle, length and width are important input in obtaining accurate estimates. Without this information, it is not possible to obtain reliable disaster estimates.

To avoid inadequate interpolation of PGA and to overcome difficulties in obtaining accurate seismic source parameters soon after strong earthquakes, NCREE has developed early seismic loss estimation (ESLE) technology. The methodology of ESLE is briefly explained as follows. A scenario simulation database was built first before earthquake occurrences. The scenario database contains simulation results of thousands of earthquakes, which may represent all possible earthquakes in the future. When a strong earthquake occurs, the ESLE system will be automatically triggered when it receives earthquake alert email from the CWB. Several scenarios are selected by matching the following criteria: they have similar earthquake magnitude, epicenter location and focal depth with the real earthquake; furthermore, the simulated PGA and the observed PGA at the CWB real-time stations are close to each other. Since the source characteristic and the ground-motion intensity pattern are similar to the observed earthquake, it can be reasonably speculated that the predicted damage and loss in the selected scenarios will be close to the actual ones. In some sense, the ESLE technology adopts every piece of information contained in the earthquake alert email from CWB.

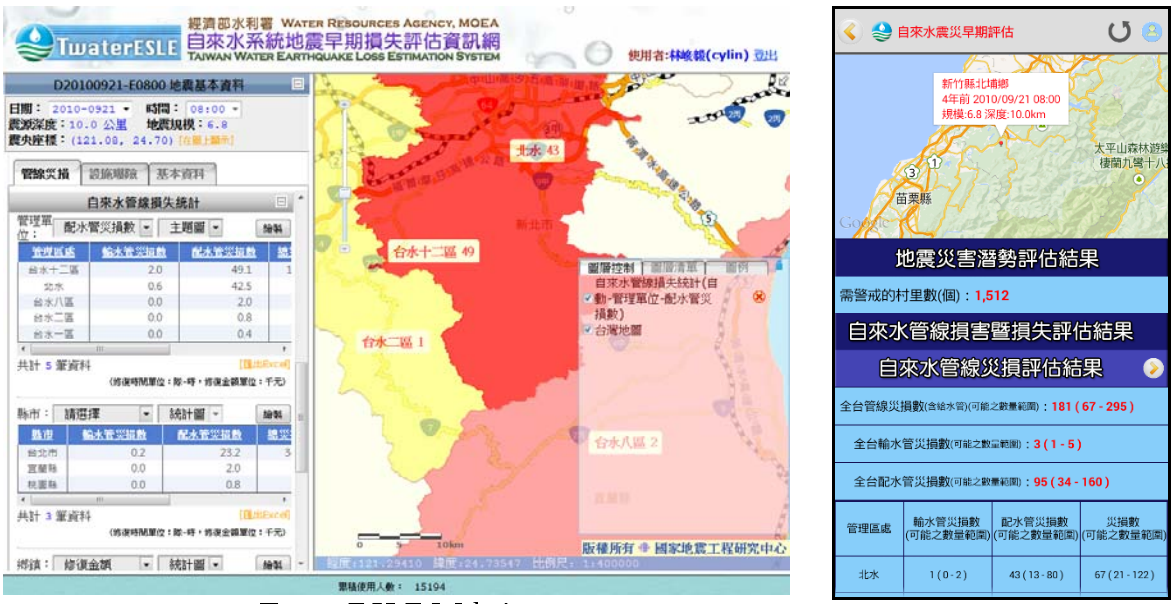
Application of ESLE immediately after earthquake may divide into two stages:

(1) First stage: within two minutes after receiving earthquake alert email from the CWB. The system automatically starts and completes assessment of probable disasters within two minutes. Emergency response personnel will be notified by simple text message, email, push notification, or other media, as shown in Figure 3. The content of simple text message had been customized to fit individual needs and contains information of the predicted disaster severity, which may be used to decide whether it is necessary to start EOC as soon as possible to gain valuable rescue time.

Other detail information, such as the distribution of water facilities and pipeline systems, the thematic maps and the statistical data of probable disasters, may be queried through the TwaterESLE Website or APP, as shown in Figure 4.

(2) Second stage: within six hours after earthquake occurrence. Combining information of the acceleration time histories at the real-time stations, the fault plane solutions provided by USGS and/or CWB, and the distribution of aftershocks, several probable sets of seismic source parameters may be proposed and justified by running additional scenario simulations. Based on the simulation results, the most probable scenario can be identified and used to avoid overlook of isolated hotspots.

Figure 3 Customized simple text messages from ESLE in Meinong, Kaohsiung Earthquake, 2016. The first text message contains estimates on number of pipe repairs in different branches of Taiwan Water Corporation; the second text message contains estimates on casualties and insurance losses



TwaterESLE Website TwaterESLE APP

Figure 4 Screen snapshot of TwaterESLE Website and APP

A strong earthquake with magnitude 6.6 occurred in Meinong, Taiwan on February 6, 2016 was taken as an example. It is noted that the earthquake magnitude was originally announced as 6.4 and modified to 6.6 several hours later.

One minute after receiving the CWB earthquake alert, the ESLE completed the disaster estimation and sent the simple text messages to notify emergency response personnel. The content of simple text message (see Figure 3) indicated that the probable number of casualties was between 5 and 30 with the best estimate 12; the residential earthquake insurance losses were between 179 and 546 million NT dollars with the best estimate 529 million NT dollars; the number of water pipe repairs was about 1432 and concentrated in Tainan area; there were more than one thousand villages (1045) with PGA greater than 0.16g. Due to the predicted severity of the disasters, it was recommended to partially initiate emergency responses. Other detailed information could be found at the related website. Six scenarios (see Figure 5) which may represent Meinong earthquake were selected automatically by ESLE in the first stage.

The acceleration time histories at the real-time stations were downloaded and analyzed soon after the earthquake, in order to understand the ground motion characteristics in different districts. It was found that the vibration in east-west direction was greater than that in south-north direction. Some of the waveforms showed significant velocity pulse. About one hour after the earthquake, the fault plane solutions were released by the US Geological Survey (USGS) and the Central Weather Bureau. Integrating the previous data and the distribution of aftershocks within three hours (see Figure 6), the seismic source parameters were judged to be as follows: the fault strike should be approximately east-west orientation, the fault plane should be slightly north-dipping, the fault rupture had a left-slip component and the directivity effect was significant. In summary, the input source parameters in the ESLE second stage were set to magnitude 6.4, focal depth 15 km, strike west 20 degree to the north, rupture length 20 km. It is noted that the rupture fault-line assumed in the ESLE second stage (see Figure 6) starts from the epicenter of Meinong earthquake to reflect the observed directivity effect.

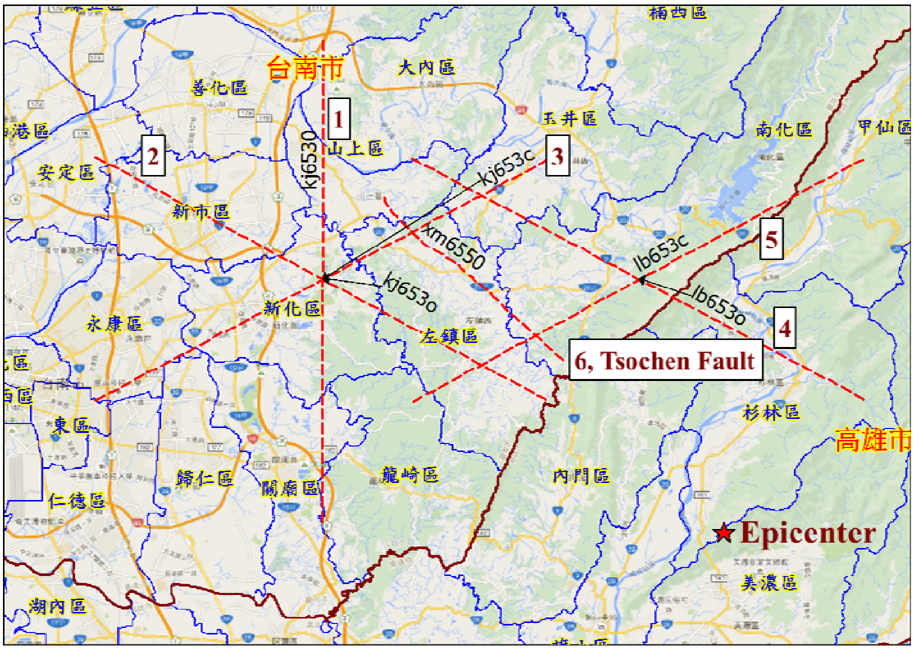


Figure 5 Six scenarios selected automatically by ESLE in Meinong earthquake, 2016

SUMMARY

There are many tasks need to be done before and after earthquakes. This paper focuses on three important tasks. The first task is to establish and continuously update multidisciplinary databases including inventory data of facilities and pipeline systems, and to collect various kinds of state-of-the-art knowledge on seismic technologies and probable hazards. Based on financial considerations, it is desirable to prioritize seismic retrofit sequence depending on the importance, vulnerability, and probable hazards of specific aged targets. The second task is to propose a feasible and efficient disaster reduction plan based on quantitative results from comprehensive scenario simulations, including those from general building stocks, essential facilities, and transportation and utility systems; because these systems may have interactions with each other after devastating earthquakes. The third task is to develop early seismic loss estimation and notification system in order to enhance emergency initialization and response efficiency. Corporation between water utilities and academic/research organizations on disaster reduction and emergency response should be put more emphasis on.

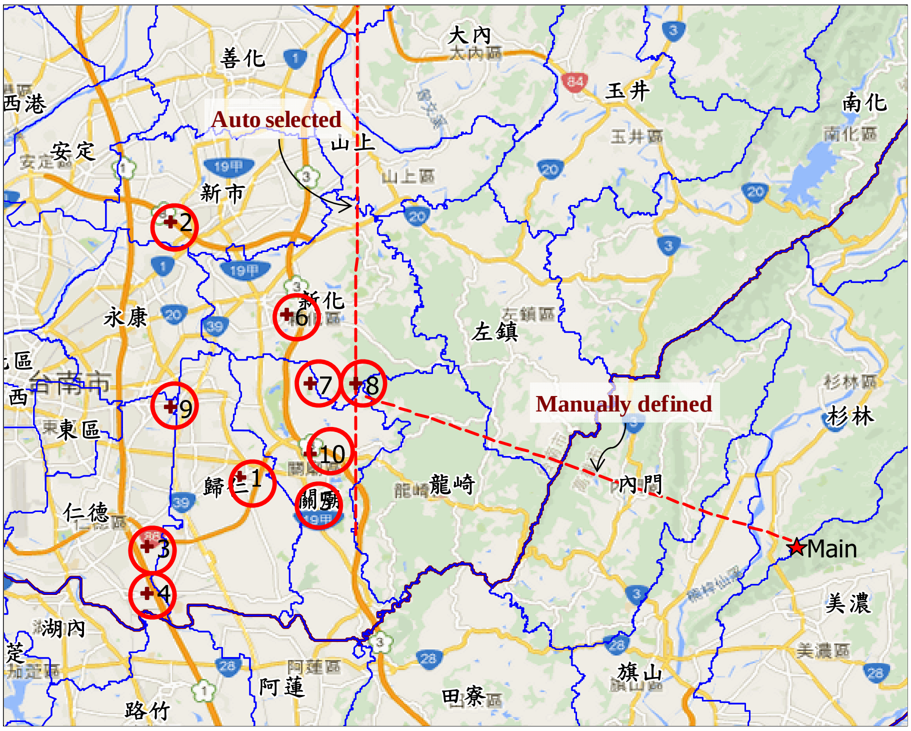


Figure 6 Main and aftershocks within 3 hours of Meinong earthquake, 2016 and the selected scenarios by ESLE

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Crisis Management by Waterworks Emergency Service Unit ; Quick Response and Prompt Securement of Water Supply in the Event of Disasters

Wataru Kiga

ABSTRACT

Bureau of Waterworks, Tokyo Metropolitan Government (BWTMG) is responsible for the mission of stably supplying safe, clean and high-quality water 24 hours a day as a core lifeline supporting the civic life and the urban activities in Tokyo Metropolitan. Especially water supply to the administrative organizations of the country that are the key to restoration in emergency situations and disaster base hospitals that protect the lives of citizens is indispensable. As a facility to support this function, Waterworks Emergency Service Unit was built. The main task of the unit is to secure water supply routes to the central agencies of the capital such as government agencies and disaster base hospitals, and others, within three days from the occurrence of a disaster such as a large-scale earthquake. Even in Tokyo during the Great East Japan Earthquake, main roads became heavy traffic congestion due to the difficulties of returning home, and others, resulting in a long and considerable time to check and confirm the water supply route. Based on this lesson learned, we constructed a system that can monitor water supply pressure so that the unit's headquarters can grasp the situation intensively. This system will be introduced for the first time in Japan as a water supply utility.

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1. Installation of Waterworks Emergency Service Unit

In case of sudden accident such as water leakage, it is necessary to respond promptly such as information communication with the accidental area, public relations activity, valve operation, security measures, and more in order to prevent the spread of damage and to restore the site.

In addition, in preparation for the occurrence of earthquake that directly hits Tokyo area the authorities have steadily promoted measures to mitigate the damage caused by the earthquake, such as strengthening the backup function of pipeline and aseismic construction method. On the other hand, it is important to further enhance the systems such as information communication, emergency water supply and emergency restoration in order to secure as much drinking water as possible and restore normal water supply as soon as possible.

Furthermore, in September 2005, the National Disaster Prevention Council of Japan established the "Outline of Disaster Countermeasures Basic Act", and as a countermeasure against Tokyo Inland Earthquakes, in order to ensure business continuity of the central capitals and other organizations, the Council set functional targets and countermeasures to be fulfilled by the waterworks facilities three days after the disaster in the lifeline infrastructure. In response to this, the authorities revised the "Earthquake Disaster Emergency Action Plan" in June 2006. Regarding the damages on pipeline related to water supply to the capital’s central agencies at the time of the earthquake occurrence, we decided to restore the equipment with the highest priority aiming at water supply within 3 days after the disaster. Based on this background, from the viewpoint of strengthening the crisis management function, as a flexible organization capable of dealing with 24 hours at 365 days, which has both quick response and flexibility, and also the technology necessary for early recovery, we decided to establish Waterworks Emergency Service Unit in April 2008 that reorganized special water work team and strengthened crisis management function.

2. Work contents of Waterworks Emergency Service Unit

At the time of the earthquake, Waterworks Emergency Service Unit is mainly responsible for securing the water supply route to the central government institutions, and others, and at the time of the accident, assisting the restoration work concerned (Table 1). In ordinary times, conducting various training to prepare for earthquake etc., and when an accident happens unexpectedly, we are engaged in assisting in restoration work using our mobility and prompt information communication, emergency publicity, emergency water supply and more.

Also, in the Great East Japan Earthquake of March 2011, we dispatched a large number of personnel and vehicles to the affected areas immediately, and are engaged in support activities such as emergency water supply. For this reason, in addition to special emergency vehicles equipped with portable personal computers capable of viewing information communications and pipeline diagrams, generators, valve operating tools, security equipment, and others, as well as information emergency vehicles on the spot, public relations vehicles, water supply cars, water control valve opening and closing cars. Waterworks Emergency Service Unit constantly maintains a dispatch state. Furthermore, among the road congestion assumed at the time of the earthquake disaster, a motorcycle (displacement of 50 CC) is deployed to expeditiously investigate the water flow situation of the central capital and other institutions, and we also developed the valve operating tools (Photo. 1).

Photo 1 Examples of Tool Development

The unit is the only specialized organization to deal with crisis management as a water supply utilities in Japan, aiming at strengthening the initial structure at the time of the earthquake disaster and accident, and is striving to improve its response capability through day and night training.

Table 1 Main duties in the event of disaster such as earthquake and accident occurrence

Category	Work contents	Details
When an earthquake or other disaster occurs	Initial operations	In the event of an earthquake with a seismic intensity of a lower 5 or greater at night or on a holiday, some of the unit members gather as first responders at the Metropolitan Government Building and carry out information room setup during the initial disaster period, etc.
	Emergency water supply	Conduct emergency water supply requested from the Disaster Response Headquarters especially to medical institutions etc.
	Securing the supply route to the central capital area	When conducting a hydraulic investigation on the water supply pipeline to central agencies of the capital and if a decrease in water pressure is discovered, valves are operated to secure the water supply pipeline
	Support for Emergency Recovery of Distribution Pipes, etc.	Under the instruction of the Water Distribution Recovery Team (head office) and branch offices, the Unit conducts water leakage investigations and water passing works (including pipeline severance works) for other routes.
When an unexpected accident occurs	Accident site safety measures	On-site security measures using safety equipment and soil etc.
	Initial Publication	Emergency publicity at the time of a sudden accident
	Emergency water supply	Using water trucks, distribute drinking water to those residents who cannot use water due to the emergency water stoppage
	Support for suspended service	Under the direction of the branch office at the time of the accident, in cooperation with the branch office, conduct the water suspended service work, system change work and drainage work etc.

	Information communication support	Information collection and dissemination of information using special emergency vehicles and on-board PCs. Emergency team creates accident report under direction of branch office and supports branch office Main pipe cutting work and under-road cavity due to water leak · radar exploration, equipment production etc.
	Tube cutting operation · Cavity inspection etc.	Main pipe cutting work and under-road cavity due to water leak · radar exploration, equipment production etc.

3. Main Deployment Vehicles

Table 2 List of vehicles of Waterworks Emergency Service Unit

Vehicle type		Main task	No.
Emergency vehicles	Special Emergency Vehicle	Information Contact · Equipment Material Transport	2
	Loudspeaker vehicle	Public information on sudden accident	2
	Emergency transporter	Emergency security measures such as secondary disaster prevention	2
	Gate valve open/ close vehicle	A vehicle equipped with a power-driven device to turn the gate valve of water pipes.	2
General vehicle	Water truck	Emergency water supply (2t, 3t, 4t)	10
	Transport Truck	Transport of work equipment	2
	Public information and research guidance vehicles	Public information · various investigations etc.	6
		Total	26

4. Activities in the event of the disasters

The first mission of Waterworks Emergency Service Unit at the event of earthquake, in order to maintain the central agencies of the capital, disaster base hospitals, tertiary emergency medical institutions, financial institutions and embassies, secure the water supply route to these 118 facilities (as of July 2017), and secure water supply route within 3 days after the disaster.

When a disaster happens, the unit goes into action immediately, and investigate the hydraulic pressure with a hydrant, and others on the pipeline along the water supply route to the capital area while exploring the road on the pipeline. Therefore, when a decrease in water pressure is confirmed, the unit shut down the water control valve of the branch destination pipe and keeps the pressure, thereby securing the water supply to the designated facility.

Also, after securing the water supply route to the central agencies of the capital, we also conduct water leakage investigation and water supply work as support for emergency restoration of the pipeline for concerned agencies.

5. Secure water supply routes

5.1 Background and purpose

Extension of water pipes is about 27,000 km (which is equivalent to approximately about two thirds of the equator), in particular Tokyo central area, where the water pipes are networked like a finely-meshed pattern, alternative lines may be secured as a "back-up route" even if water leakage occurs in some parts of the area. In order to maintain the capabilities of the function of Tokyo metropolitan area in the event of the earthquake disaster, it is necessary to promptly secure water supply, especially for the capital's central agencies. For this reason, after the earthquake, regarding these facilities, promptly confirm water pressure at the site, secure water supply within 3 days for facilities that suffered damage such as water pressure drop by valve operation.

However, the Great East Japan Earthquake that occurred in March 2011, although Tokyo Metropolis is more than 300 km away from the epicenter, main roads encountered heavy traffic jams due to the suspension of operations of public transportation and it took considerable time to check the water supply to important facilities by vehicles. Meanwhile, in the Kumamoto earthquake last April, there was also a report that some medical institutions hindered medical activities because of suspension of water supply.

Based on these lessons learned, from this fiscal year 2017, the unit decided to install hydraulic pressure monitoring devices which use PHS lines (*1) at water meters of important facilities so that the situation can be intensively grasped at the headquarters of the unit. The reason for adopting the PHS line is that while another mobile phone line implemented the call restriction at the time of the Great East Japan Earthquake, the PHS line was regulated.

With this system, it is possible to pinpoint the damaged water supply route and quickly secure water supply to important facilities in a short time.

As for the water supply route to important facilities such as the central agencies of the capital, we work diligently to complete the seismic coupling by the end of FY2019.

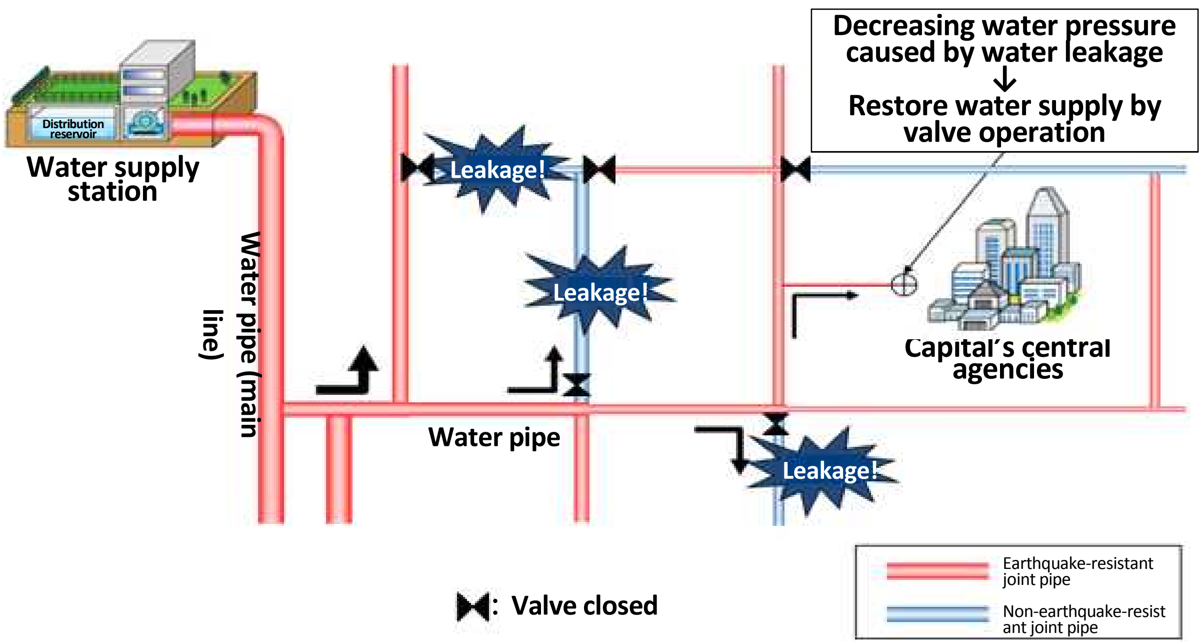

Figure 1 Image of water supply provided at the time of disaster

5.2 System Configuration

The system formulated in this project is constituted of “communication lines” which sends and receives the water supply pressure data, a “terminal unit” which measures water supply pressure on site, and the “data collection center” in the office which monitors the water supply pressure. Thus, this system allows the monitoring of the water supply pressure on site from the data collection center via communication lines.

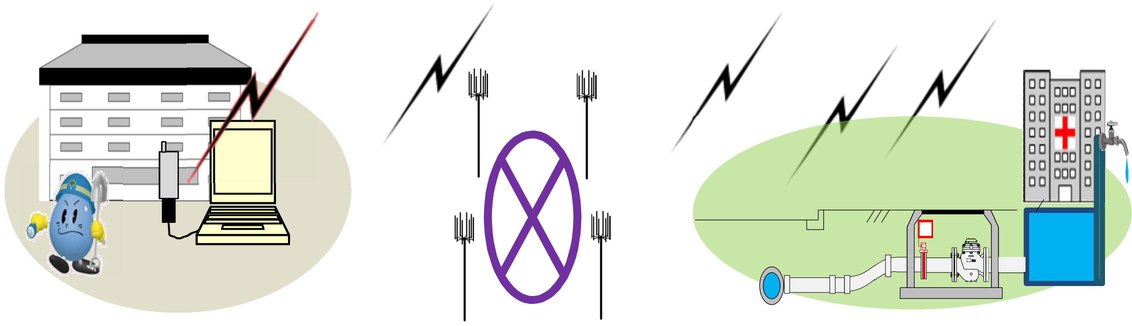

Figure 2 Image of system configuration

5.3 Utilization of PHS Communication Lines

For the communication line, we decided to use the PHS line. The reason for this is that the PHS line is easy to secure a line even in the event of a disaster in urban areas among current communication infrastructure in Japan. As evidence based on the fact, communication was restricted due to the concentration of access to mobile phone lines at the time of the Great East Japan Earthquake, but the PHS line was not subject to communication restrictions. Another reason is that with the PHS lines we can save more energy and call rates compared to using other mobile network systems. Furthermore the PHS lines have low electromagnetic waves which may less affect medical devices at the target hospitals compared to using other mobile network systems.

5.4 Development of a Terminal Unit for Checking Pressure

Bureau of Waterworks, Tokyo Metropolitan Government aims to develop a terminal unit that can be installed at the pipe joint which allows to measure water supply pressure in a distribution pipe at the facility.

(1) Performance requirement of a terminal unit

① Water supply pressure can be measured at a point close to the facility.
② No affection to existing water supply pipes including water meters.
③ Battery-powered, easily replaced.
④ Have a predetermined waterproof function.
⑤ Daily maintenance and inspection are not required.

(2) Configuration and specification of a terminal unit

The terminal device is composed of a pressure sensor and data conversion/transmission apparatus.

[Pressure Sensor]

A protective guard made of resin was attached to the pressure sensor, and a special fitting for measuring water pressure was sandwiched between the flanges in the upstream part of a meter (18 to 24 mm thick).

Also, the special fitting shall satisfy the requirements to be provided as part of the water supply pipe.

[Data conversion/transmission apparatus]

The data conversion/transmission apparatus shall be a box (201 mm wide × 151 mm high × 80 mm thick) with waterproof levels equivalent to IP 67 under the International Electrotechnical Commission (IEC) standard, accommodating the "communication line unit," the "pressure conversion unit" and "replaceable lithium batteries."

As a result of trial calculation of battery life, it was confirmed that continuous operation can be performed without battery replacement for 10 years or more under the following operation conditions.

- The "communication line unit" is always kept on “standby”.
- To confirm water supply pressure, receive data once a day by communication.

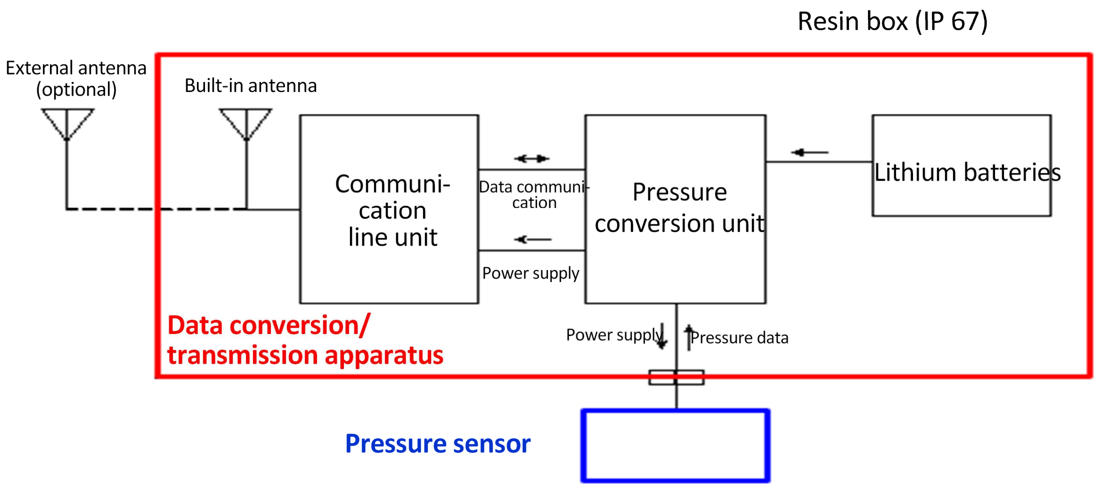

Figure 3 Configuration of terminal device
(Data conversion/transmission apparatus and pressure sensor)

5.5 Development of the Data Collection System

A data collection system was developed to collect data from terminal units via communication lines, which enables the main unit to check the water supply pressure of many target facilities.

(1) Performance Requirement of Data Collection System

① Water pressure can be confirmed at an arbitrary timing.
② The acquired water pressure data, electric field intensity, and remaining battery power can be displayed with spreadsheet software.
③ The schedule function which acquires the data at the specified day and time in advance is carried.

(2) Configuration and specification of data collection system

The data collection system is composed of a personal computer and a communication terminal on which dedicated software is installed.

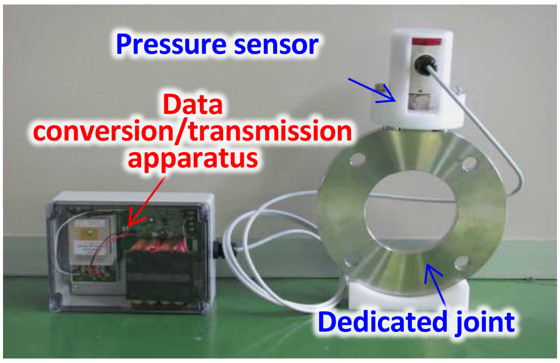

Photo 2 Terminal unit set

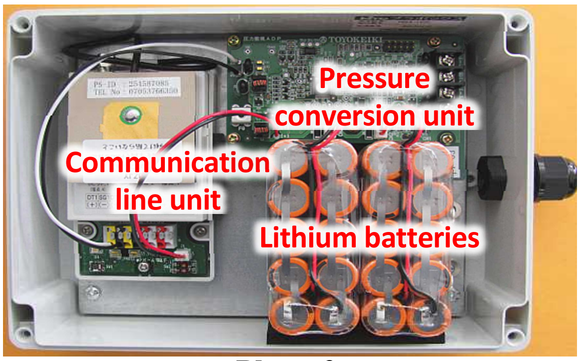

Photo 3
Data conversion/transmission apparatus

【Software functions】

In order to satisfy required performance, software having the following functions was developed.

- Function 1: It is possible to collect water supply pressure values of target facility as a data batch method (available period collection with an interval of 1 min to 60 min)
- Function 2: It is possible to simultaneously measure the remaining battery level and the electric field strength of the transmitter of water supply pressure value and data conversion unit and display it on the screen and automatically save data with the spreadsheet software
- Function 3: Automatic collection schedule setting and normal pressure range can be set for each target facility.

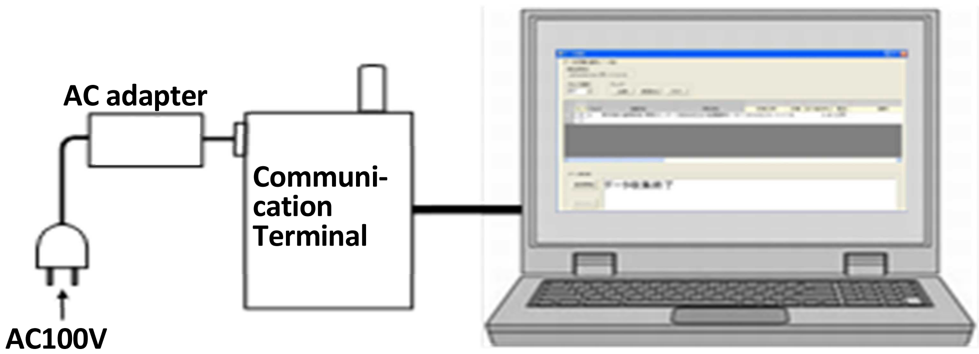

Figure 4 Configuration of Data Collection System

Figure 5 Configuration of Data Collection (sample screen)

5.7 Result of the Network Test

Three disaster base hospitals distant from the unit were chosen and the network proof test was executed in order to validate the developed system.

(1) Installation of terminal units

After checking the electric field strength in the water meter BOX in advance in the premises of three sites, we installed the pressure sensor and the data conversion transmitter.

【Installation of pressure sensor】

The pressure sensor was installed, sandwiched by the upstream flange portion of the water meter.

Photo 4 Installation of Pressure Sensor

【Installation of data conversion/transmission apparatus】

As for the data conversion/transmission apparatus, we measured the electric field intensity in a water meter box using the PHS communication unit for about two weeks in advance, and installed it in the water meter box when the communication is stable.

Photo 5 Installed Data Conversion/Transmission Apparatus

(2) Result of the Network Proof Test

As a result of performing the test at three disaster hospitals for three months, we were able to construct what can satisfy the original performance required, with a satisfactory result from both of the terminal units and the data collection center.

【Communication success rate】

We checked communication on the hour (24 times a day) for 3 months after installation (6,549 times in total). Initially there was no retry function, which led to failure sometimes due to the weak electric field and busy base station. However, all communication attempts succeeded after we added one retry function, achieving 100% of the communication success rate.

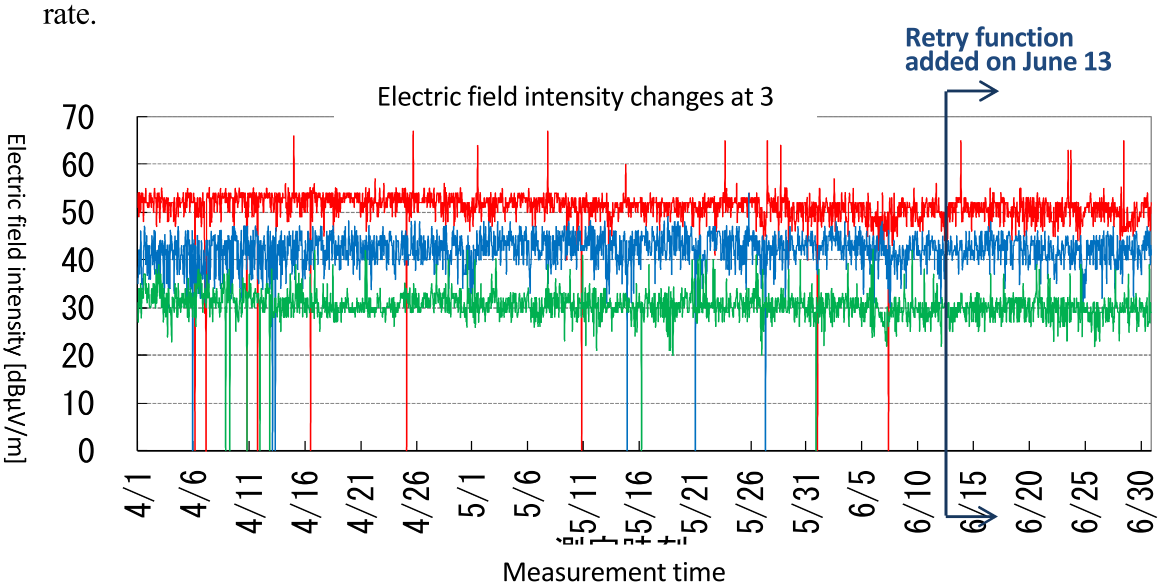

Figure 6 Electric field intensity changes at 3

【Measured values of water supply pressure】

We reviewed whether the water supply pressure value measured on site using the pressure sensor was appropriate. As a result, it was confirmed that the water supply pressure values detected at the target facility were similar to the values measured at the neighboring fire hydrant, and were appropriate.

【Data collection function】

We reviewed whether the water supply pressure data communicated to the data collection system was correctly collected and stored via the terminal units installed. As a result, each communication was saved correctly in an Excel file.

	ﾌﾞﾛｯｸ	施設名	所在地	収集日時	収集	圧力値(MPa)	電池	備考
83	ﾃｽﾄ		江戸川区臨海町1-4-2	2014/02/04 00:00	OK	0.29	正常	
84	ﾃｽﾄ		江戸川区臨海町1-4-2	2014/02/04 01:00	OK	0.31	正常	
85	ﾃｽﾄ	B病院	江戸川区臨海町1-4-2	2014/02/04 02:00	OK	0.31	正常	
86	ﾃｽﾄ		江戸川区臨海町1-4-2	2014/02/04 03:00	OK	0.32	正常	PHS電波微弱/
87	ﾃｽﾄ		江戸川区臨海町1-4-2	2014/02/04 04:00	OK	0.32	正常	
88	ﾃｽﾄ		江戸川区臨海町1-4-2	2014/02/04 05:00	OK	0.31	正常	

Figure 7 Storage status of collected data

6. Conclusion

By adopting this system, water supply pressure in capital's central agencies can be monitored from the office. This will make it possible for us to identify facilities with decreasing water supply pressure early on and to quickly narrow down facilities to be investigated and recovered on a priority basis.

As a result of the measures, time needed to recover the damaged facilities will be shortened. For example, if 58 facilities (about half of the existing 115 facilities) are damaged, they will be recovered in 40 hours in the new system. It is shorter by 40 % than the estimated 63 hours under the conventional system, and water supply will be restored much quicker.

BWTMG plans to implement this system to all of the 137 central capital institutions by the end of FY2017.

BWTMG will further enhance emergency measures by introducing the system to more than 800 key facilities, including refugee centers and medical institutions, which give aid to and accommodate disaster victims.

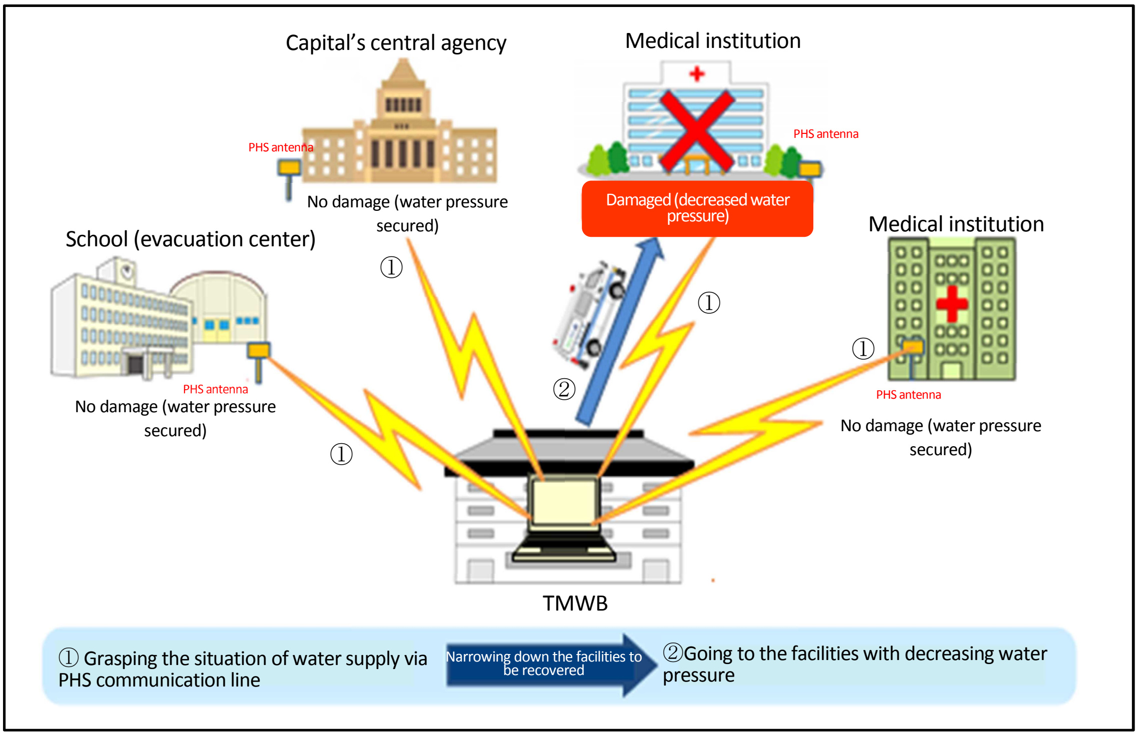

Figure 8 Image of Facilities targeted for Accommodation

(※1) Abbreviation for Personal Handy-phone System
Wireless communication lines using the frequency of the 1.9 GHz band in Japan

The Effectiveness of the Dispatch of Support Staff to Small Waterworks

Takuya KUDO[1], Yoshihito HIGUCHI[2]

ABSTRACT

After the Great East Japan Earthquake of 2011, technical support for damaged waterworks was focused on the major waterworks while the small waterworks did not receive sufficient support. The Niigata City Waterworks Bureau was asked to support such small waterworks and it dispatched one pipeline engineer to the town of Shichigahama (population 20,000) for four months.

The water distribution system of Shichigahama and the main supply pipe of the Enterprise Bureau in the Miyagi district were seriously damaged by the earthquake. The water supply system had to be shut down and was repaired within a month with the exception of the components in the lowlands that were damaged by the tsunami. In the reconstruction plan, the town of Shichigahama decided to relocate people living in tsunami-damaged communities to hilly regions, which do not face the danger of tsunamis. Thus, essential utilities, including a water supply, are urgently required in these new residential areas.

The dispatched staff engaged in the following work:

1. Supporting normal routine work
2. Carrying out tasks related to disaster-recovery
3. Managing the model project in Shichigahama

In particular, the preparation of the documents to apply for government subsidies was time-consuming. Furthermore, the waterworks reconstruction plan had to be repeatedly changed in response to the town's changing urban plan.

The dispatch of the engineer enabled Shichigahama to participate in a model project by the Ministry of Health, Labour and Welfare. With financial and technical support, the town of Shichigahama prepared an efficient waterworks reconstruction plan. The dispatched engineer brought valuable experience to the city of Niigata: before the dispatch, none of the staff in Niigata City Waterworks Bureau had experience in the design of a pipeline reconstruction plan but the knowledge gained through this experience will help prepare Niigata for future earthquakes and tsunamis. Further, during the project, the engineer took on a range of responsibilities and gained knowledge and skills through the experience.

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INTRODUCTION

This paper reports on the dispatch of technical support staff to Shichigahama following the Great East Japan Earthquake (GEJE) of 2011.

Further, in July 2017, an interview survey in Shichigahama and with several waterworks entities was conducted.

1.THE DAMAGE IN SHICHIGAHAMA BY THE GEJE OF 2011

1-1. Characteristics of the GEJE of 2011

The specifications of the GEJE of 2011 are shown in the Table 1.

Table 1. The 2011 GEJE off the Pacific coast of Tohoku [1]

Date and time	2011/3/11 14:46
Maximum seismic intensity	7 (JMA* Seismic Intensity) at the Miyagi prefecture north
Moment magnitude	9.0 (moment magnitude)
Hypocenter	38’6’12N 142’51’36E 24km deep
Epicenter	offshore from Sanriku
Maximum tsunami height	15 m high

*JMA: Japan Meteorological Agency

1-2. The town of Shichigahama and the Damage Caused by the GEJE

Table 2 and Figure1 show the characteristics of Shichigahama and the damage to the town caused by the GEJE.

Table 2. Characteristics of Shichigahama [2][3]

Location	East of Sendai, center of the Miyagi prefecture
Geography	Peninsula; the center of the town is elevated and the topography slopes downward to the coast.
Population	Approximately 20,000 (in 2011)
Maximum seismic intensity	5+ (JMA seismic intensity)
Maximum tsunami height	12.1 m, flooding 30% of the town.
Number of deaths	94 (directly by the earthquake or tsunami) +3 (indirectly relating to the disaster)
Number of damaged houses	674 completely destroyed, 237 more than half destroyed, 413 half destroyed , and 2,603 partially destroyed

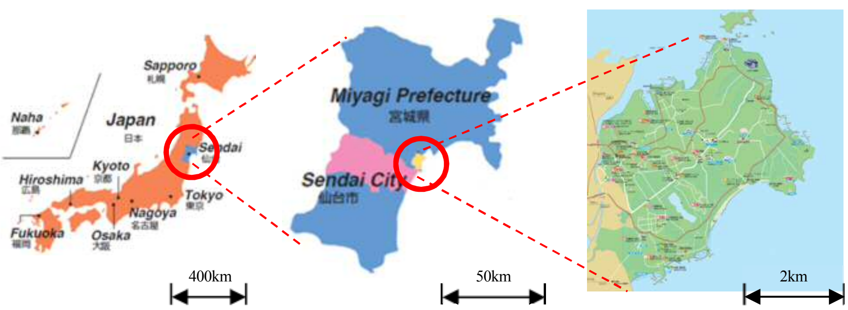


Figure 1. Location of the town of Shichigahama

1-3. The Effects of the Tsunami on Shichigahama

The earthquake damage was not serious in Shichigahama but its lowland areas were hit by a huge tsunami. The tsunami caused significant loss of life and damage to the infrastructure such as the waterworks. Figure 2 depicts the area hit by the tsunami. Picture 1 and Picture 2 show the impacts of the tsunami.

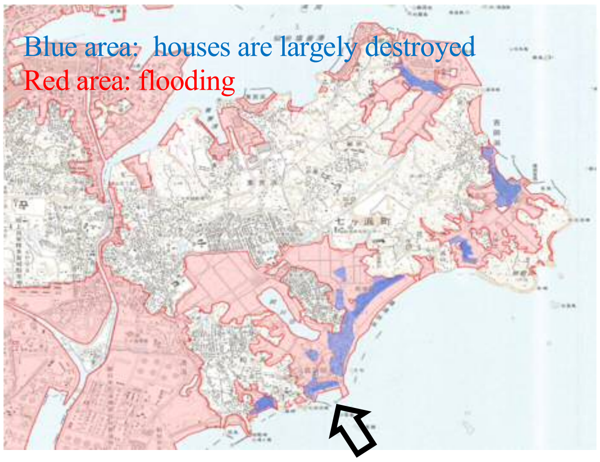
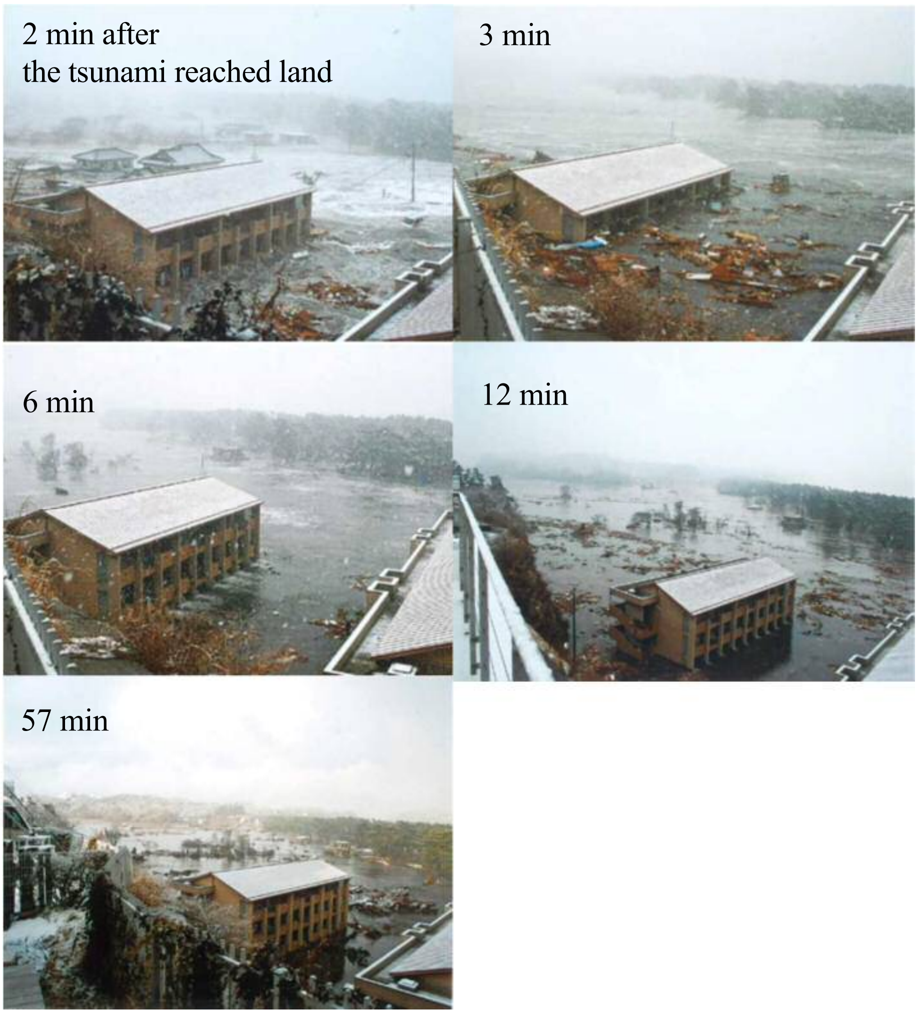


Figure 2. Flooded area due to the tsunami[4]
(the black arrow denotes the angle of Picture 1.)

Picture 1. Aerial photo of Shichigahama
(a few days after tsunami)



Picture 2. The town of Shichigahama after being hit by the tsunami

1-4. Shichigahama Waterworks

Table 3 shows the specifications of the Shichigahama waterworks immediately before the GEJE. The water-supplied population decreased by 5% after the GEJE.

Table 3. Specifications of the waterworks in Shichigahama[3]

Water-supplied area	13.27 km^2
Population in water-supplied area	20,743
Planned population for water supply	22,500
Adoption rate	100%
Water supply capacity	9,000m^3/day
Purification method	Does not have its own purification plant; water is received from the Enterprise Bureau in Miyagi and Sendai City
Maximum daily water supply	5,913 m^3/day
Average daily water supply	5,203 m^3/day
Number of staff	1 technical staff member and 4 clerical staffs members

The Shichigahama waterworks does not have its own purification plant and therefore depends on a supply of water from other waterworks entities, Sendai City and the Enterprise Bureau in Miyagi into the Kimigaoka distribution tank. (In Japan, municipalities are mandated to manage their water supply on their own so municipalities usually have their own purification plants. In case a municipality without its own purification plant, like Shichigahama, the municipality buys water from other waterworks entities.) Figure 3 shows Shichigahama's water distribution system.

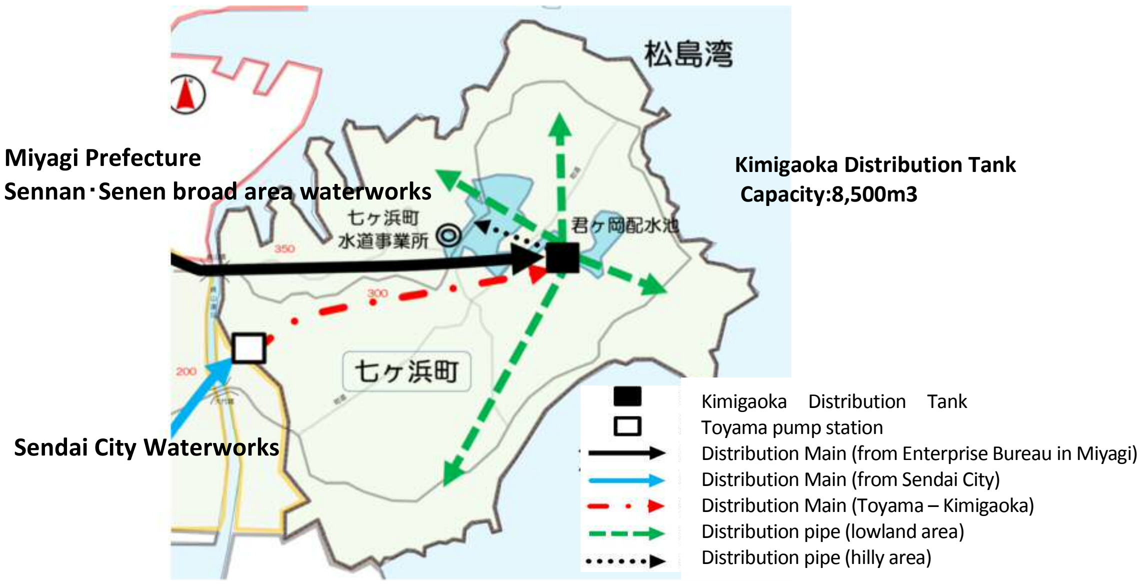


Figure 3. The distribution system in Shichigahama

The town of Shichigahama had limited human resource compared with the city of Niigata, as shown in Table 4.

A small waterworks entity with a small staff like Shichigahama is not rare in Japan as this human resources shortage is becoming a problem. The Japanese government recommends wide-area waterworks or the use of the private sector as an answer for this challenge.

Table 4. Scale of the waterworks in the town of Shichigahama compared with that in the city of Niigata

	Niigata City Waterworks Bureau		Shichigahama Waterworks
Maximum daily water supply	300,000 m^3/day	⇔(1/50)	5,900 m^3/day
Water supply population	Approximately 800,000	⇔(1/40)	Approximately 21,000
Number of staff members	360 (260 technical, 100 clerical in 2017)	⇔(1/70)	5 (2 technical, 3 clerical in 2017)

1-5. Damage to Shichigahama's Waterworks caused by the GEJE

As previously explained, as Shichigahama does not have its own purification plant, its waterworks was completely cut off when the distribution main pipe from Enterprise Bureau in Miyagi was broken by the earthquake. The distribution pipes in Shichigahama were also damaged by the earthquake. In particular, the air valve and the water pipe bridge were severely damaged in the coastal area. It took 35 days to fix the water failure in the distribution main from the Enterprise Bureau in Miyagi but the coastal area remained out of service because there were no houses remaining to service.

2. DISPATCH OF SUPPORT STAFF FROM THE CITY OF NIIGATA TO THE TOWN OF SHICHIGAHAMA

2-1. How and Why Niigata Dispatched Staff

In Japan, waterworks recovery support during major disasters has been done systematically based on the rule of the Japan Water Works Association (JWWA). The JWWA consists of waterworks entities all over Japan. After major disasters, prefecture leaders and district leaders managing other waterworks entities provide support to the damaged entity.

However, after the GEJE, the city of Sendai, which was the Tohoku district leader, and the Ishinomaki Water Supply Enterprise, which was the Miyagi prefecture leader, were also damaged. Therefore neither of these entities were capable of supporting other waterworks entities. This was one of the reasons that the recovery of small waterworks entities was delayed.

Because of this situation, the Japanese government created "The Liaison Council for Supporting the Restoration of the Water Supply Affected by the Great East Japan Earthquake" in July 2011. The council managed to match support entities with supported entities in a manner which was different from the conventional way.

To conduct this matching, the council surveyed the needs for recovery support, revealing that there were manpower shortages within small waterworks entities. Thus, the council requested the large waterworks entities dispatch support staff to such small waterworks entities.

2-2. The Dispatched Staff

The dispatched staff was selected to have technical capabilities in construction control and pipe maintenance as well as the ability to provide psychological support. At that time, there was only one young staff member eligible to be responsible for the waterworks in Shichigahama.

The profile of the dispatched staff member is as follows:

Age: 40 (in 2011)

Profession: civil engineer
Post: technical staff chief (in 2011)
Career: worked as a waterworks pipeline engineer for 17 years
(12 years as a construction project manager and 5 years in pipeline maintenance; in middle of his career, he also worked in sewerage for 3 years)

During the dispatch, the staff member's affiliation remained the Niigata City Waterworks Bureau.

Below is a comment provided in an interview with the dispatched staff member about his feelings at the time.

"After I started my career, there were some major disasters. I was chosen as a dispatched staff member several times, but I couldn't go. After the GEJE, my family was willing to send me and I was able to go without hesitation. I have thank to my family and my co-workers."

His section chief provided the following comment:

"Truthfully, it was very tough to send him, as he was an ace in my section. It was difficult to redistribute the responsibilities with my section. However, we were willing to send him because it was our way of support to the area impacted by the disaster. All of his co-workers worked hard in his absence."

2-3.Work of the Dispatched Staff

After disasters, waterworks entities are very busy with particular tasks such as the recovery of the waterworks system, preparing documents to apply for subsidies, etc. Thus, the dispatched staff member engaged in the following work:

･*Supporting routine work*
He assisted with normal routine work such as water-quality test, responding to inquiries, checking water leaks, etc.

･*Carrying out tasks related to disaster recovery*
The costs for disaster recovery can be subsidized by the government. The preparation of the documents for applying for such government subsidies was a time-consuming process. Additionally, several meetings with other agencies were held to coordinate views and schedules of construction projects.

･*Managing the model project in Shichigahama*
The town of Shichigahama recognized that a waterworks reconstruction plan should be made as quickly as possible but it was difficult to form the plan because there was a shortage of manpower. With the support of dispatched staff, it became possible to engage in the model project run by Ministry of Health, Labour and Welfare (MHLW), which helped to form the plan as quickly as possible.

Picture 3. Dispatched staff working at the office, on site, and in a meeting

3. WATERWORKS RECONSTRUCTION MODEL PROJECT BY MHLW

Every waterworks planning project is the responsibility of that waterworks entity, and waterworks reconstruction planning is not an exception. Therefore, the government cannot help with planning directly. However, the waterworks reconstruction model project run by the MHLW is a new support scheme which had not been tested before the GEJE. With this project, the government is able to support impacted districts in an indirect way. This model project facilitates consideration of how the reconstruction of waterworks should be done in the afflicted areas.

For this project, 12 districts were chosen as the models and the following policies were implemented.

→Facilities were constructed in accordance with the town's urban reconstruction plan.
→Adequate stability of facilities and the water supply against seismic activity was ensured.
→Facilities were designed while considering the cost in the future.

Some waterworks entities offered the following reactions to the model project.

"We were concerned that it would take a lot of time to participate, so we did not request to join the project."

"The model project itself seems to be useful, but we were nervous that the project might require follow-up research."

Although no entity executed the model project in its original form, the deliverables of the model project were utilized as the bases of the reconstruction plans.

In the model project, the town of Shichigahama focused on the hydrological estimation in hilly areas by considering the collective relocation of the residents from coasts areas. Applying the model project make the reconstruction of the town very smooth compared to the reconstruction efforts of other waterworks entities as shown by Picture 4 and Picture 5.

Picture 4. Shichigahama public housing in 2011, 2013, and 2017(from left to right)

Picture 5. Shobuta-hama beach(south area of Shichigahama)
in 2011, 2013, and 2017(from left to right)

4. CONCLUSION

・*Supporting the needs of small waterworks entities*

Through our experience in supporting disaster-affected waterworks, the needed support time and scale can be described as follows:

→Large waterworks entities require large-scale, short-time-span support.

→Small waterworks entities require small-scale, long-time-span support.

According to the interviews conducted with the affected entities about the staff dispatched for long periods of time, a long-time continuous single dispatched staff member is desirable. Dispatched staffs mainly handle construction work and damaged waterworks entities hope that dispatched staff members will take care a construction project from the beginning through the end. But dispatching one staff member continuously is tough on the staff member, his family, and his office co-workers.

Countermeasures for these challenges include taking enough takeover period or remaining on site through the completion of the work. In the case of Shichigahama and Niigata, the dispatched staff member remained at the dispatched office for 4 months and he followed up continuously thereafter via e-mail, telephone, and short-term visits. In this way, he could complete his task successfully.

・*Characteristic waterworks reconstruction in an area impacted by a tsunami*

If an area impacted by a tsunami, structures such as houses completely collapsed. Therefore, urban design standards must be reviewed and the waterworks reconstruction must be adjusted accordingly.

In the survey conducted in July 2017, it was widely reported that coordinating the schedules of related projects is difficult as there are several projects being executed by several entities in the same place. Therefore, it is ideal for a single entity to take the initiative and control the project.

Further, once water source is damaged by a tsunami, it may take a long time to be operational once again. Thus, some affected entities recommend securing multiple or tsunami-resistant water resources. For example, Shichigahama, which is receiving water from Sendai City and the Enterprise Bureau in Miyagi, is considering increasing the percentage of water received from Sendai in case their waterworks are again cut off due to another disaster.

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Determining Water Distribution System Pipe Replacement Given Random Defects – *Case Study of San Francisco's Auxiliary Water Supply System*

Charles Scawthorn[1], David Myerson[2], Douglas York[3], Eugene Ling[3]

ABSTRACT

For a water distribution system (WDS) subjected to random leaks or breaks, key questions exist as to which pipe in the network should be the first pipe to be mitigated, which pipe the second, and so on – in other words, what is the ranking, importance or priority of the network's pipes? To address this problem, a new algorithm termed **P**ipe **I**mportance and **P**riority **E**valuation (**PIPE** algorithm) for evaluating the importance or priority of pipes in a hydraulic network given random defects such as leaks or breaks has been developed and validated.

The essence of the PIPE algorithm is determining each pipe's Average Deficit Contribution (ADC), defined as the average contribution of each pipe to each demand point's deficit (deficit is the difference between required and furnished flow at a demand point). The pipe with highest *ADC* is the pipe that contributes most to the demand's deficit, 2^{nd} ranked pipe contributes next most etc. If the highest ranked pipe is mitigated, deficit is reduced the most and so on. *ADC*'s can be individually calculated for multiple demand points, or for any combination such as the total of all. A key aspect in implementing the PIPE algorithm is the determination of pipe weights via generalized linear modeling, which is discussed in some detail.

The PIPE algorithm was validated by a series of case studies of a gridded network with multiple demand points and then applied to San Francisco's seismic environment and a scenario earthquake – essentially a repeat of the 1906 event. Permanent ground displacements and shaking hazard were determined with special emphasis placed on capturing the randomness of shaking effects using recent work on efficient selection of hazard maps for simulation. Recent work on pipe breaks due to shaking, and due to permanent ground displacement were employed to model defects, which were then applied as random defects conditioned on hazard in Monte Carlo simulations (in some cases, more than 100,000 trials) of the AWSS, in which each trial included a demand-driven hydraulic analysis of the damaged system, using EPANET. We believe this use of EPANET in large demand-driven hydraulic Monte Carlo analyses is the first such analysis. Application of the PIPE algorithm resulted in a ranking of all 6,000 pipes in the AWSS, based on each pipe's contribution to average demand point flow deficits.

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[3] San Francisco Public Works

INTRODUCTION

For a water distribution system (WDS) subjected to random leaks or breaks (collectively termed "defects"), key questions exist as to which pipe in the network should be the first pipe to be mitigated (the "**Most Important Pipe", MIP**), which pipe the second, and so on – in other words, what is the ranking, importance or priority of the network's pipes – which are the MIPs? A pipe's importance with regard to reliability is a function of several factors including the demands on the network, a pipe's 'hydraulic location' in the network, and the likelihood of failure or defect of all pipes in the network. Consider a simple gridded network supplied by one pipe which has a very low likelihood of defect. While the network is not functional if that pipe fails, by definition it is very unlikely to do so. If the network has one demand point served by redundant pipes in the grid with significantly higher likelihood of failure, then the failure of one or more of these pipes, which is much more likely to occur, may reduce likelihood of furnishing the required demand – that is, reduce the network's reliability. Given limited resources, which of these pipes should first be mitigated, so as to most improve the reliability of the network? Solution of the MIP problem – that is identification of pipe importance is an important problem for WDS operators, and has so far eluded solution although it has been the subject of much research [1-4]

SAN FRANCISCO AUXILIARY WATER SUPPLY SYSTEM (AWSS)

The issue of determining pipe importance emerged as a key problem for the City of San Francisco in considering maintenance, replacement and enhancement of its Auxiliary Water Supply System (AWSS). The San Francisco Auxiliary Water Supply System (AWSS) is a water supply system intended solely for the purpose of assuring adequate water supply for firefighting purposes. It is separate and redundant from the domestic water supply system of San Francisco, and until recently was owned and operated by the San Francisco Fire Department (SFFD). It was built in the decade following the 1906 San Francisco earthquake and fire, primarily in the north-east quadrant of the City (the urbanized portion of San Francisco in 1906 and still the Central Business District), and has been gradually extended into other parts of the City, although the original portion still constitutes the majority of the system. The AWSS consists of several major components, Figure 1, including:

(1) Static Supplies: The main source of water under ordinary conditions is a 10 million gallon reservoir centrally located on Twin Peaks, the highest point within San Francisco (see Figure 1). Water from this source supplies three zones including the Twin Peaks zone, the Upper Zone (pressure reduced at the 0.5 million gallon Ashbury Tank) and the Lower Zone (pressure reduced at the 0.75 million gallon Jones St. Tank).
(2) Pump Stations: Because the Twin peaks supply may not be adequate under emergency conditions, two pump stations exist to supply water from San Francisco Bay. Pump Station No.1 is located at 2nd and Townsend Streets, while Pump Station No.2 is located at Aquatic Park - each has 10,000 gpm at 300 psi capacity. Both pumps were originally steam powered but were converted to diesel power in the 1970's.

(3) Pipe Network: The AWSS supplies water to dedicated street hydrants by a special

pipe network with a total length of approximately 120 miles, Figure 2. The pipe is bell and spigot, originally extra heavy cast iron (e.g., 1" wall thickness for 12" diameter), and extensions are now Schedule 56 ductile iron (e.g., .625" wall thickness for 12" diameter). Restraining rods connect pipe lengths across joints at all turns, tee joints, hills and other points of likely stress. San Francisco had sustained major ground failures (leading to water main breaks) in zones generally corresponding to filled-in land and thus fairly well defined. Because it was anticipated these ground failures could occur again, these zones (termed "infirm areas") were mapped and the pipe network was specially valved where it entered these infirm areas. Under ordinary conditions, all of the gate valves isolating the infirm areas are closed, except one, so that should water main breaks occur in these infirm areas, they can be quickly isolated. On the other hand, should major fire flows be required in these areas, closed gate valves can be quickly opened, increasing the water supply significantly.

(4) Other portions, including fireboats, underground cisterns and a Portable Water Supply System (i.e., hose tenders each with a mile of Large Diameter Hose).

The AWSS is a system remarkably well designed to reliably furnish large amounts of water for firefighting purposes under normal and post-earthquake conditions. However, the AWSS is now more than one hundred years old, essentially failed in the 1989 Loma Prieta earthquake (Scawthorn et al, 1990) and is in need of pipe replacement. Additionally, its reliability has never been quantified.

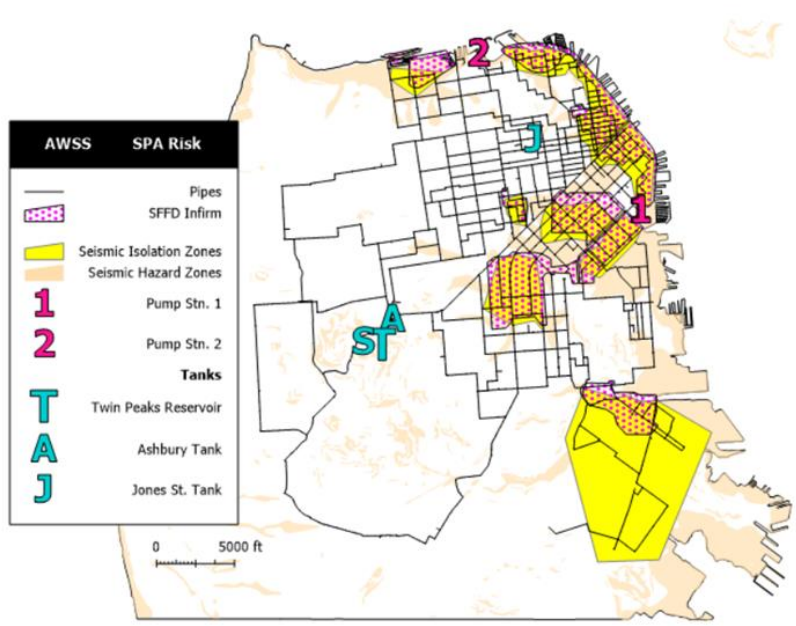

Figure 1 San Francisco AWSS network with Fire Department Infirm Zones, Seismic Isolation Zones, Seismic Hazard Zones, Pump Stations, Tanks and Reservoir

PIPE IMPORTANCE AND PRIORITY EVALUATION (PIPE) ALGORITHM

In order to assess the reliability of the AWSS, and identify which are the MIPs, a new algorithm termed **Pipe Importance and Priority Evaluation (PIPE)** was developed (by the second author) which solves this problem. The essence of the PIPE algorithm is determining each pipe's Average Deficit Contribution (ADC), defined as the average contribution of each pipe to each demand point's deficit (deficit is the difference between required and furnished flow at a demand point). Deficits are determined via Monte Carlo simulation in which for each trial multiple simultaneous defects are randomly imposed (e.g., if earthquake is considered, based on probability of ground motions and pipe vulnerability) and the network's hydraulics solved via pressure driven analysis (PDA). Given the set of trials, generalized linear modeling is then employed to determine each pipe's ADC, which are then ranked in descending order. The ranking is the relative importance of each pipes' contribution to the average of deficits for all simulations. The pipe with highest ADC is the pipe that contributes most to the demand's deficit, second highest ranked pipe contributes next most, and so on. If the highest ranked pipe is mitigated, that mitigation contributes most to overall average deficit reduction, and so on. ADC's can be individually calculated for multiple demand points, or for any combination such as the total of all. A key aspect in implementing the PIPE algorithm is the determination of pipe weights via generalized linear modeling. The PIPE algorithm was validated by application to a series of case studies of a gridded network with multiple demand points.

A simple example illustrating the the PIPE algorithm is shown in Figure 2, which is a 10x10 grid of pipes all 100 feet in length and 12 inch diameter, except:

- P221 which is 24 inch diameter (100 ft. long) and feeds the system from Reservoir R1 at elevation 100 ft.,
- pipe P1 (E-W pipe at NW corner of grid) which is 100 inch diameter (100 ft. long),
- P222 which is 6 inch diameter and 10 ft. in length, and which is a check valve (CV) allowing flow towards J1 but not towards J100. This is combined with a 12 inch diameter flow control valve (FCV) VLV1 set to 900 gpm, which is effectively an emitter with a maximum flow of 900 gpm. The CV-FCV combination is a modification to EPANET which simulates a broken pipe and avoids negative pressures [5]. This 900 gpm is the only demand on the (unbroken) system.

Figure 3 shows the EPANET results for the unbroken system. With the exception of flow at the NW corner, particularly in pipe P1 (which is 48 inch diameter), the flow is relatively symmetric (if P1 is set 12 inch diameter, the flow pattern is perfectly symmetric about the E-Q J50-J510 line). For the unbroken system, the MIPs are easily identified as those carrying the most flow – P221 and P222, followed by P1, P101, P120 and so on.

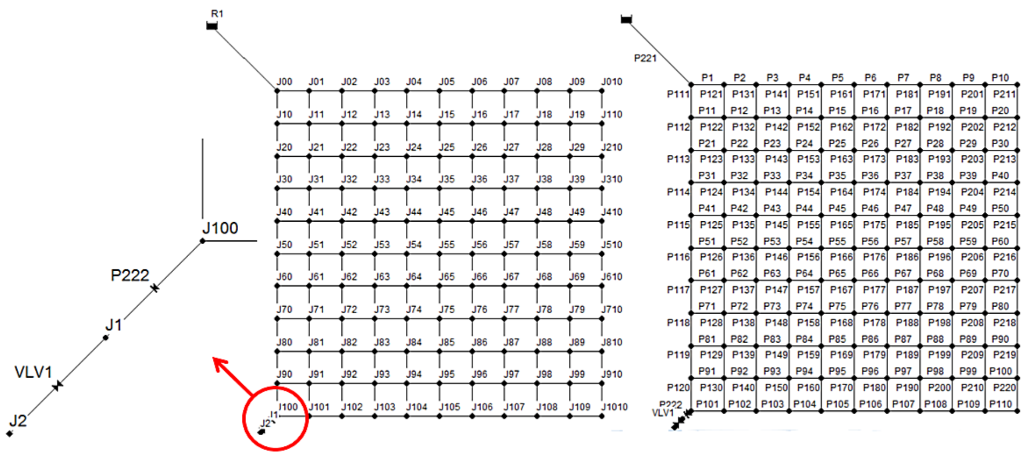

Figure 2 Example grid: (r) pipes; (mid) joints numbering; and (l) detail of CV/FCV assemblage

However, if several pipes have varying probability of defects, the problem becomes much more difficult. For example, set only three pipes to have the following independent probabilities of defect: P1 (48 inch diam., probability of defect = p(d) = 0.01 per annum, P91 (12 inch diam., p(d) = 0.05), and P110 (12 inch diam., p(d) = 0.20). Thus, P1 is the largest pipe in the system (and has the greatest flow in the unbroken system) but has a low probability of defect, P91 has an intermediate vulnerability but is relatively close to the demand point, and P110 has by far the greatest vulnerability but is "far" from the demand point and has rather low flow (in the unbroken system). Which of these is the highest priority for mitigation is very unclear – that is, which of these pipes if mitigated (i.e., set to p(d) = 0, no vulnerability) will reduce demand deficit (i.e., flow required – flow furnished, at the demand) the most?

To solve this problem, we run EPANET with the above configuration many times. Each run (or trial) randomly allows any or all of the vulnerable pipes to break or leak, per the probabilities of defect. We tabulate run results in a Deficit vector D of demand flow deficits for each run, and a FR (flow rate) matrix which for each run is the flow from each pipe's defect – if a pipe has no defect, the FR entry is zero. That is:

$$|\mathbf{D}| = |\mathbf{FR}||\mathbf{w}| \tag{1}$$

where **D** is an Nx1 vector, **FR** is an n x p matrix and **w** is a px1 vector of pipe weights, with n being the number of trials, and p the number of pipes. The pipe weights **w** are unknown and found via linear regression.

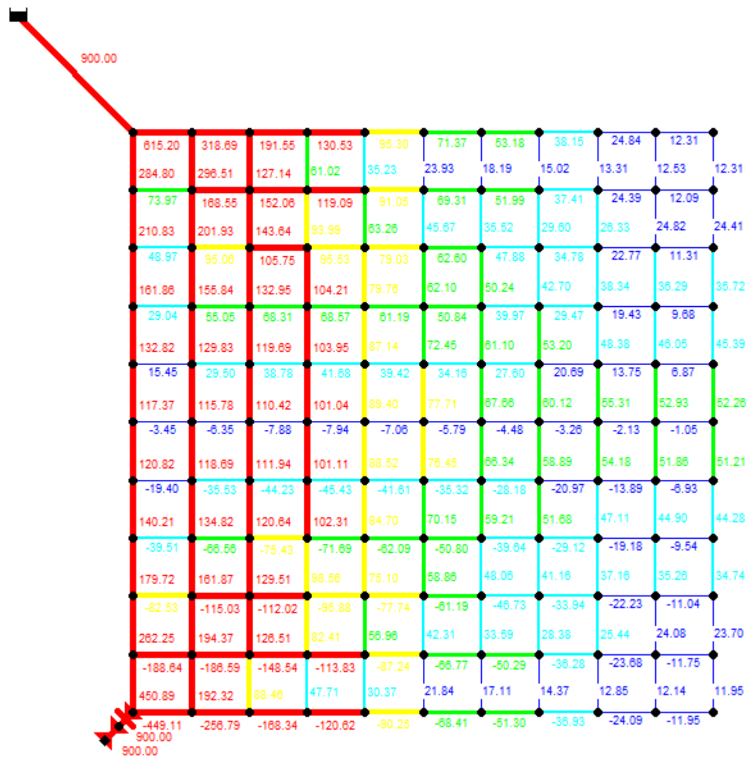

Figure 3 EPANET pipe flow results, unbroken system -

Using the above, we ran 5,500 trials (25 times the number of pipes) of the example grid, resulting in P1, P91 and P110 having 70, 301 and 998 defects, respectively (i.e., in the simulation the defect rates were 0.013, 0.055 and 0.181, respectively – more runs would have had defect rates closer to the specified rates). Using the Bayesian Regression package in python, the weights **w** were found to be 0.00013, 0.1462 and 0.00693 for the three pipes (all others negligibly small or zero). The ADC for each pipe is the found as:

$$ADC_i = \sum_{j=1}^{n} FR_i w_i / n \tag{2}$$

where subscript *i* refers to pipe *i* and summation is over *n* simulations – that is, for a given pipe, the average of the column vector in FR corresponding to that pipe is multiplied by the regressed weight for that pipe. This closely approximates that pipe's average contribution to the overall deficit in demand furnished – its Average Deficit Contribution, ADC (units for example of gpm). For the example network, the ADC values were found to be 0.034, 1.23 and 1.79 for P1, P91 and P110, respectively. Thus, in this example, reducing P110's defect rate to zero will reduce the deficit more than either of the other two pipes. To test this, we set P110 defect rate to zero, resulting in an average deficit for 5,500 trials of 1.80 gpm. Similarly, setting P1 and P91 to zero yielded average deficits of 2.17 and 1.84 gpm, respectively. While the differences are admittedly small in this example, they're intended simply to be illustrative.

APPLICATION TO AND ANALYSIS OF THE AWSS

The application of the PIPE algorithm is shown in Figure 4 and began with a review of San Francisco's seismic environment and selection of a suitable scenario earthquake, essentially a repeat of the 1906 event. Permanent ground displacements and shaking hazard were determined for this scenario, with special emphasis placed on capturing the randomness of shaking effects using recent work on efficient selection of hazard maps for simulation [6]. In Figure 4, the distribution of ground shaking (center top map, PGV) is one of fifteen such maps, which captured the uncertainty associated with this one earthquake scenario ground shaking.

Ground shaking will also result in the outbreak of numerous simultaneous fires, the distribution of such ignitions depending on the nature and distribution of buildings and other fuels [7-9] which was then quantified, taking into account fire department operations and resources, in terms of firefighting water demands on the AWSS, center left. These demands, discretized at 37 points in the network (corresponding to one demand point per Fire Response Area, FRA) and totaling in aggregate about 65,000 gpm, are the demands that the AWSS is required to meet.

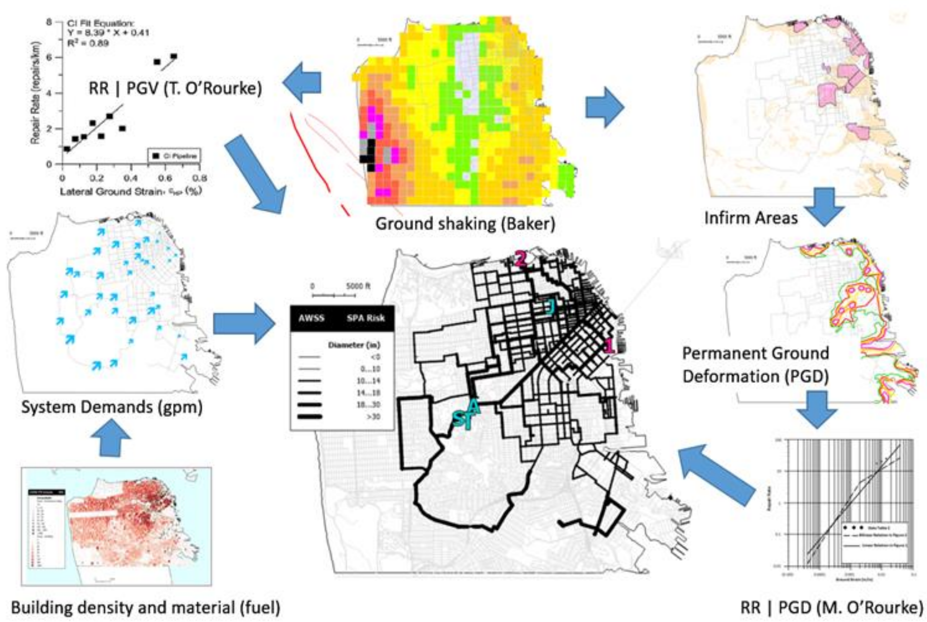

Figure 4 Schematic of analysis employed for the AWSS which begins at lower left with (1) building density and materials. These are combined with (2) ground motions to estimate (3) firefighting water demands (middle left). These demands are combined with (4) break rates due to shaking (PGV, upper right) and (5) break rates due to Permanent Ground Displacement, PGD (right side) in an (6) EPANET hydraulic analysis of the pipe network (center). This process is repeated tens of thousands of times.

Countering these demands are additional pressure-driven demands on the AWSS due to breaks and leaks, caused by ground shaking (upper right) and ground failure (right side of the figure). Recent work on pipe breaks due to shaking [10], and due to permanent ground displacement [11] were employed to model defects randomly conditioned on hazard. This process was repeated in Monte Carlo simulations (in some cases, more than 100,000 trials) of the AWSS, in which each trial included a pressure-driven hydraulic analysis of the damaged system, using EPANET. Two aspects of this analysis warrant discussion: (a) the pressure-driven analysis, and (b) the Monte Carlo simulation, both employing EPANET [12].

The pressure-driven hydraulic analysis of the damaged system is among the first such analyses of its kind using EPANET. Prior analyses using EPANET [13] have been demand-driven and have suffered the flaw of generating 'negative pressures' in which imposed demands coupled with leaks and breaks, the combined effects of which cannot be met from hydraulic sources, result in analytical solutions yielding negative pressures in selected pipes, thus causing spurious inflows at selected sources, leaks or breaks. Until recently, the solution to this problem has been to remove pipes with negative pressures from the network and re-analyze, a clearly unsatisfactory solution. However, Sayyed et al [5] recently developed "a simple non-iterative method … in which artificial string of Check Valve, Flow Control Valve, and Emitter are added in series at each demand node to model pressure deficient water distribution network", which solves this problem.

EPANET has been previously employed in Monte Carlo simulations but the scale of such simulations in this application may be a first. Basically, Python code was written which calculated breaks and leaks due to earthquake shaking (Peak Ground Velocity, PGV) and Permanent Ground Displacement (PGD) as described above, and which then correspondingly modified the EPANET input (INP) file to include each break and leak as a pipe the same as in GIRAFFE "A pipe leak is simulated as a fictitious pipe with one end connected to the leaking pipe and the other end open to the atmosphere, simulated as an empty reservoir. A check valve is built into the fictitious pipe, only allowing water to flow from the leaking pipe to the reservoir but not reversed." (GIRAFFE, 2008).

In summary, the pressure-driven analysis varied for each trial of the Monte Carlo simulation – initial firefighting water demands were always the same while breaks and leaks varied randomly depending on hazard, pipe materials and size. Each trial's EPANET solution returned a different set of flows in the network depending upon that trial's network configuration, and a different set of final firefighting water flows were furnished at each demand point. Using the Python code, calculation of breaks and leaks for the 6,000 pipe network, writing of the EPANET INP file, hydraulic analysis of the network and writing of the resulting pipe flows and furnished demand point flows, required about 1 second per trial on a 2016 vintage laptop Windows 10 personal computer, or about 8 hours for 30,000 trials. We believe this use of EPANET in large pressure-driven hydraulic Monte Carlo analyses is the first such analysis. Figure 5 shows a comparison of demand deficits for the AWSS network as determined from nearly 30,000 EPANET simulations (abscissa) versus demand deficits based on linear regression (ordinate), with an indicated value of r = 0.989.

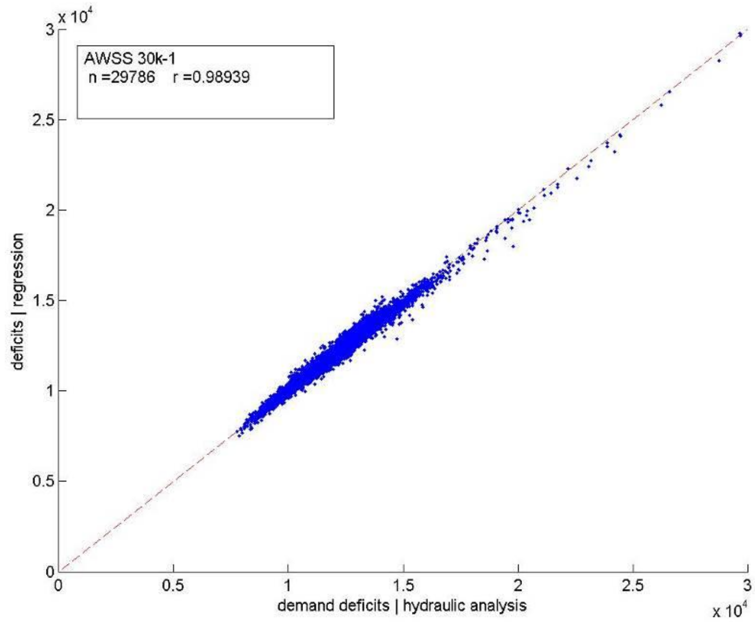

Figure 5 Comparison of deficits for AWSS network for 29,786 trials estimated using linear regression (ordinate) vs. source data from hydraulic analyses (abscissa).

The resulting set of simulations provided the basis for correlation of each pipe's break or leak rate against the "deficit" (difference between FRA demand and furnished flow). Application of the PIPE algorithm resulted in determining which pipes contributed most to FRA deficits. Each pipe's contributions when averaged over the entire set of simulations were termed that pipe's Average Deficit Contribution or ADC, and are a function of the frequency and severity of pipe defect, combined with its location in the hydraulic path. The pipe with the highest ADC is the "most important pipe", in that it contributes the most to the overall deficit in firefighting water flow. Ranking of all 6,000 pipes in the AWSS, based on each pipe's ADC, provides an absolute measure of pipe importance, for that network. However, once the "most important pipe" is identified and upgraded in some manner so as to reduce the frequency and severity of pipe defect, another set of simulations is required to identify the 'next most important pipe'.

Using the above iterative or cascading series of Monte Carlo simulations, the AWSS was analyzed, resulting in an identification of tranches of pipes for upgrading, as shown in Figure 6. With initial pipe improvements, losses in firefighting water supply are greatly reduced, Figure 7, which shows that fixing only 25 pipes reduces losses by almost 4,900 gpm. Additional pipe improvements however quickly reaches a point of diminishing returns.

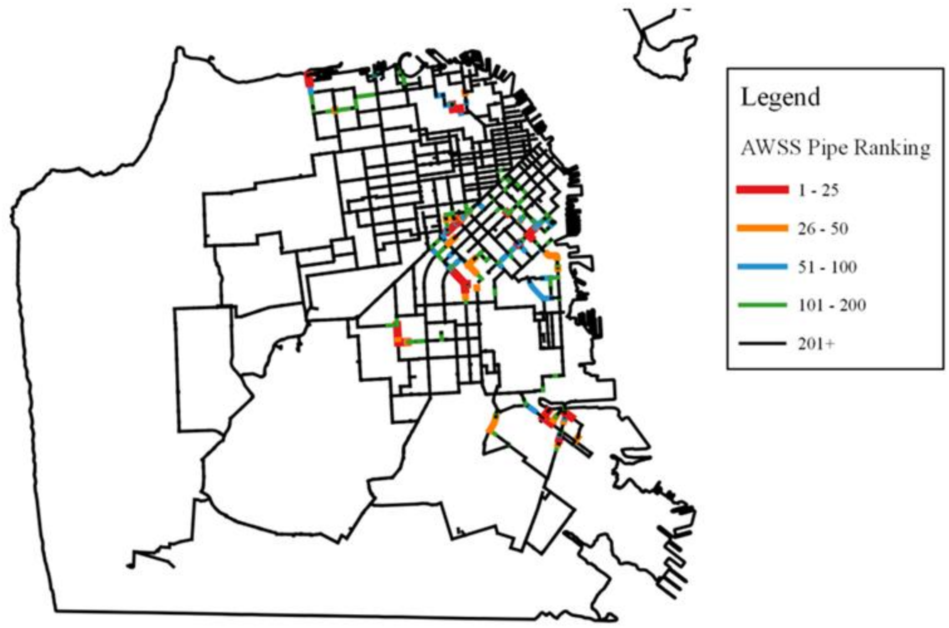

Figure 6 Four tranches of pipe importance – red indicates the 25 pipes contributing most to overall deficits in firefighting water supply, orange the next 25, blue the next 50 and so on.

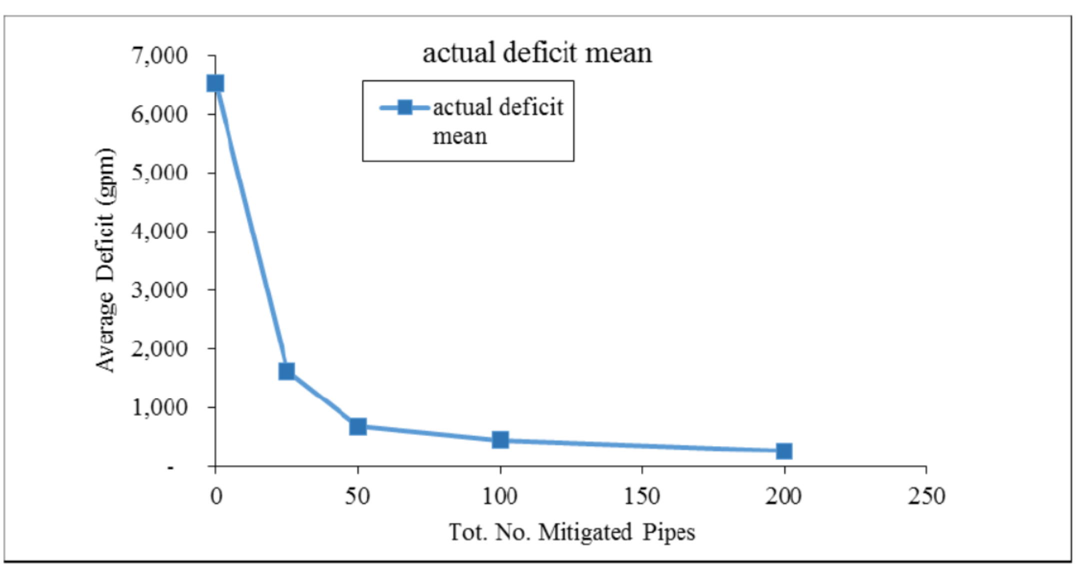

Figure 7 Change in system deficit as pipes are mitigated. Upgrading the first 25 pipes reduced average deficits in firefighting water furnished by about 4,893 gpm. Fixing the next 25 pipes reduces the deficit by an additional 943 gpm, fixing the next 50 reduces the deficit by 228 gpm, and fixing the next 100 pipes only reduces the deficit by 197 gpm.

CONCLUDING REMARKS

San Francisco suffered a loss of 28,000 buildings in the 1906 earthquake, 80% of which loss was attributed to the fire that followed the earthquake. The fire, the largest peace-time urban fire in history to that time and only exceeded since by the fire following the 1923 Tokyo earthquake, grew to such size largely due to many pipe breaks in the water supply network and resulting lack of firefighting water supply. Following the 1906 event, San Francisco was built largely as before, and is today a very dense concentration of highly flammable wood buildings in a high seismicity region. The city's AWSS is a piece of infrastructure critical to reducing fire losses in a future earthquake, and is required to be highly reliable. The analysis of such a system's reliability, and the identification of which pipes contributed most to lack of reliability, proved to be daunting task. Pursuing the solution resulted in the development of a new algorithm that rigorously permits identification of those pipes contributing most to lack of reliability, and development of a capital improvement program for upgrading the system and achieving high reliability.

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Seismic Screening of Large Water Pipelines for TWC's Seismic Improvement Program

Gee-Yu Liu, Chin-Hsun Yeh, and Lee-Hui Huang

ABSTRACT

Mitigation of water supply systems against earthquake hazard is always a crucial task in Taiwan. In order to mitigate the seismic risk of water pipes more effectively, a screening of the large pipelines is essential. A study was therefore conducted to utilize existing or develop new seismic hazard maps of ground shaking, soil liquefaction, active faults, and landslide relating to the cause of damages in buried pipes. The inventory of pipelines of Taiwan Water Corporation (TWC) with a diameter of 800mm or greater was collected and calibrated. It consists of 2,229 km of pipes of various sizes and pipe types (joints). The seismic risk of each pipe as a combination of hazard severity and pipe vulnerability was quantified and ranked. The importance of each pipe has also been classified according to the volume of water it conveys and the existence of any redundancy. Finally, pipes of high importance and at high seismic risk have been screened out. They were grouped into three priorities ready for TWC to implement seismic improvement program in the near future.

BACKGROUND

Taiwan is located on the circum-Pacific seismic belt, one of the most earthquake-prone areas in the world. In the 1999 Chi-Chi earthquake (Mw 7.6), the most devastating event in decades, a widespread damage in water supply systems occurred. As many as 4,411 damages to water pipes were recorded, among which 28 occurred in pipes of ϕ500mm or larger. The worst single damage occurred near Fengyuan, Taichung. It is a ϕ2000mm steel pipe, the only common outlet of Fengyuan First and Second Water Treatment Plants, which met 70% of the water demand from Taichung metropolitan area before the event. It was bent 90 degree and buckled by the offset of Chelungpu fault rupture (TWC, 2000). The 2016 Meinong earthquake (Mw 6.6) caused substantial damage to water pipelines in Tainan, especially in its southern area metropolitan area. The ϕ2000mm pipeline conveying water from Nanhua Water Treatment Plant to downtown Tainan was damaged at three sites. These damages caused widespread water outage lasting for quite some time (Liu et al., 2016).

Evidences indicate that many of the large water pipes of TWC do not have enough strength to withstand medium to large seismic actions. In order to mitigate the risk more effectively, a seismic screening of the large pipelines is desired.

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GOAL AND METHODOLOGY

This study focused on the water pipelines of TWC with a diameter of 800mm or greater (up to 3,200mm). Its goal is to: (1) make a sorting of the target pipelines according to their importance to the water supply systems, (2) make a ranking of the target pipelines according to the seismic risk they are exposed to, and (3) screen out pipelines of high importance and at high risk for the seismic improvement program of TWC.

The seismic risk of pipelines is very difficult to define or quantify. For the sake of simplicity, the "hazard" and "vulnerability" of a pipeline are assumed independent on each other. Efforts were done to collect existing or develop new seismic hazard maps of Taiwan. Hazards of ground shaking, soil liquefaction, active faults and landslide, which are inevitably the causes of pipe damages, have all been considered. Each type of hazard to a pipeline was quantified. A normalized "summation of hazards" and a normalized "pipeline vulnerability" were defined and finally "combined" to get the "risk" of a pipeline.

According to the value of risk, all target pipelines could be ranked from high to low, and evenly divided into an array of "risk groups." By spreading out the array with respect to the importance of pipelines, a seismic risk matrix could be generated, from which the pipes of high importance and at high seismic risk could be easily identified.

PIPELINE INVERTORY AND IMPORTANCE

The inventory of the target pipelines was first collected and calibrated. The total length of the pipelines is 2,229 km. The digitized GIS data consist of more than 6,500 polylines, some of which being very short and some other very long. They were re-organized into 1,687 units of similar length so as to be of roughly equal representation. This was achieved by either grouping of neighboring pipes or division of long pipes. These units were termed "pipe evaluation units," and were employed as the base units for analysis and further seismic risk mitigation.

The importance of large water pipes consists of two different elements. One is about the pipes' role. TWC operates several large water supply systems in urban areas. Some pipelines convey a very large volume of raw or clear water daily, and are therefore very important to the people's lives and socio-economic activities. The other is about their criticality, namely the existence of any redundant pipe as backup when they fail.

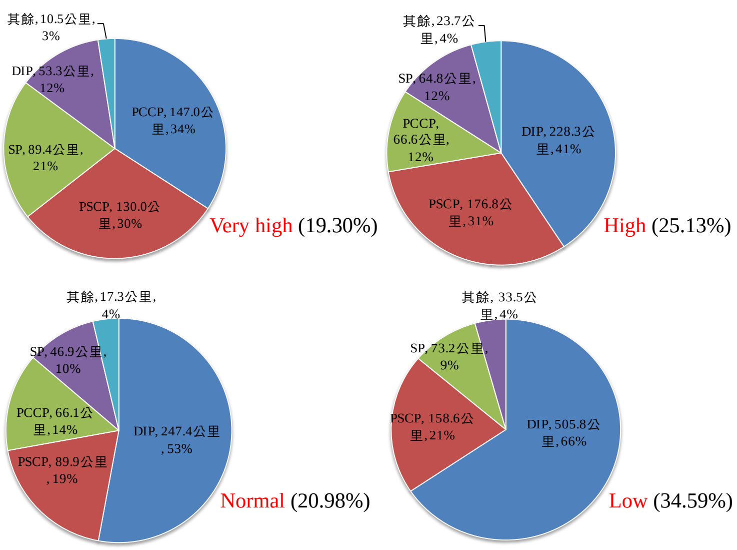

Figure 1. Percentages of pipes of various classes of importance, and percentages of various types of member pipes they consist of.

Taking the two elements into account, each pipe evaluation units was classified as one of the four classes of importance: very high, high, normal, and low importance. Figure 1 summarizes the percentages of pipes of various classes of importance, and the percentages of various types of member pipes they consist of. It is worth noticing that, for pipes of very high importance (19.30% of total pipelines), the majorities are PCCP (pre-stressed concrete cylinder pipes, 34%) and PSCP (pre-stressed concrete pipes, 30%). Such pipes are brittle and seismically very vulnerable.

SEISMIC HAZARD TO PIPELINES

Ground Shaking

Ground shaking is inevitably the most common cause of pipe damage. Theoretically, peak ground velocity (PGV) is proportional to the ground strain, the seismic action exerting upon a pipe and may cause its damage during ground shaking. It is employed to measure the rate of pipe damage (number of repairs per unit pipe length) conventionally.

Therefore, the value of PGV at a return period of 10% in 50 years (design earthquake) is used to specify the hazard of ground shaking in this study. A formula for estimating the value of PGV (unit: cm/s) of a site is employed. It is expressed as

$$PGV = 0.885 \cdot \frac{9.81 \cdot S_{D1}}{2\pi} \tag{1}$$

where S_{D1} is the code-specified value of spectral acceleration at period T = 1.0s at a return period of 10% in 50 years (design earthquake), with the amplification by both site and near-fault effects (Taiwan Building Seismic Design Code, Version 2011) considered. This formula is actually a simplified formula to the one suggested by AASHTO (2010). As a result, a hazard map of PGV of Taiwan can be prepared.

According to a study in Japan (Miyajima, 2013), the rate of pipe damage is proportional to $(PGV-15)^{1.14}$, where 15 cm/s stands for the threshold of damage occurrence. If the size of the interested pipes is large (e.g. with a diameter of 800mm or greater), then a base value with respect to, say, 30 cm/s should be specified and removed to count for the damaging effect of ground shaking. As a result, the hazard of ground shaking H_{GS} to a pipeline evaluation unit may be defined as

$$H_{GS} = (\overline{PGV}-15)^{1.14} - (30-15)^{1.14} = (\overline{PGV}-15)^{1.14} - 21.915 \tag{2}$$

where $\overline{PGV}$ is the weighted PGV of the pipeline evaluation unit, or

$$\overline{PGV} = \sum_j \frac{A_j}{A} \cdot PGV_j \tag{3}$$

where A_j and PGV_j are the jth area and its PGV value, respectively, of a 10m radius buffer of the pipeline evaluation unit.

Soil Liquefaction

Soil liquefaction is one of the major causes of pipe damage, too. Conventionally, the liquefaction potential index (P_L) proposed by Iwasaki, et al. (1982) is used to indicate how susceptible a site is for liquefaction to occur.

Similar to the concept of soil liquefaction susceptibility categories in HAZUS (RMS, 1997), a map of soil liquefaction susceptibility categories of Taiwan has been proposed by Dr. C. H. Yeh of NCREE. It is based on the borehole database from Central Geological Survey, MOEA, together with the map of geology, digital terrain model, and map of drainage. A site will be classified as one of the nine categories, i.e. Cat. 1 to 9, depending on how easily liquefaction will occur given the same excitation. A site of Cat. 0 suggests that liquefaction will never occur there. In addition, a set of empirical formulas for have been proposed by Yeh et al. (2015) to assess the P_L value of each soil liquefaction susceptibility category. The peak ground acceleration (PGA), earthquake magnitude (M) and ground-water depth (D) are the three parameters required in the formulas. With the code-specified PGA and M at a return period of 10% in 50 years (design earthquake), a hazard map of liquefaction potential index P_L can be prepared again. An illustration of this procedure is given in Figure 2.

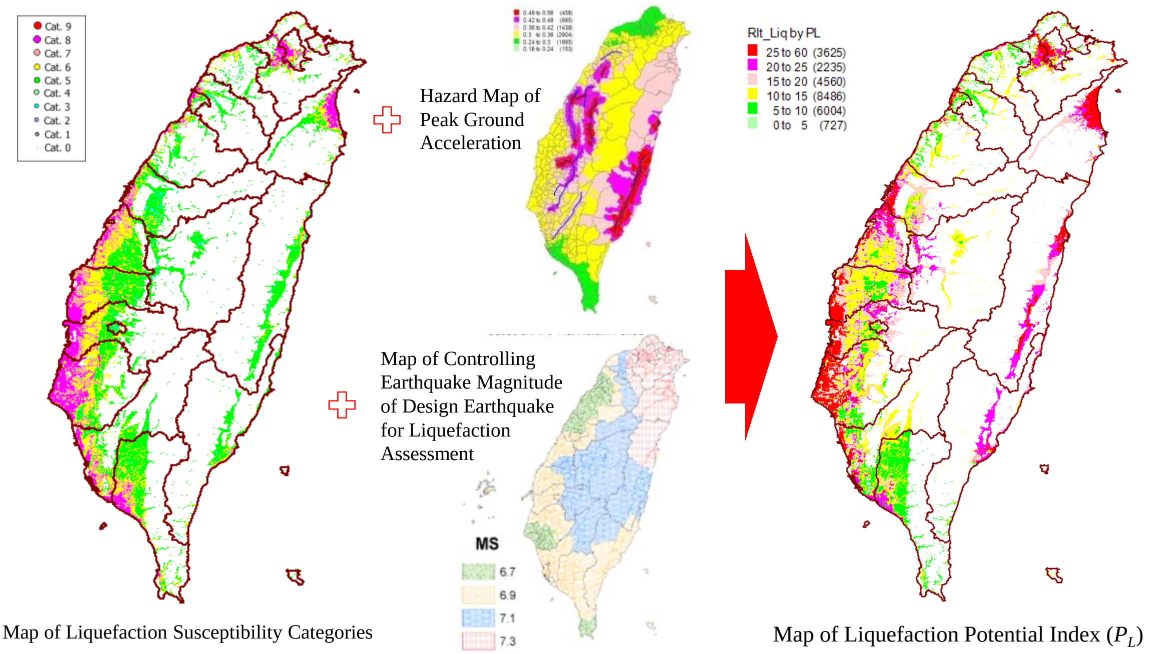

Figure 2. The procedure for creating the hazard map of liquefaction (potential index).

As a result, the hazard of soil liquefaction H_{LQF} to a pipeline evaluation unit is defined as

$$H_{LQF} = \overline{PL} \cdot \log_{10} L \tag{4}$$

$$\overline{PL} = \begin{cases} 0 & P_L < 10 \\ P_L - 10 & 10 \le P_L < 30 \\ 20 & P_L \ge 30 \end{cases} \tag{5}$$

where P_L is the weighted soil liquefaction potential index of a pipeline, which can be computed similarly to Equation (3), except that a 100m radius buffer is employed instead. The factor $\log_{10} L$ is for reflecting that fact that, given the same liquefaction potential, the affected range of the member pipes and its severity of a pipeline evaluation unit are positively correlated to the total length L.

Fault Rupture

According to the active fault map of Taiwan by Central Geological Survey (CGS), MOEA, there are 33 active faults on the island, 20 of which belonging to the Category I and the rest Category II. The former refers to faults that activate within past 10,000 years and are considered more active, while the later activate within past 100,000 years and less active (CGS website).

In order to account for the damaging effect of fault rupture on pipelines once it occurs, two buffers have been created for each fault trace, as depicted in Figure 3. The first is a 15m radius buffer denoted as "fault crossing area," while the second is a 150m radius buffer denoted as "fault vicinity area." For the case of a normal or reverse fault, the buffers will be shifted to the hang-wall side by 5m and 50m, respectively, to account for the hang-wall effect.

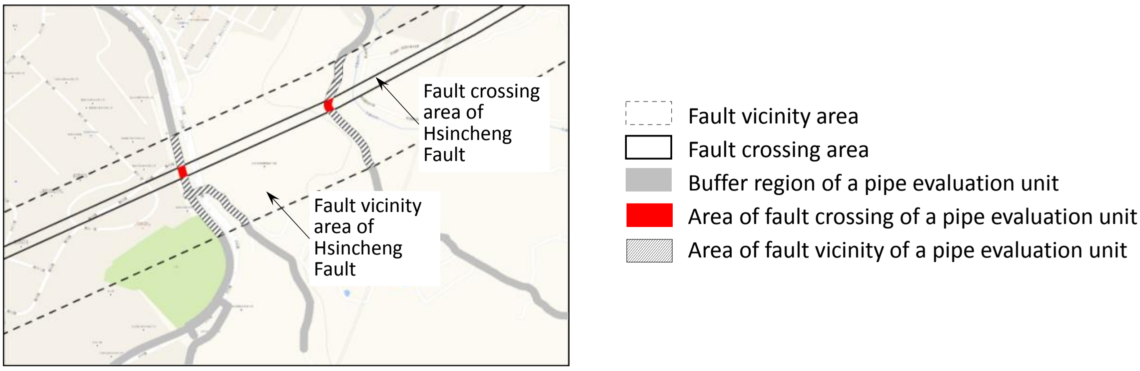

Figure 3. Example fault crossing area and fault vicinity area of an active fault trace.

In addition, the 10m radius buffer of a pipeline buffers is overlaid upon these two buffers to decide the sizes of area within, denoted as A_c and A_v. Accordingly, the effective length of fault-crossing and length of fault-vicinity of the pipeline can be defined as $L_c = A_c / 20$ and $L_v = A_v / 20$, respectively. As a result, the hazard of fault rupture H_F to a pipeline evaluation unit is defined as

$$H_F = \min(10L_c + L_v, 600) \cdot \overline{D} \cdot \bar{f} \tag{6}$$

$$\overline{D} = \begin{cases} D & D < 1.0 \\ 1.0 & D \geq 1.0 \end{cases} \tag{7}$$

$$\bar{f} = \begin{cases} 1 & R \geq 500 \\ 2 - \dfrac{R - 200}{300} & 200 < R < 500 \\ 2 & R \leq 200 \end{cases} \tag{8}$$

where D and R are the average fault offset (unit: m) predicted by using the model of Wells and Coppersmith (1994), and the return period (unit: year) of the fault.

Landslide

The map of landslide potential in Taiwan has been released by Central Geological Survey, MOEA. It classifies the landslide potential into four categories: none, low, medium, and high. It is supposed that the occurrence of landslides induced by earthquake in Taiwan is closed correlated to the potential specified on this map. A landslide score of 3, 1, 0, and 0 is specified to these categories, respectively. As a result, the hazard of landslide H_{LS} to a pipeline evaluation unit is defined as

$$H_{LS} = \sum_{j=1}^{4} \frac{A_j}{A} \cdot LS_j \tag{9}$$

where A_j and LS_j are the jth area and its landslide score, respectively, of a 100m radius buffer of the interested pipeline evaluation unit.

SEISMIC VULNERABILITY OF PIPELINES

Following the formula of pipe damage rate by Miyajima (2013), of which the rate is proportional to $C_p \cdot C_d \cdot C_g \cdot (PGV - 15)^{1.14}$, where C_p, C_d, C_g are the correction factors of pipe type (joint), pipe diameter, and micro-topography, respectively. Generally speaking, the stronger the pipe (type-joint), the lower the C_p value and pipe damage rate; the larger the pipe diameter, the lower the C_d value and pipe damage rate.

The proposed values of C_p of various water pipe (joint) types were summarized in Table 1. They are either following the values by Miyajima or simply specified by the authors according to judgment.

Table 1. Correction factors of pipe type (joint) for pipe damage rate estimation.

Type of pipe (joint)	Correction factor C_p
DIP(K) – Ductile cast iron pipes of K-type joint	0.5
DIP(U) – Ductile cast iron pipes of U-type joint	
SP – Welded steel pipes	
WSP – Segmented steel pipes (installed by pipe jacking method)	
SP(F) – Segmented steel pipes with flange joint	1.0
CIP – Cast iron pipes	2.5
PSCP – Pre-stressed concrete pipes	
PCCP – Pre-stressed concrete cylinder pipes	
ACP – Asbestos pipes	7.5
RCP – Reinforced concrete pipes	

Therefore, given a pipe of specific type (joint) and diameter, its vulnerability V is quantified in this study as

$$V = \log_{10}(10 \cdot C_p) \cdot \left(\frac{800}{\phi} \right)^{0.125} \tag{10}$$

where ϕ is the pipe diameter (unit: mm). This functional form of V is very carefully specified such that, given the wide ranges of C_p and ϕ, the range of V is small but enough to distinguish the fragile pipes from the others. Whenever a pipeline evaluation unit consists of more than of pipes, its V value should be the summation of vulnerability of all member pipes weighted by their length ratio, or

$$V = \sum_k \frac{L_k}{L} \cdot V_k \tag{11}$$

where L and L_k are the total length of the pipeline evaluation unit and the length of the kth member pipe, respectively. Finally, the normalized vulnerability $\overline{V}$ of every pipeline evaluation unit is computes as

$$\overline{V} = \frac{V - V_{\min}}{V_{\max} - V_{\min}} \tag{12}$$

which has a numeric range of $[0,1]$.

SEISMIC RISK AND ENHANCEMENT PRIORITIES OF PIPILINES

The hazards to a pipeline evaluation unit defined in Equations (2), (4), (6), and (9) have completely different physical meanings and numeric ranges. They have to be transformed into numbers which are normalized and addible. As the goal here is merely making a comparison among the "hazard," the sum of four quantified hazards, to each and every pipeline evaluation units, the numbers can be anything that provides information of high or low hazard potential. For that reason, the "order point" is employed in this study. For example, if the H_{GS} value of a specific pipeline evaluation unit is 67.3 cm/s, which is ranked the jth among all 1,687 units sorted from low to high, then the order point of its ground shaking hazard is $\overline{H}_{GS} = r(j/1687)$, where $r(\cdot)$ is the round-off operator. The other three values of quantified hazards can be transformed into the corresponding order points in the same way.

Finally, the "hazard" of a pipeline evaluation unit in terms of hazard order points is defined as

$$\overline{H} = 0.45 \cdot \overline{H}_{GS} + 0.45 \cdot \overline{H}_{LQF} + 0.08 \cdot \overline{H}_F + 0.02 \cdot \overline{H}_{LS} \tag{13}$$

which has a numeric range of $[0,1]$, too. The weighting numbers 0.45, 0.45, 0.08, and 0.02 are carefully chosen so as to keep balance of the contribution from different hazards.

Eventually, the risk of a pipeline evaluation unit is defined as

$$R = \left(1 + \overline{H}\right) \cdot \left(1 + \overline{V}\right) \tag{14}$$

which has a numeric range of $[1,4]$. The higher the risk of a pipeline evaluation unit is, the higher the seismic hazard potential it is exposed to, or the more vulnerable it is seismically.

According to the value of risk, all pipeline evaluation units could be ranked from high to low, and evenly divided into ten "risk groups" from R1 to R10. Combining with the pipelines' importance classified earlier, a risk-importance matrix can be achieved as summarized in Table 2. It can help decide that, among all, which pipeline evaluation units should be enhanced first.

In order to assure an effective and financially feasible seismic enhancement of large water pipes, a prioritized implementation is preferred. From the risk-importance matrix, three priorities could be suggested, as specified in Table 3. Each priority consists of two elements from the matrix. For example, the first priority consists of 82 units, of which 29 are from the combination of (Very high, R1), while the other 53 are from (Very high, R2). A total of 232 pipeline evaluation units are suggested to TWC for seismic enhancement in the future.

Table 2. The numbers of pipeline evaluation units distributed in the risk-importance matrix.

Risk group	Very high	High	Normal	Low	Sum
R1	29	51	38	51	169
R2	53	33	40	43	169
R3	46	38	34	51	169
R4	20	56	28	65	169
R5	34	55	30	50	169
R6	18	45	47	59	169
R7	22	35	57	55	169
R8	24	34	44	67	169
R9	41	27	31	70	169
R10	6	48	26	86	166
Total	293	422	375	597	1687

Table 3. The number and priority of pipeline evaluation units suggested for seismic enhancement.

Priority	Order	Combination of (Importance, Risk group)	No. of evaluation units
First	1	(Very high, R1)	29
	2	(Very high, R2)	53
Second	3	(High, R1)	51
	4	(Very high, R3)	46
Third	5	(High, R2)	33
	6	(Very high, R4)	20

In reality, the suggested 232 pipeline evaluation units are not evenly distributed. The units located in Taichung (74) and Kaohsiung (65 in total), as illustrated in Figures 4 and 5, respectively, outnumber those in other areas in Taiwan. Both are vast and densely populated areas relying on water supply from limited water treatment plants. Particularly, Taichung area is of high potential in ground shaking and fault rupture hazards due to the existence of many active faults in the neighborhood.

CONCLUDING REMARKS

Water pipelines of high importance and at high seismic risk have been screened out. They were grouped into three priorities ready for TWC to implement seismic improvement program in the near future. Major assumptions behind the analysis include: (1) the hazard and vulnerability of a pipeline are independent on each other, and (2) the existing or developed seismic hazard maps of ground shaking, soil liquefaction, active faults and landslide are reliable and with enough resolution. At the present stage of preliminary screening, they seem fine. Nevertheless, TWC should adopt field-investigated hazard and more rigorous hazard-vulnerability analysis in the next stage of pipeline seismic assessment and enhancement.

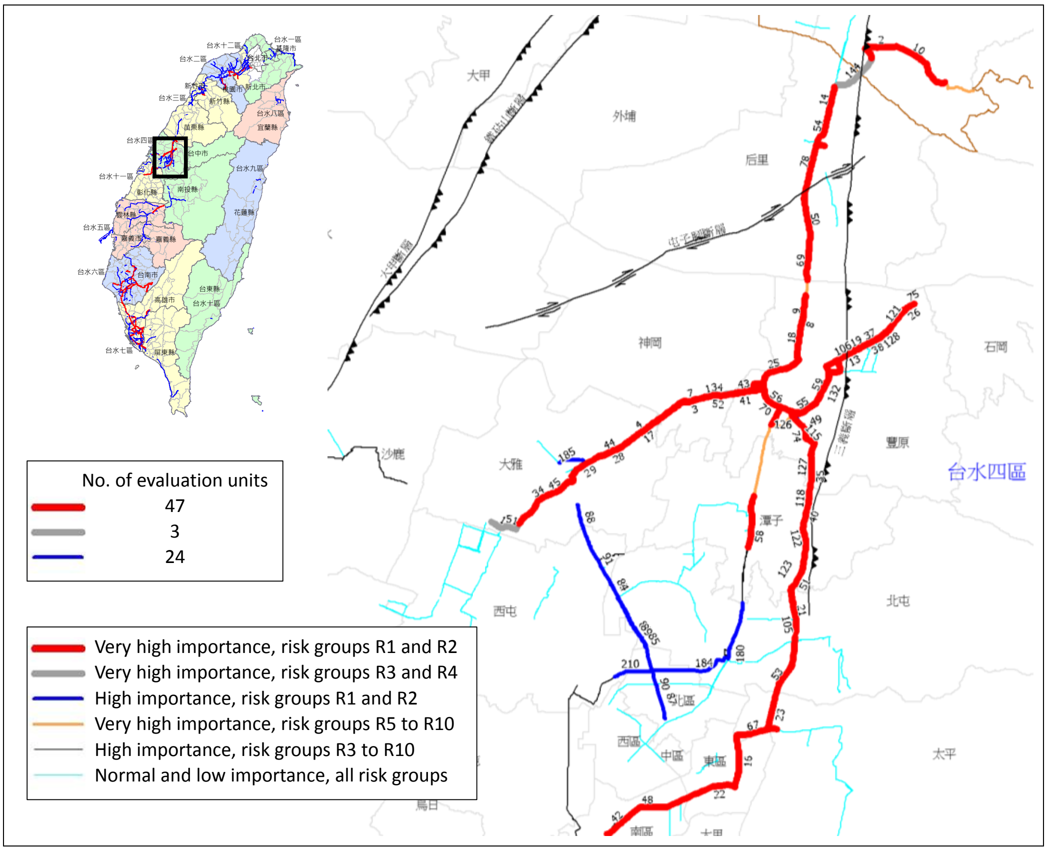

Figure 4. The suggested pipeline evaluation units in Taichung for seismic enhancement.

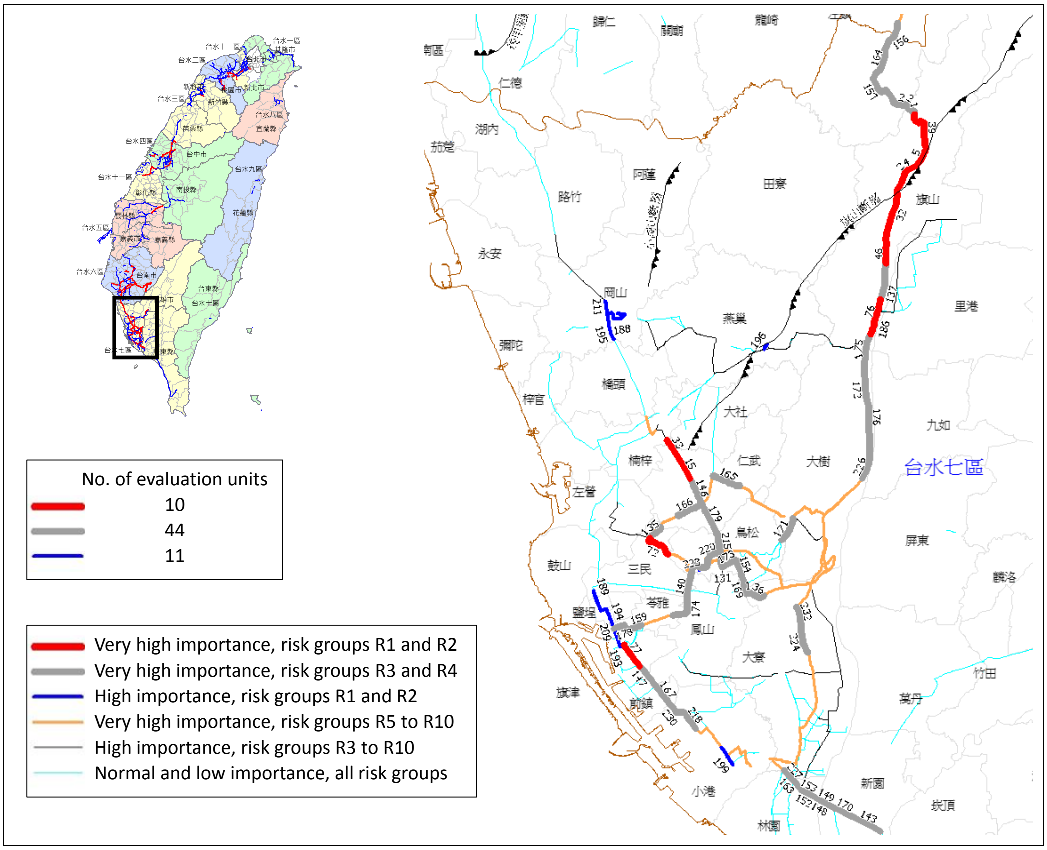

Figure 5. The suggested pipeline evaluation units in Kaohsiung for seismic enhancement.

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Mitigation of Potential Impacts of Seismic Events on a Regional Water Distribution System

Gordon Johnson*, Ricardo R. Hernandez**

ABSTRACT

The Metropolitan Water District of Southern California owns and operates a conveyance and distribution system that consists of approximately 1,770 km (1,100 miles) of large capacity aqueducts, pipelines, and tunnels to distribute untreated and treated water throughout Southern California. This system crosses a number of active faults and is susceptible to fault rupture, ground failure, and shaking damage. Construction of this conveyance and distribution system was completed in phases from the 1930's through the 2000's, and included few special provisions for seismic events. Since the system was completed, overall knowledge of the geology and seismicity within Southern California has greatly increased, while significant advancements have occurred in earthquake engineering and design. Based on this increased knowledge, Metropolitan has established an ongoing seismic resilience program to periodically reassess the seismic risk to its infrastructure, and to address key vulnerabilities. Over the past two decades, Metropolitan has focused primarily on addressing the susceptibility of above-ground structures, aqueducts, and tunnels. Presently, Metropolitan is developing a standardized approach for addressing seismic issues during the rehabilitation of existing large diameter pipelines, and for the construction of new pipelines. This paper presents Metropolitan's strategy for assessing seismic issues for existing pipelines, and provides two examples of this standard being applied to fault zone crossings: 1) the Second Lower Feeder crossing of the Newport-Inglewood Fault, and 2) the Casa Loma Siphon crossing of the Casa Loma Fault.

INTRODUCTION

The Metropolitan Water District of Southern California is a consortium of 26 cities and local water agencies that provides drinking water to 19 million people over a 13,470 square kilometer (5,200 square mile) service area along the Southern California coastal plain. On average, Metropolitan delivers 6.4 million cubic meters (1.7 billion gallons) of water per day to its customers. Metropolitan owns and operates five water treatment plants, nine pumping plants, 16 hydroelectric plants, 20 dams and reservoirs, over 1,335 km (830 miles) of large diameter pipelines and tunnels up to 6.25 m (20.5 feet) in diameter, and the 390 km (242 mile) Colorado River Aqueduct (CRA).

Figure 1: Southern California Imported Water Supply Aqueducts

Metropolitan imports Colorado River water from the border of California and Arizona into coastal Southern California through the CRA. Metropolitan also imports water from Northern California, which is conveyed through the California Department of Water Resources' California Aqueduct (see Figure 1). In an average year, these two aqueducts supply nearly 60 percent of the water used within Southern California. Imported water conveyed through the CRA is stored in surface reservoirs and may be treated at one of Metropolitan's five water treatment plants before distribution to member agencies. The distribution system is comprised primarily of concrete and steel pipelines, with a small amount of cast iron pipe.

Approximately 256 km (159 miles) of the distribution system consists of prestressed concrete cylinder pipe (PCCP) that was constructed between 1965 and 1985, and which ranges in diameter from 1.07 m (42 inches) to 5.10 m (201 inches). The remainder of the distribution system consists of precast concrete and metallic pipelines that were installed between 1935 and 2011 that range in diameter from 1.22 m (48 inches) to 3.86 m (152 inches).

Metropolitan's service area is crossed by a number of known faults with varying levels of activity. The major aqueducts that convey imported water into Southern California and the major regional faults are both shown in Figure 1. The 2013 Uniform California Earthquake Rupture Hazard Forecast (UCERF3) [1] estimates a 93 percent likelihood of a magnitude M6.7 or greater earthquake occurring within Southern California within the next 30 years. Specifically for the Southern San Andreas Fault, which is crossed by all of the water conveyance systems into the region, UCERF3 estimates a 19 percent likelihood of a M 6.7 or greater earthquake within 30 years.

As a regional provider of drinking water, Metropolitan recognizes the importance of continuous water deliveries following a major seismic event, both for general welfare and fire suppression. The National Infrastructure Advisory Council defines resilience as the ability to anticipate, absorb, adapt to, and recover rapidly from a potential disruptive event [2]. Metropolitan takes steps to prepare and respond to seismic events so that regional water delivery interruptions are minimized, and that regional deliveries can be restored within a reasonable period.

Metropolitan has taken a multi-faceted approach to seismic resilience that involves planning, engineering, and operational functions as well as coordination with external agencies. The planning portion addresses system flexibility and emergency storage through Metropolitan's Integrated Resources Plan. The engineering portion addresses vulnerability studies, design criteria, and seismic resilience projects. The operational portion involves emergency response planning and construction capabilities. In addition, Metropolitan is collaborating with the two other owners of imported water conveyance systems that cross the Southern San Andreas Fault to address the unique seismic vulnerabilities of imported water aqueducts to Southern California. This multi-agency effort complements Metropolitan's internal efforts to maintain reliable water deliveries.

Metropolitan's seismic resilience strategy addresses both existing and new infrastructure, including structures, reservoirs, aqueducts, tunnels, and pipelines. This paper focuses on pipelines. It provides an overview of Metropolitan's evolving strategy for assessing seismic resilience for existing pipelines, and describes two examples of how this strategy is being applied. In the case of existing pipelines, many of which are located in densely populated regions, Metropolitan aims to mitigate potential seismic risks while executing long-term rehabilitation programs, leveraging every project as an opportunity to improve seismic resilience.

COMPREHENSIVE RELIABILITY STRATEGY

Metropolitan has developed a comprehensive approach to reliability through a collaborative effort with its member agencies. The strategy was first developed in 2007 as an element of the Integrated Area Studies, which aim to maximize the coordination between Metropolitan and its member agencies to reliably meet the region's water supply needs. Through this effort, five components of system reliability were defined:

- *Water Supply Reliability* – the ability to obtain water to meet member agency demands under all foreseeable hydrologic conditions.
- *System Capacity* – the ability to convey, treat, and distribute supplies to meet firm demands under peak conditions.
- *Infrastructure Reliability* – the ability to maintain facilities in a state of readiness to make water deliveries. *Seismic preparedness activities under this component include Metropolitan's long-term Seismic Upgrade Program and periodic vulnerability assessments. To date, Metropolitan has invested over $230 million to enhance the seismic performance of its existing facilities, while $163 million is planned to be expended over the next five years.*
- *System Flexibility* – the ability to respond to short-term changes in water supply, water demands, and water quality; and the ability to meet member agency needs during planned outages, and to minimize impacts from unplanned outages.
- *Emergency Response* – the ability to respond to unplanned outages and restore service quickly.

The five components of Metropolitan's comprehensive reliability strategy were discussed in detail in ref. [3]. Seismic resilience is primarily contained within the Infrastructure Reliability component.

SEISMIC RESILIENCE STRATEGY

Metropolitan's initial approach to seismic resilience was developed during the 1930's during planning and design of the CRA. This section illustrates how Metropolitan's initial approach for pipeline seismic resilience has evolved over time.

Initial Seismic Resilience Approach

The majority of Metropolitan's distribution system was constructed between the 1930's and the 1970's. In that era, there were no special earthquake-resistant joints available for large diameter pipelines. Despite having no provisions within design codes, the historical records show that Metropolitan engineers took proactive measures to address seismic resilience in design of the CRA. For example, the aqueduct was designed to cross active faults at the ground surface in inverted siphons and at right angles to the fault traces, in order to minimize adverse effects that horizontal fault slip would have on the aqueduct and to simplify access for repairs. The designers opted for a flexible siphon design rather than rigid monolithic concrete construction. Based on available knowledge at that time, Metropolitan geologists and engineers considered the ground shaking and deformation that had occurred along the San Andreas Fault system during the 1857 Fort Tejon and 1906 San Francisco earthquakes, and supplemented their understanding of regional active faults through geologic mapping and analysis of stereo aerial photographs [4][5].

During major events such as the 1971 San Fernando and 1994 Northridge earthquakes, Metropolitan experienced relatively minor damage to its pipelines, including a single pipe break due to each event. The 2.13 m (84 inch) diameter pipeline that ruptured as a result of the Northridge earthquake took less than 72 hours to repair and return to service.

Metropolitan has applied the lessons learned from these two major earthquakes to improve seismic design practices. For instance, following the 1971 San Fernando event, a committee of experts was convened to investigate the causes of damage to structural elements of the Joseph Jensen Water Treatment Plant, which was then under construction, and to provide recommendations to improve seismic performance. Historical records [6] show that, by 1993, Metropolitan incorporated a fault crossing policy that pipelines crossing fault zones would be constructed of steel with welded joints; the crossing would be at a right angle to the fault zone to limit damage; and pipelines would be buried relatively shallow to provide ready access for repair. Above-ground crossings of faults were avoided due to the property requirements, increased maintenance (i.e. painting and expansion joints), and the risk of vandalism. Metropolitan's only above-ground section of large diameter pipe occurs along the Upper Feeder where it crosses the Santa Ana River. In this unique case, base isolators have been installed at the bridge crossing to increase seismic performance by decoupling strong ground motions from being transmitted to the pipe. Similarly, after the 1994 Northridge earthquake, numerous capital projects were identified and completed to strengthen buildings and critical facilities.

In addition to the original design features of the distribution system, Metropolitan has maintained a robust pipeline repair capability for over 50 years. Stockpiles of steel and other materials are kept on hand to roll new pipe in Metropolitan's machine and fabrication shop within a short time after an earthquake or other event. In addition, Metropolitan maintains the capability to repair up to six pipeline breaks within one week of a major seismic event (two breaks by Metropolitan construction forces and four breaks by prequalified contractors).

This evolving seismic resilience strategy has helped Metropolitan's distribution system achieve strong seismic performance over the last 80 years.

Refined Seismic Resilience Approach

During the last several decades, significant advancements have occurred in earthquake engineering and pipeline design. In recognition of these advancements, and that the consequences of a major earthquake in an increasingly dense urban area could be severe, Metropolitan has refined its seismic resilience strategy to take advantage of the latest seismicity data, modern computer modeling techniques, recently developed seismic resistant products, extensive industry research, and updated codes.

Metropolitan's pipelines have always been constructed in conformance with standards of practice at the time of design. These pipelines are exposed to a number of geohazards of varying risk: fault zone crossings, permanent ground deformation from causes such as liquefaction or landslides, and ground shaking during seismic events.

The seismic resilience strategy for pipelines has three components: Part 1 addresses vulnerability assessments of the existing distribution system; Part 2 identifies potential mitigation measures for existing pipelines; and Part 3 establishes design and performance criteria for new pipelines. Parts 1 and 2 are described below in more detail. Part 3 for new pipelines will be developed in conjunction with several new large-diameter pipeline projects that are planned over the next 5 to 10 years.

<u>Part 1 – Assessment of Vulnerable Existing Pipelines</u>: Due to the relatively good performance of large-diameter pipelines within Metropolitan's distribution system during previous earthquakes, Metropolitan will focus on the most vulnerable existing pipelines to determine the need and priority of future mitigation. It is anticipated that there will be relatively few cases where it would be considered cost-effective to upgrade a pipeline solely to enhance seismic resilience. In most cases, mitigation measures will be incorporated into planned rehabilitation programs for aging pipelines. For example, Metropolitan is incorporating seismic resilience features into its $2.5 billion program to rehabilitate over 255 km (159 miles) of its PCCP lines.

Vulnerability assessments of pipelines within the distribution system follow the multi-step approach of traditional risk assessments:

Step 1 – Analysis and Integration of Geologic, Seismologic, and Geodetic Data – The first step analyzes the most recent information available relating to seismicity along the route of a pipeline including:

geology, tectonics, paleoseismology, seismicity, and geodesy. This information is obtained from historical data, available geologic mapping, available logs from exploration wells, and any other recent investigations. Where required, additional field investigations are performed to supplement existing information.

Step 2 – Identification of Seismic Hazards **–** The second step identifies geohazards such as fault zone crossings, liquefaction zones, and landslide hazards along a pipeline route using historical records and available information from the U.S. Geological Survey and California Geological Survey. For Metropolitan's pipelines, three scenarios are considered: (a) a frequent seismic event (i.e. 220-year return period, sometimes referred to as the operational event), (b) a moderate event (i.e. 475-year return period, roughly equivalent to building code design levels); and (c) a severe event (i.e. 2,475-year return period, if the probabilistic event governs). Both deterministic and probabilistic seismic hazard approaches are considered in selecting the appropriate design conditions.

Step 3 – System-wide Hazard Assessment – This step performs a system-wide assessment to determine the probability of pipe leaks and breaks as a result of simulated potential earthquake scenarios. The suite of simulated scenarios is generated from different faults in Southern California. Seismic hazards such as liquefaction are also included based on available regional data. For this assessment, each feeder is discretized into pipe reaches to facilitate the modeling. The simulation provides a bounded solution that includes expected probable and maximum probable damage for each earthquake scenario.

Step 4 – Evaluation of the Consequence of Disruption **–** The resulting damage to the pipeline due to the three design seismic scenarios provides an insight into the corresponding consequences of disruption. The consequences that are evaluated in Step 4 include:

- *Life Safety Impacts*: Damage to high pressure pipelines located in densely populated regions.
- *Delivery Impacts*: Damage to pipelines that may result in water delivery disruptions. This damage needs to be evaluated in light of the combined flexibility and backup capability of both Metropolitan and its member agencies' systems. Areas with inadequate backup supplies result in a higher consequence.
- *Societal/Environmental Impacts*: In some areas, damage to a large pipeline may not only result in significant monetary damage, but may hinder emergency response after an earthquake, or may damage wildlife habitat. These areas may include highly urbanized zones and areas near critical infrastructure such as streets and highways; areas near critical emergency response structures like hospitals, fire departments, and police departments; or highly sensitive environmental areas.

Step 5 – Preliminary Screening to Identify Vulnerable Pipelines – For this step, judgment is required to perform a preliminary screening of which pipelines are most vulnerable and that warrant further analysis.

Step 6 – Analysis of the Seismic Performance of the Pipeline – The sixth step analyzes the pipeline under the design seismic event. Depending on the nature of the seismic hazard, Metropolitan may perform a preliminary assessment using a simplified analysis based on probable ground strain and pipeline material properties. However, in some cases, a more detailed finite element model is required to fully determine the behavior of the pipe and the surrounding support strata under given seismic shaking. This comprehensive analysis includes soil-structure interaction, rupture modeling, and permanent pipeline deformation. If acceptable seismic performance is achieved under the severe event, then there is no need for further analysis of the less significant events.

Step 7 – Identify Mitigation Measures for Vulnerable Pipelines – This step will provide recommendations for mitigation measures to achieve the expected seismic performance objectives. Additionally, the order and timing of projects to mitigate risks as part of the overall rehabilitation strategy will be determined.

Step 8 – Critical Review and Documentation of Results – Metropolitan will retain an independent third-party expert reviewer during the process on an individual project basis. The independent reviewer is tasked to provide objective feedback on design parameters, mitigation approach, computer modeling and other analytical aspects of the process.

Part 2 – Mitigation Measures for Existing Pipelines: Where mitigation is recommended in order to minimize the consequences of service disruption, general design goals are as follows:

- *Fault crossings and areas of known permanent ground deformation, including liquefaction, subsidence, and landslides*: At these hazard locations, the goal is to install pipe segments and joints that can withstand the vertical and horizontal movement that imposes both transverse and axial deformation on the pipeline. Using site-specific geotechnical data and critical seismic events, Metropolitan analyzes hazard locations utilizing advanced computer modeling, where appropriate, but also maintains a practical approach. Where specialized earthquake resistant joints cannot achieve acceptable seismic performance at a hazard location, other options may be considered to minimize the consequences of a severed pipe. These options may include installation of isolation valves; addition of a vault with a removable pipe spool to allow quick insertion of a bulkhead; stiffening of the joints and pipe section; and enlarged vault sections to isolate the pipe from maximum ground deformation. Metropolitan may also evaluate alignment options to relocate existing pipes, if feasible, to avoid areas of known fault crossings or expected permanent ground deformation that may result in significant disruption.
- *At areas of significant ground shaking*: Metropolitan's distribution system is located in a seismically active region where ground shaking is expected to be strong over vast areas in the event of a major earthquake. Continuous welded steel pipe with adequate wall thickness and joint welds is expected to perform well under significant ground shaking. For existing pipelines that are not structurally continuous at the joints or have thin walls that may be susceptible to axial or flexural buckling, Metropolitan will consider mitigation measures to provide continuity across the joint, or may consider replacing pipe segments or inserting a steel liner within the pipe.
- *At connections from pipelines to structures*: In most cases, a simplified analysis will provide sufficient insight into seismic performance at these joints. However, in some cases, it may be necessary to analyze the pipeline and its connected structure using an integrated three-dimensional finite element model (such as FLAC3D or ANSYS) to capture the relative displacements, strain, and stresses under the maximum seismic event. Metropolitan combines available site-specific geohazard information and applies the appropriate computer modeling to evaluate the deformation compatibility of these connections and may provide flexibility using sleeve couplings or seismic joints to accommodate deformation demands.

CASE STUDIES

Metropolitan has begun to incorporate mitigation measures from its refined seismic resilience strategy at four locations where pipelines are subject to seismic hazards. Two of these locations are discussed below as case studies: (1) the Second Lower Feeder at its crossing of the Newport-Inglewood Fault, and (2) the Casa Loma Siphon on the CRA at its crossing of the Casa Loma Fault (see Figure

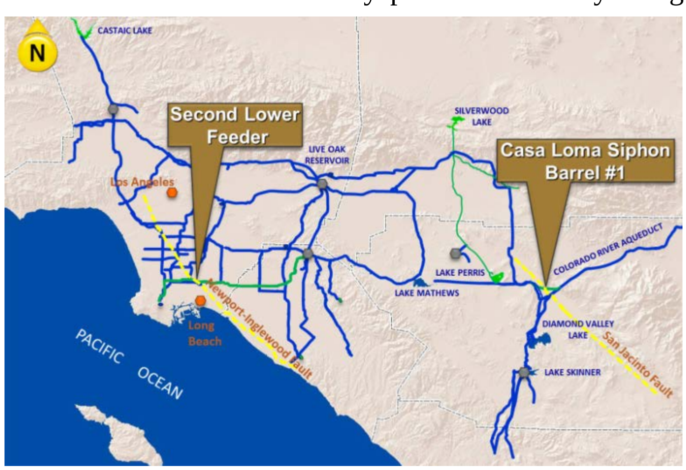

Figure 2: Location Map for Case Studies

2). The latter location is also experiencing regional ground subsidence. While Metropolitan is also evaluating other hazard locations along these feeders, this paper is focused on the mitigation measures for these specific locations.

Second Lower Feeder

The Second Lower Feeder (SLF) delivers treated water from the Robert B. Diemer Water Treatment Plant in the city of Yorba Linda to Palos Verdes Reservoir in the city of Rolling Hills Estates. The feeder was constructed in 1967 and originally contained approximately 48 km (30 miles) of PCCP, with diameters ranging from 1.98 m (78 inches) to 2.13 m (84 inches). The remainder of the feeder is constructed of welded steel pipe with a diameter of 2.13 cm (84 inches). The Second Lower Feeder operates at pressures up to 2 MPa (300 pounds per square inch) and passes through areas with highly corrosive soils. In addition, there are numerous underground utility lines, natural gas lines, and oil lines within the vicinity, which expose the feeder to significant stray current interference. The pipeline traverses a highly urbanized area and crosses several freeways, several flood control channels, and an airport. In addition to supplying water to the central portion of Metropolitan's distribution system, the Second Lower Feeder has 11 member agency service connections.

In recognition of the lower-than-expected service life now anticipated for PCCP, and the risk of service disruption in the event of PCCP failure, Metropolitan initiated a comprehensive program in September 2014 to inspect, manage, and rehabilitate its 163 miles of PCCP lines. The Second Lower Feeder is the first pipeline to be addressed under that program.

The initial construction contract, which includes installation of smaller-diameter steel liner pipe, was awarded in August 2017. The new coiled steel liners will be inserted into the existing pipe, moved into

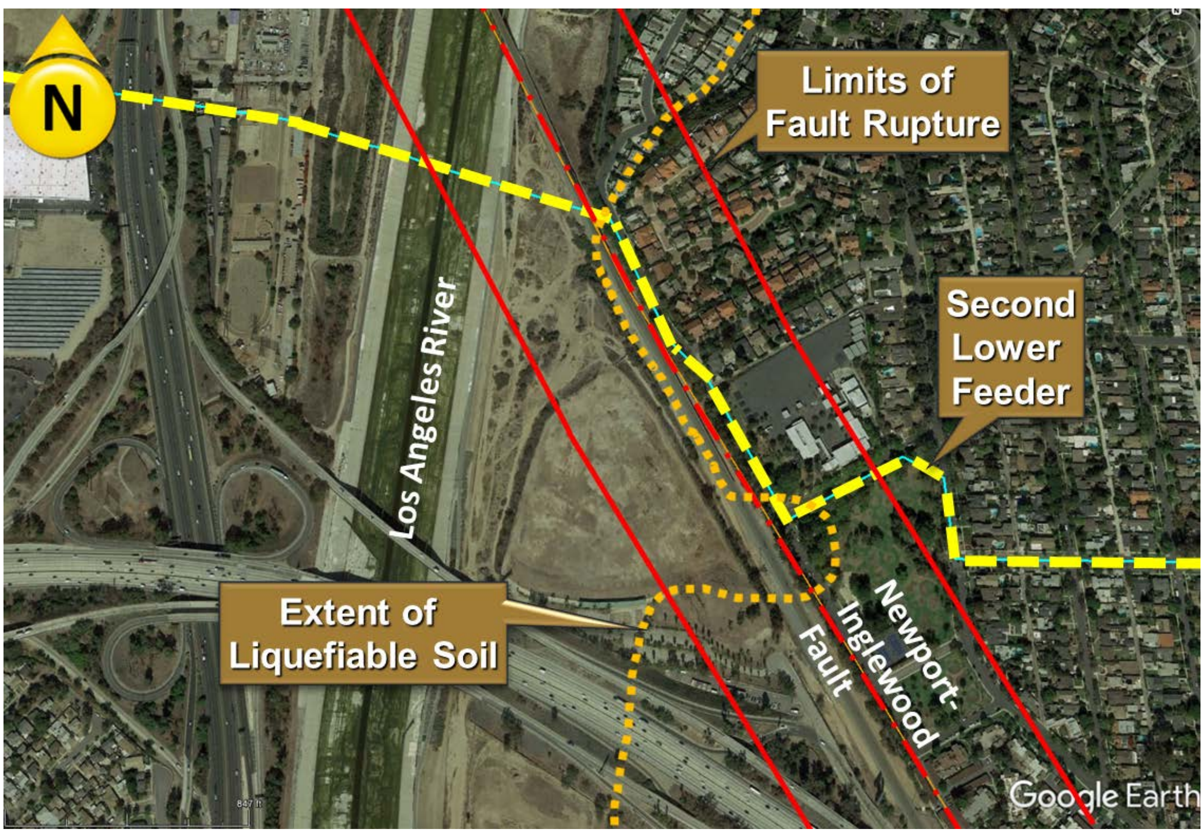

Figure 3: Second Lower Feeder Fault Crossing

position, expanded to the design diameter, and welded together. The new pipe section will include an annular space between the steel liner and the existing PCCP pipe segments that will be filled with low-density cellular concrete grout.

The objective of the hazard analysis for the Second Lower Feeder is to improve current understanding of the pipeline's seismic hazards using best-available analytical tools, including numerical simulations to evaluate the potential mitigation. Based on the results of the study, guidelines will be developed that may be applied for future pipeline designs in evaluating impacts of seismic hazards and the selection of appropriate mitigation methods. The comprehensive analysis is also intended to serve as a model for seismic design for both new and existing pipelines.

Parametric studies will be performed to develop a range of results for each hazard level to provide the upper and lower bounds for performance-based seismic design. The following discussion summarizes the seismic hazard, performance objectives, and proposed mitigation options for the pipeline crossing of the Newport-Inglewood Fault.

Seismic Hazard

A section of the Second Lower Feeder crosses and runs parallel to the Newport-Inglewood Fault, which is capable of generating a M7.5 earthquake (see Figure 3). In addition, the pipeline's alignment is entirely underlain by the Compton Blind Thrust Fault, which is capable of generating a M7.4 earthquake. Some sections of the Second Lower Feeder are supported by a wide and large extent of alluvial deposits, which are potentially liquefiable during ground shaking. As a result, during a seismic event on any of the above faults, the pipeline will be exposed to simultaneous adverse effects of a regional shaking hazard, liquefaction, and a localized rupture hazard. These hazards could potentially affect the structural integrity of the feeder, which may lead to disruptions in deliveries to Metropolitan's member agencies. [7] [8]

Performance Objectives

For the section of pipeline that crosses the fault zone, three earthquake scenarios will be considered, as previously described, for evaluating the pipeline's seismic performance. Metropolitan's goal is for critical feeders to perform well during seismic events and be repairable within a reasonable amount of time afterwards.

Technical Approach

Seismic demands on underground pipelines are best characterized in terms of the deformations and strains imposed on the pipeline by the surrounding ground. Two general approaches in evaluating the impact of ground deformation on the pipeline will be considered: de-coupled Free-Field Method (FFM) and coupled Integrated Soil-Structure Method (ISSM). FFM will be used to establish the baseline evaluation, and will be supplemented by ISSM to provide additional insight.[9]

The interaction of the pipeline with the surrounding ground is ignored in the FFM on the basis of the size, mass and stiffness of the pipeline relative to the surrounding deforming soil. FFM is well-accepted and will be used to evaluate pipeline resilience for the three earthquake scenarios. Using the FFM, Metropolitan will estimate the possible ground displacements and impose these displacements on a separate pipeline model to evaluate the response of the pipeline to these displacements.

The interaction between the pipe and the surrounding ground as a result of pseudostatic fault rupture and ground shaking is explicitly accounted for by analyzing the soil and pipe system together in one analysis in the ISSM.

The ISSM analysis will model the underlying fault rupture and propagate the rupture through a shallow crustal model. The soil near the surface, to a depth of approximately 30 m (100 feet), will be represented with continuum elements. Soil material located far from the fault rupture zone will be modeled as linear elastic and the soil material near the fault rupture zone-field as nonlinear.

The pipeline will generally be modeled as a combination of a three-dimensional layered shell and resultant beam, and fiber (integrated) beam finite element. The model will be used to simulate the response of the pipe segments for steel pipe alone and steel-lined PCCP near the fault rupture zone. Beam elements, which are used to model the global elastic response of the PCCP, will be used for the pipeline far from the fault rupture zone to simulate reasonable boundary conditions. Pipe joints will be explicitly modeled so that the global performance of the pipeline and the local performance of the joint can be evaluated.

The planned analysis will utilize modern computing capabilities, traditional mechanics, and engineering judgment to gain greater insight into expected performance of the Second Lower Feeder at the fault crossing. The study is expected to be completed in late 2017 and will be the basis for developing the scope of work for design of the pipeline mitigation.

Mitigation Options
Metropolitan is considering the following mitigation options for the Second Lower Feeder at the fault crossing:

- Replacement of portions of the PCCP feeder with welded steel pipe within the fault zone, either within the existing alignment or crossing perpendicular to the fault.
- Replacement of portions of the PCCP feeder with earthquake-resistant pipe/joints to allow large deformation between two segments of pipe, either within the existing alignment or crossing perpendicular to the fault.
- Installation of new isolation valves to mitigate the impacts of pipe damage and enable quick return to service.

It should be noted that relocating extensive portions of the Second Lower Feeder would be very costly and will be considered only as a last resort where the expected objectives cannot be met. The goal of the relocation would be to modify the orientation of the fault crossing to minimize damage to the pipeline.

Casa Loma Siphon

The CRA conveys water from the Colorado River across the California desert to Lake Mathews in Riverside County. The CRA crosses the Casa Loma Fault near the city of Perris through inverted siphons (see Figure 4). The initial barrel of that siphon, known as Casa Loma Siphon Barrel No. 1, was constructed in 1941. The siphon originally consisted of 3.76 m (148 inch) diameter concrete pipe that extends eight kilometers (5 miles) across a valley. In the early 1960s, cracks and significant leakage began to develop in the pipe as a result of movement at the fault crossing. In 1968, ninety-one meters (300 feet) of the concrete pipe was replaced with 3.76 m (148 inch) diameter steel pipe joined with sleeve-type couplings. This type of flexible joint was selected to permit minor movement of pipe segments without leaks or rupture. In addition, multiple inspection structures were installed to monitor the ground displacement and its effect on the pipeline joints (see Figure 5).

Since that time, the ground movement has continued, intermittent leaks have reoccurred, and numerous repairs have been required. In November 1996, internal seals were installed at several locations within the steel portion of the siphon due to leakage at the joints.

In November 2016, a new leak was observed on the ground surface above the steel pipe portion of Casa Loma Siphon Barrel No. 1. The leak may be the result of deterioration of the existing sleeve-type couplings, recent tectonic creep, or regional subsidence due to groundwater extraction. The occurrence of

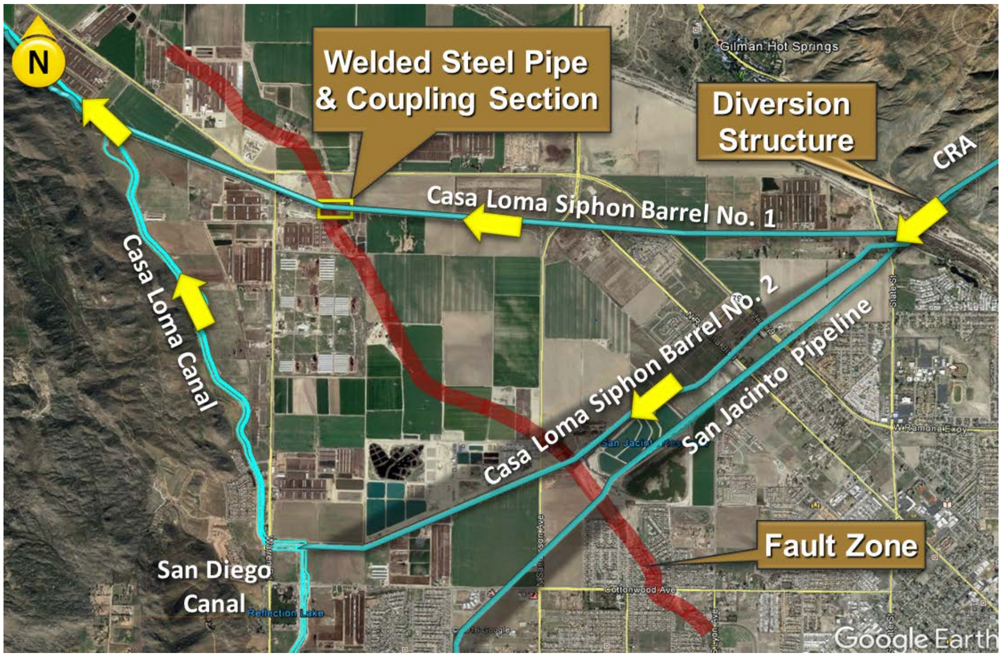

Figure 4: Casa Loma Location Map

other ground deformation hazards, such as seismically triggered liquefaction and/or lateral spreading, have not been reported along the siphon. The leakage does not immediately jeopardize structural integrity of the siphon. However, continued leakage over time could erode soil, undermine the siphon, and cause structural damage.

The internal seals have recently been replaced and more seals were added as part of the initial stage of repairs to the siphon. Metropolitan is now evaluating options for permanent repairs to provide pipe joint flexibility, accommodate permanent ground deformation, and prevent future leaks.

Ground Subsidence

The Hemet-San Jacinto Valley is filled with deep Quaternary alluvial sediments that form a groundwater basin. The limited historic recharge to the valley due to its arid climate, along with increased groundwater pumping over the last century, has caused lowering of the groundwater table by several hundred feet. During the past 80 years, ground subsidence has ranged from 3.6 cm/yr [1.4 in/yr] to 4 cm/yr [1.6 in/year]. The total amount of subsidence that occurred in the valley since the 1970’s exceeds 0.61 m [2 ft]. While groundwater levels are believed to have stabilized, it is anticipated that subsidence may continue for years.

Seismic Hazard

The Casa Loma Siphon crosses the Casa Loma Fault nearly perpendicular within the Hemet-San Jacinto Valley. The Casa Loma Fault is a primary segment of the San Jacinto Fault Zone which in turn is a major branch of the San Andreas Fault System. The Casa Loma Fault is capable of generating a M6.5 to M6.7 earthquake with estimates of seismic displacement ranging from 0.3m [1 ft] if the fault ruptures on its own, to about 2.7m to 3m [9 to 10 feet] if the fault ruptures with adjacent fault sections. Therefore, during a major earthquake, the pipeline will be exposed to simultaneous adverse effects of a regional shaking hazard and a localized rupture hazard. [10]

Performance Objectives

The Casa Loma Siphon Barrel No. 1 is an important component of the CRA. The seismic performance objective for the siphon is similar to the Second Lower Feeder, as described previously. However, if seismic activity along the Casa Loma fault zone caused significant damage to Casa Loma Siphon Barrel No. 1, downstream storage at Lake Mathews and an emergency supply of water is available in Metropolitan’s Diamond Valley Lake (DVL). DVL, which is Southern California’s largest surface water reservoir, was constructed on the coastal side of major fault zones in order to supply the southern

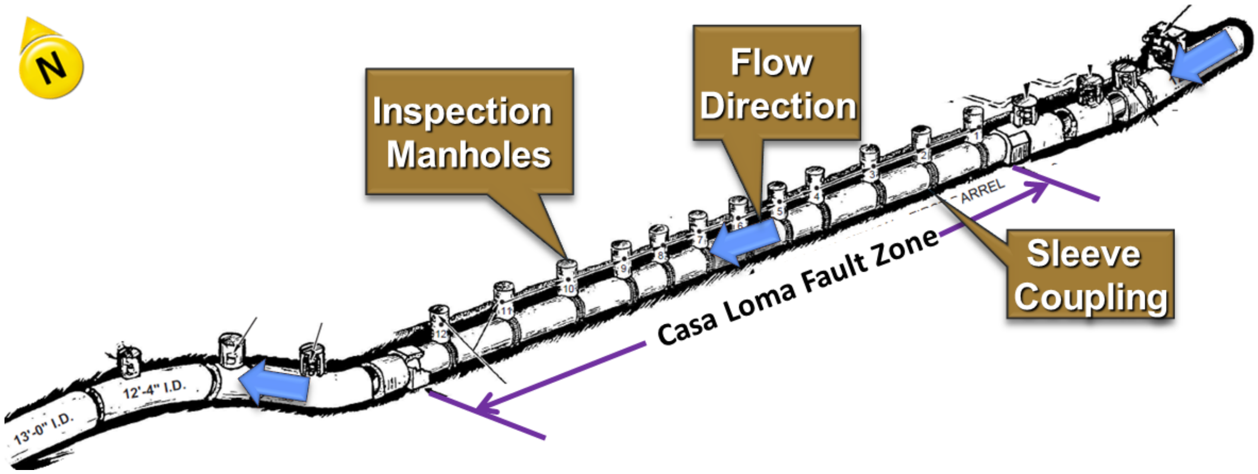

Figure 5: Casa Loma Siphon Barrel No. 1

California region if deliveries from the CRA are interrupted. Therefore, it may be acceptable for more extensive repairs to be required for Barrel No. 1 after a 475-year return period event.

Technical Approach

Due to the long history of repairs to the Casa Loma Siphon, there is significant data regarding local geology, groundwater conditions, tectonic setting, seismic hazards, subsidence records, historic photographic imagery, LiDAR, and aerial geodetic survey data in the area. Nevertheless, additional field investigations are needed, such as trenching, monitoring land subsidence and tectonic ground deformation, and use of satellite imagery to evaluate global spatial surface deformations.

A similar technical analysis that was used for the Second Lower Feeder is expected to be employed for the Casa Loma Siphon. The challenge for the Casa Loma analysis, however, will be to properly model the effects of the long-term subsidence and the expected seismic deformation. Typically, this is addressed by a probabilistic combination of imposing some initial deformation to model the effect of the subsidence, and then to follow with the expected seismic deformation. The pipeline performance will then be evaluated based on the total displacement for each anticipated risk level.

Mitigation Options

The existing eleven segments of 3.75 m (148 inch) diameter welded steel pipe along the Casa Loma Siphon Barrel No. 1 are connected by flexible sleeve couplings and can undergo slight deflections. Because of the historic poor performance of these sleeve couplings, the following mitigations options will be considered:

- Replacement of the existing sleeve-type couplings, with potential addition of more couplings over a longer reach of the siphon
- Replacement of Barrel No. 1 with earthquake-resistant pipe/joints
- Encapsulation of the siphon in a vault to isolate the pipeline from ground motion
- Application of ground treatment below the pipeline, or support of the pipeline on piles with base isolators, if possible, to mitigate the ground subsidence

CONCLUSION

Metropolitan's initial approach to seismic resilience dates back to the original design and construction of the CRA in the 1930's, and it has long been a component of Metropolitan's overall reliability strategy. The actions taken to maintain delivery reliability in the event of a major earthquake include the strengthening essential facilities; assessing system vulnerabilities as new research and data become available;

conducting emergency response exercises and planning; maintaining the capability to perform emergency repairs; and maintaining stockpiles of key supplies and equipment.

Metropolitan has refined its seismic resilience strategy to take advantage of modern computer modeling techniques, recently developed seismic resistant products, industry research, and updated codes. This refined strategy proactively addresses seismic risks of pipelines at active fault crossings, areas of known permanent ground deformation, and areas of significant ground shaking. Metropolitan may utilize a variety of mitigation measures at such locations, including earthquake-resistant pipe/joints, when available at larger diameters. This refined approach is initially being applied in four pipeline rehabilitation projects, including: the Second Lower Feeder, a 48 km (30 mile) long PCCP line with diameters from 1.98 m (78 inches) to 2.13 m (84 inches) that is being relined under a long-term PCCP rehabilitation program; and the Casa Loma Siphon, a 3.76 m (148 inches) diameter steel pipe that has a history of leaks and ground subsidence due to lowering of the local groundwater table.

Metropolitan's seismic resilience approach addresses both existing and new infrastructure. In the case of existing pipelines, much of which is located in densely populated regions, Metropolitan aims to mitigate potential seismic hazards through long-term rehabilitation programs, leveraging every project as an opportunity to make significant improvements in seismic resilience over time. As new pipelines are designed and constructed, Metropolitan will develop project-specific seismic resilience measures that are consistent with its comprehensive reliability strategy.

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TWC's Thoughts on Implementing Seismic Improvement to Large Water Pipelines

Tsung-Jen Chiu, Feng-Ming Lu, Sheng-I Tseng, Glaus Ou, and Gee-Yu Liu

ABSTRACT

Many of the pipelines and facilities of Taiwan Water Corporation (TWC) were built in early years without any seismic consideration. They are very vulnerable to earthquake hazards. One of the most important tasks in front of TWC is to improve its large water pipelines seismically. In order to help all branches and headquarter of TWC to implement in a more uniformly manner, some shared criteria and procedures should be specifies first. To be precise, TWC needs to (1) specify the seismic objectives for pipelines of different importance, (2) specify the procedure that TWC should follow to develop pipeline seismic assessment reports and implement seismic countermeasures. In this paper, some of TWC's thoughts on these topics have been summarized.

INTRODUCTION

Taiwan Water Corporation (TWC) is the largest water utility in Taiwan. It consists of 12 branches all over the island, which operates 144 systems with a total capacity of 11.42 million CMD. It provides water supply to 6.87 million customers or 17.98 million people (2016). It was established in 1974. Since then, it has made a significant contribution to the welfare of the people, and played as a pivotal role to the rapid economic development of the country.

However, many of TWC's pipelines and facilities were built in early years without any seismic consideration. They are very vulnerable to earthquake hazards. Especially, the majority of large water pipelines are concrete pipes installed in early years. This is due to the fact that concrete pipes cost less and are easy to install. Many of them are PCCP (pre-stressed concrete cylinder pipes) and PSCP (pre-stressed concrete pipes), which are brittle and very vulnerable to medium to large seismic actions. Aging and material deterioration have made the situation even more worsen. As a result, one of the most important tasks in front of TWC now is to improve the large water pipelines seismically.

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Recently, a prioritized seismic retrofit scheme has been proposed to TWC (Liu et al., 2017) regarding all water pipes with a diameter of 800mm or greater (up to 3,200mm). A total of 232 pipes called “pipeline evaluation units” have been suggested for seismic enhancement. The suggestion was made according to two factors. The first is the importance of the pipes. All pipes were classified into four classes of importance: very high, high, normal, and low. This was done according to the volume of water a pipe conveys daily, as well as the existence of any redundant pipe as backup. The second is the seismic risk of the pipes. It is a combination of seismic hazard level a pipe is exposed to, and the seismic vulnerability of the pipe itself.

Therefore, TWC is about to implement the proposed scheme to enhance the target large water pipelines of (very) high importance and at high seismic risk in the near future. In order to help all branches and headquarter of TWC to implement in a more uniformly manner, some shared criteria and procedures should be specifies first. To be precise, TWC needs to

- Specify the seismic objectives for pipelines of different importance,
- Specify the procedure that TWC should follow to develop pipeline seismic assessment reports and implement seismic countermeasures,
- Specify the analysis/design methods for pipeline seismic enhancement.

This paper aims at providing an overview of TWC’s thoughts on the first two topics.

SEISMIC DEMANDS

The seismic design (enhancement) of water pipelines and their appurtenances should be based on the intended operational performance level the system must achieve in a post-earthquake disaster situation. This requires seismic performance objectives to be selected for the system (ALA, 2005). A performance objective consists of two elements: seismic demand (hazard level) and performance level.

Seismic demand refers to the site-specific hazard at prescribed level. It is employed to the assessment/design/analysis of a pipeline, which will qualify the performance objective if the associated performance level can be satisfied. In the following sub-sections, the proposed seismic demands of ground shaking, soil liquefaction, fault offset, and landslide will be introduced. In the next section, the proposed seismic performance level will be introduced.

Ground Shaking

Conventionally, peak ground velocity (PGV) is employed in the design of buries pipelines against earthquake ground shaking. This is because ground strain, the seismic action that exerts upon a pipe and causing damage, is theoretically proportional to PGV.

Therefore, the value of PGV of a site at a return period of 10% in 50 years (design earthquake) is proposed as the seismic demand due to ground shaking. It can be employed in the analysis and design of segmented and continuous pipes following various seismic design guidelines. A formula for estimating the value of PGV (unit: cm/s) of a site is expressed as

$$PGV = 0.885 \cdot \frac{9.81 \cdot S_{D1}}{2\pi} \tag{1}$$

$$S_{D1} = F_v^{\ D} \cdot N_v^{\ D} \cdot S_1^{\ D} \tag{2}$$

where $S_1^{\ D}$ is the code-specified spectral acceleration at a structural period of 1.0s at a return period of 10% in 50 years (design earthquake), and the multiplier F_v^D and N_v^D stand for the site amplification and near fault effects specified. Equation (1) is actually a simplified formula to the one by AASHTO (2010).

Soil Liquefaction

Soil liquefaction may result in settlement and lateral spreading of the ground. The resulted permanent ground displacement (PGD) is one of the major causes of pipe damage. Similar to the concept of soil liquefaction susceptibility categories in HAZUS (RMS, 1997), a method to decide the soil liquefaction susceptibility categories of a site in Taiwan has been proposed by Yeh et al. (2015). In addition, a set of empirical formulas have been proposed for assessing the mean ground settlement. Therefore, with the code-specified PGA and M at a return period of 10% in 50 years (design earthquake), the site-specific settlement PGD can be estimated according to the susceptibility category determined by borehole data.

While for the lateral spreading PGD, there is no prediction model ready for use in Taiwan. Site-specific geoscience investigation to decide the mean value and pattern, either longitudinal or transverse to the pipe orientation, see Figure 1, is preferred.

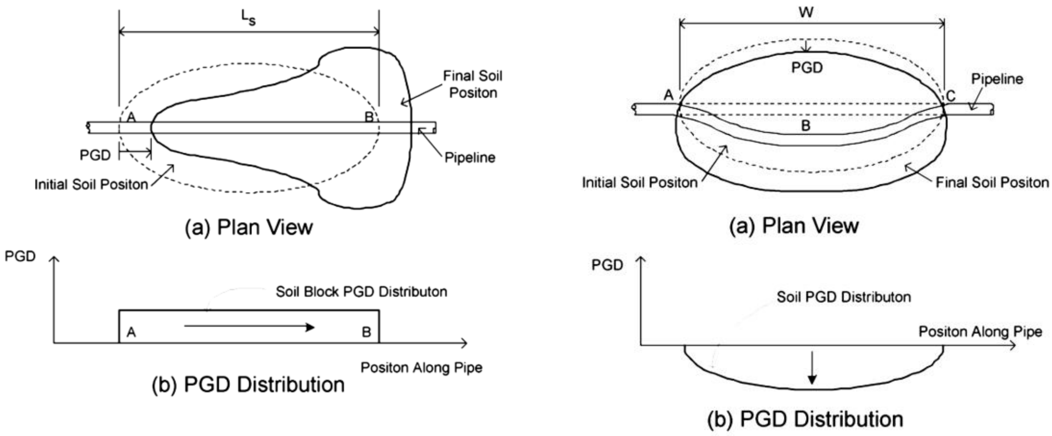

Figure 1. Pipe response to longitudinal (left) and transverse (right) PGD (ALA, 2005).

Once the mean liquefaction PGD is estimated, the design movement specified in Table 1 should be adopted to the analysis and design of pipes through the liquefaction zone. These values follow the suggestion by ALA (2005).

Table 1. The design movement of a liquefied site for pipe analysis and design.

Class of pipeline importance	Design movement
Normal and low	PGD
High	1.35 × PGD
Very high	1.50 × PGD

Fault Offset

Fault offset is the most severe hazard to buried water pipes. A pipeline should be designed to account for fault offset whenever there is a fault crossing. The amount of offset occurred in a fault rupture event can be estimated by using the model of Wells and Coppersmith (1994), which reads

$$\log \overline{D} = \begin{cases} 1.04 \cdot \log L - 1.7 & \text{strike-slip faults} \\ 0.31 \cdot \log L - 0.6 & \text{reverse faults} \\ 1.24 \cdot \log L - 1.99 & \text{normal faults} \\ 0.88 \cdot \log L - 1.43 & \text{all faults} \end{cases} \tag{3}$$

where $\overline{D}$ is the average offset (unit: m) and L is the length of the fault, respectively. As denoted by Wells and Coppersmith (1994), to estimate the offset of a reverse fault, the expression for all faults should be employed instead.

Once the average fault offset is estimated, the design offset specified in Table 2 should be employed to the analysis and design of pipes at fault crossing. These values follow the suggestion by ALA (2005), too.

Table 2. The design offset of a fault for pipe analysis and design.

Class of pipeline importance	Design offset
Normal and low	$\overline{D}$
High	$1.5 \cdot \overline{D}$
Very high	$2.3 \cdot \overline{D}$

Whenever a design offset is decided, its components should be determined according the specific pattern of fault offset at the fault crossing. As depicted in Figure 2, the vector of the design offset consists of two components: dip slip (Sd) and strike slip (Ss). The vector of dip slip consists of two components: vertical displacement (Sv) and thrust displacement (Sh).

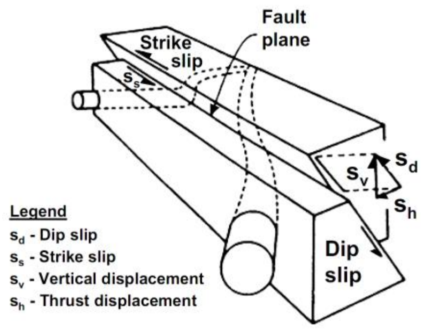

Figure 2. The schematic diagram for the various components of a design offset (ALA, 2005).

Finally, in order to take into account the uncertainty of ground rupturing along a fault trace, various scenarios of offset should be considered. For the sake of simplicity, the offset is suggested at three locations for a strike-slip fault: (1) the fault trace, (2) 150m to one side of the fault trace, and (3) 150m to the other side of the fault trace. While for a normal or reverse fault, the three locations are: (1) the fault trace, (2) in the hanging wall 200m away from the fault trace, and (3) in the footwall 100m away from the fault trace.

Landslide

The hazard of earthquake-induced landslide won’t be considered at this stage. This decision is made according to evidences from past earthquake experiences in Taiwan.

SEISMIC PERFORMANCE LEVELS

There are generally two issues involved in specifying the seismic performance levels of large water pipes. The first is about the pipes' behavior and structural characteristics, for example the chance to survive a prescribed seismic hazard (e.g. ground shaking or failure), the ability to be bypassed, and the pipes' reparability. The second is about their criticality to the water systems, for example the existence of any redundancy.

TWC operates several large water supply systems in urban areas in Taiwan. Some of the large pipelines convey a very large volume of raw or treated water daily, and is therefore very important to the people and socio-economic activities there. Under such circumstance, it is reasonable to assume that half of the volume is the minimum required amount of water supply to keep the lives and activities go without much inconvenience or disruption. Therefore, it is proposed that pipes of very high importance in TWC should meet one of the following seismic performance levels:

- The pipes are functional under the specified seismic demand; or
- The pipes have redundant pipes, or the associated area is connected with supporting pipes from elsewhere, such that while becoming not functional, the redundant and supporting pipes are able to provide 50% routine water need or more; or
- Following above, the redundant and supporting pipes are able to provide 25%, while temporary pipes could be installed within 24 hours and able to provide additional 25%; or
- The pipes could be repaired and functional again within 3 days, and sufficient water storage exists for the first 3 days' urgent need.

The likely numerous damages in transmission, distribution, and customer pipelines at the same time should be considered in the scenarios. In the meanwhile, the surge of urgent water need for firefighting, medical caring, shelters, and mobile water delivery to the affected people should be well considered, too.

Similarly, pipes of high importance should meet one of the following levels:

- The pipes are functional under the specified seismic demand; or
- The pipes have redundant pipes, or the associated area is connected with supporting pipes from elsewhere, such that while becoming not functional, the redundant and supporting pipes are able to provide 30% routine water need or more; or
- Following above, the redundant and supporting pipes are able to provide 15%, while temporary pipes could be installed within 24 hours and able to provide additional 15%; or
- The pipes could be repaired and functional again within 7 days, and sufficient water storage exists for the first 7 days' urgent need.

Finally, for pipes of normal or low importance, TWC won't specify any seismic performance levels. They will be upgraded by routine pipeline replacement.

DEVELOPING AND IMPLEMENTING PIPELINE SEISMIC IMPROVEMENT

The procedure for developing and implementing seismic enhancement of large water pipelines is depicted in Figure 3. Typically, a pipeline network consists of many links and nodes. Each link may consist of several pipes. Any link survives only if all its member pipes survive. Therefore, from the viewpoint of a pipeline network, if some of the pipeline evaluation units belong to the same link, they should be grouped together and be enhanced seismically at the same time. In addition, the rest pipe (s) of the same link should be grouped together, too. The rest pipe(s), although at lower risk, may be damaged and fail the link if without any enforcement and unable to withstand the seismic load in future earthquakes. Such “node-to-node” link in the pipeline network, as shown in Figure 4, is termed a “pipeline conveyance unit.” Therefore, the first thing that should be done is to identify all the pipeline conveyance units. Afterward, each unit should be associated with a seismic assessment project.

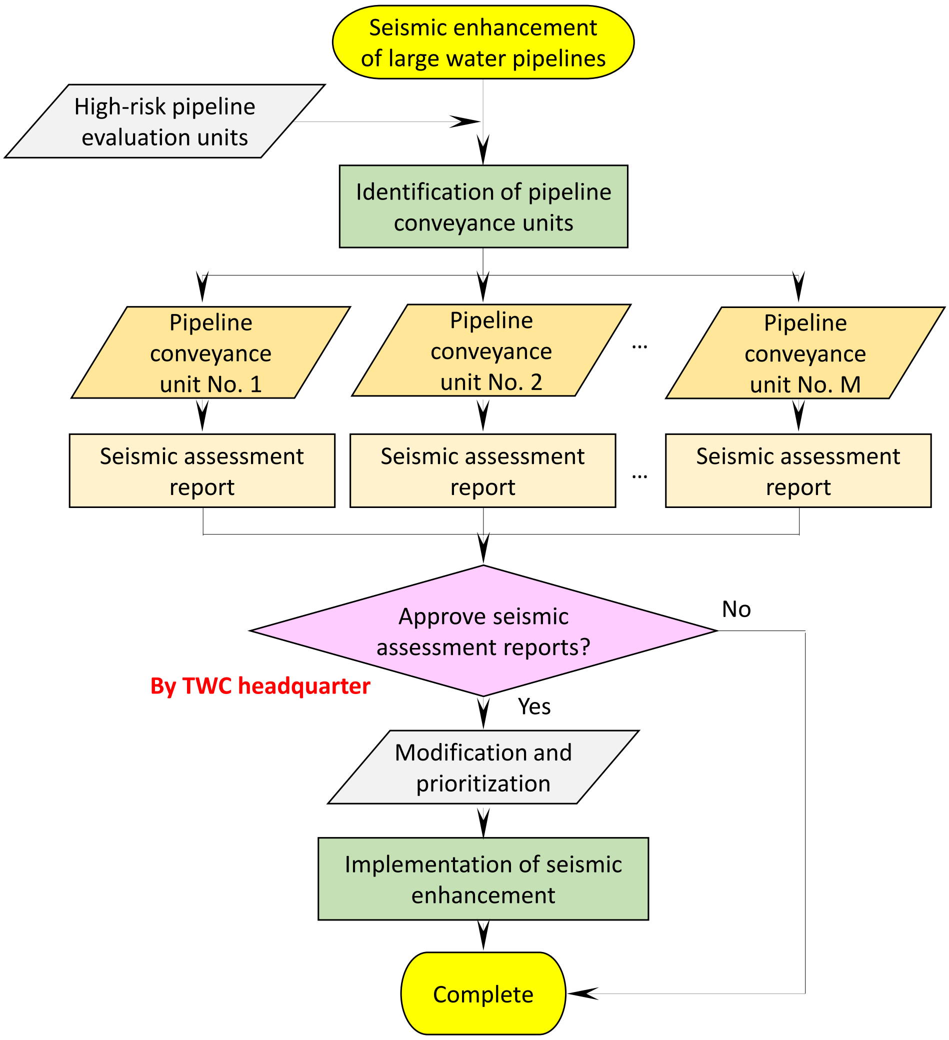

Figure 3. The procedure for developing and implementing large pipeline seismic enhancement.

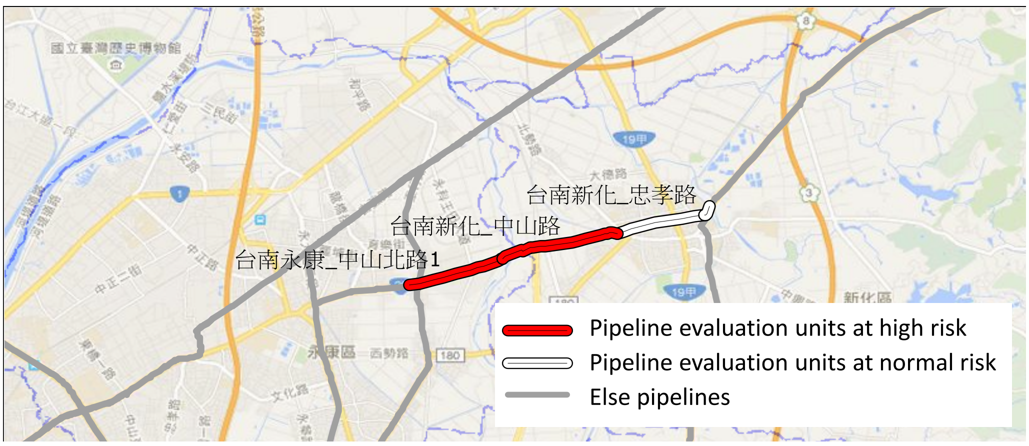

Figure 4. Example of a pipeline conveyance unit, a node-to-node link in a pipeline network.

When a seismic assessment project of a target pipeline conveyance unit is launched, the procedure depicted in Figure 5 should be follow. Surveys of the involved pipelines and the site condition of where they locate should be done first. The site survey is for identifying the soil properties and site condition, fault zone (if any) and pattern of offset, ground water level and liquefaction-induced ground movement (if likely), etc. Site survey involves not only technical reviews of various geological maps, but also drillings at carefully selected sites along the pipelines and its neighborhood for additional geological evidences needed for seismic assessment of the target unit. The pipeline survey is for confirming the location and properties of the pipelines, and the current condition of deterioration. The role of the pipeline conveyance unit in the water supply system should be clarified, too. The impact to the system performance due to the failure of this unit should be investigated. The redundancy (if any) to and the likely redundant pipes of the target unit should be identified.

Within a TWC branch, a technical working group (TWG) should be organized. The TWG should include system operator, pipeline engineer, geotechnical scientist and engineer, pipe flow analyzer, and third-party consultants as its members. The TWG should decide whether or not a target pipeline conveyance unit meets any of the performance levels given the specified seismic demands. If not, they should develop several countermeasures to the target unit such that, once it is implemented, the performance levels can be satisfied. Additional feasibility and cost-and-benefit analysis to each countermeasure should also be considered in detail. The likely impact to water supply, traffic and environment should be minimal. Finally, the TWG should prepare the seismic assessment report. It should be submitted to TWC headquarter for approval.

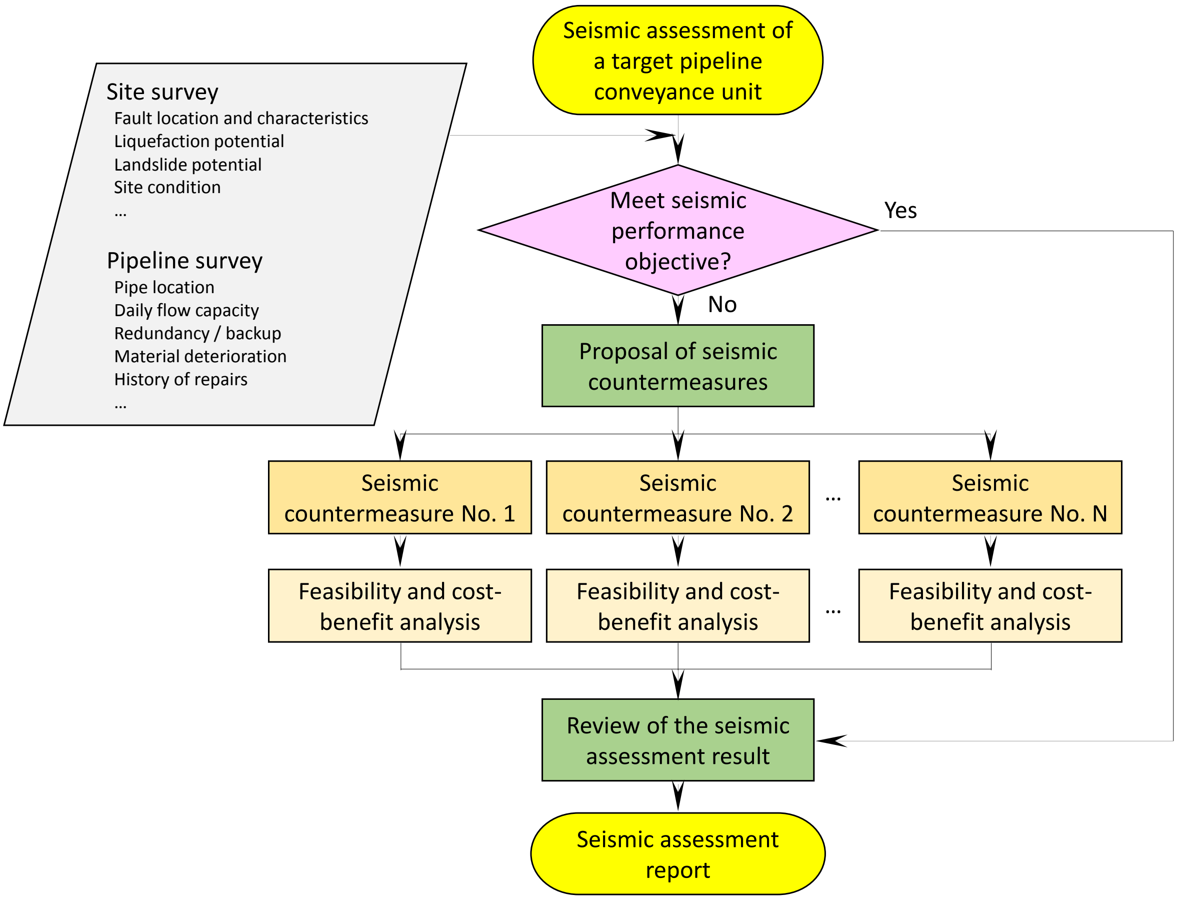

Figure 5. The procedure for seismic assessment of a target pipeline conveyance unit.

A special committee should be established in the TWC headquarter. The members of the committee should include chief engineer, department managers, finance officer, accounting officer, representatives from TWC branches, etc. After all TWGs submit their pipeline seismic assessment reports to the committee, the reports should be carefully reviewed. As each report has already been settled with the best seismic countermeasure according to feasibility and cost-benefit analysis, the mission of the committee is very simple. It should decide whether or not each project should be granted, and, for the granted projects, what should be prioritized for implementation. The decision should be made by taking into consideration the following issues:

- The optimal seismic improvement outcome to TWC as a whole,
- The capital and resources available within the frame of time,
- The expectation and supports from the authorities and communities,
- Else managerial and financial concerns.

CONCLUDING REMARKS

As TWC is about to enhance large water pipelines of high importance and at high seismic risk, some shared criteria and procedures have seen specified by TWC to help future implementation in a more uniformly manner. The seismic demands and performance levels for the assessment/ design/analysis of a pipeline of a specific class of importance have been proposed. A procedure for developing pipeline seismic assessment reports and implementing seismic countermeasures has been proposed, too. Issues that TWC should take into consideration to review and approve a pipeline seismic assessment report issued by TWC branches have been identified.

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Water System Pipeline Damage Seattle Public Utilities Case Study

William F. Heubach[1]

ABSTRACT

Seattle Public Utilities (SPU) provides water to approximately 1.4 million people in the central Puget Sound area. In addition to providing direct service to approximately 700,000 residents, SPU wholesales water to 20 cities and water districts near Seattle.

SPU is completing an update of a 1990 seismic vulnerability assessment that was performed by Cygna Energy Services [1]. This assessment update accounts for changes in the understanding of the seismic hazards that threaten the Puget Sound region. The 2017 update emphasizes pipeline performance and overall system response.

The 2017 findings show that although some important "vertical" facilities such as reservoirs and pump stations are vulnerable, the most significant effect on water system response will be pipeline damage. Damage to transmission and distribution system pipeline damage is expected to severely disrupt system operation and delay system restoration. In order to mitigate the effects of this pipeline damage, SPU's mitigation strategy is to employ both short-term measures to manage the current vulnerability of the SPU water system and longer-term measures to reduce the vulnerability of the SPU water system. The five basic elements of SPU's mitigation approach are

Short Term

- Implement Isolation and Control Measures to Mitigate the Effects of Pipeline Damage on System-Wide Water Pressure
- Improve Earthquake Emergency Preparedness and Response Planning to Reduce Recovery Time

Long Term

- Construct an Earthquake-Resistant Transmission Pipeline That Will Supply Minimal Water Demand to SPU's Direct Service Area
- Use earthquake-resistant pipe in permanent ground displacement susceptible areas and for pipelines that are essential for fire-fighting or that serve critical facilities
- Seismically Upgrade Critical Reservoirs, Tanks, Pump Stations and Support Facilities

This paper summarizes the findings of SPU's seismic vulnerability study update and SPU's mitigation approach.

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INTRODUCTION/BACKGROUND

Seattle Public Utilities (SPU) provides treated water to 1.4 million residents in the Seattle area. Approximately half of these residents are in SPU's direct service area and the other half are served by 20 other cities and water districts. Total average daily demand is approximately 120 million gallons (450,000 cubic meters) per day.

Typically, two-thirds of SPU's water supply comes from the Cedar River Watershed which is located approximately 30 miles (50 kilometers) southeast of downtown Seattle in the Cascade Mountains. The Tolt River Watershed, located approximately 30 miles (50 kilometers) northeast of downtown Seattle in the Cascade Mountains, typically provides the other one-third of SPU's water supply. The Seattle Well Fields can provide an additional 10 million gallons (38,000 cubic meters) per day on an emergency basis for up to four months.

Approximately 193 miles (310 kilometers) of transmission pipelines convey water from the Landsburg Diversion on the Cedar River and the Tolt Reservoir to SPU's customers. Most of the Cedar River system transmission system consists of riveted or lock bar steel pipe with some alignments constructed from either concrete cylinder pipe or welded steel pipe. The newer Tolt 2 Pipeline is welded steel pipe with welded lap joints and the older, early 1960's vintage Tolt 1 pipeline is primarily concrete cylinder with some newer welded steel or ductile iron pipe.

SPU's direct service area is served by almost 1680 miles (2700 kilometers) of distribution pipelines. Cast iron mains comprise 79% of the distribution pipeline system with ductile iron pipe accounting for another 15%.

Chester Morse Lake and Lake Youngs provide storage for the Cedar River Watershed and the Tolt Reservoir and Regulating Basin provide storage for the Tolt Watershed. Storage within SPU's transmission and distribution system is provided by

- 10 below grade reservoirs ranging in capacity from 2.5 million gallons to 60 million gallons
- Three above grade concrete reservoirs
- Four elevated steel tanks
- Five steel standpipes
- Two surge tanks

Although most areas within SPU's direct service area can usually be served by gravity, SPU operates 31 transmission and distribution pump stations.

In 2015, SPU initiated a comprehensive seismic vulnerability assessment update. The purpose of this update was to re-evaluate the seismic vulnerability of SPU's facilities with the current understanding of the seismic risks in the Puget Sound region and with an emphasis on pipeline and overall system performance.

PUGET SOUND SEISMICITY

There are three source zones that are capable of producing damaging earthquakes in the Puget Sound region (see Figure 1). The subduction of the Juan de Fuca Plate by the North American Plate has produced M9.0 subduction earthquakes with an average return interval of 500 years. The fault rupture can extend 700 miles (1100 kilometers) along the Pacific Northwest coast from Northern California to southern British Columbia. Since it has been 300 years since the last full rupture of the interface between the Juan de Fuca and North American Plates, seismologists estimate there is a 0.14 probability that this interface will rupture in the next 50 years. Ground motions between 0.2g and 0.3g would be expected in SPU's transmission and distribution area. Ground shaking would be expected to last several minutes.

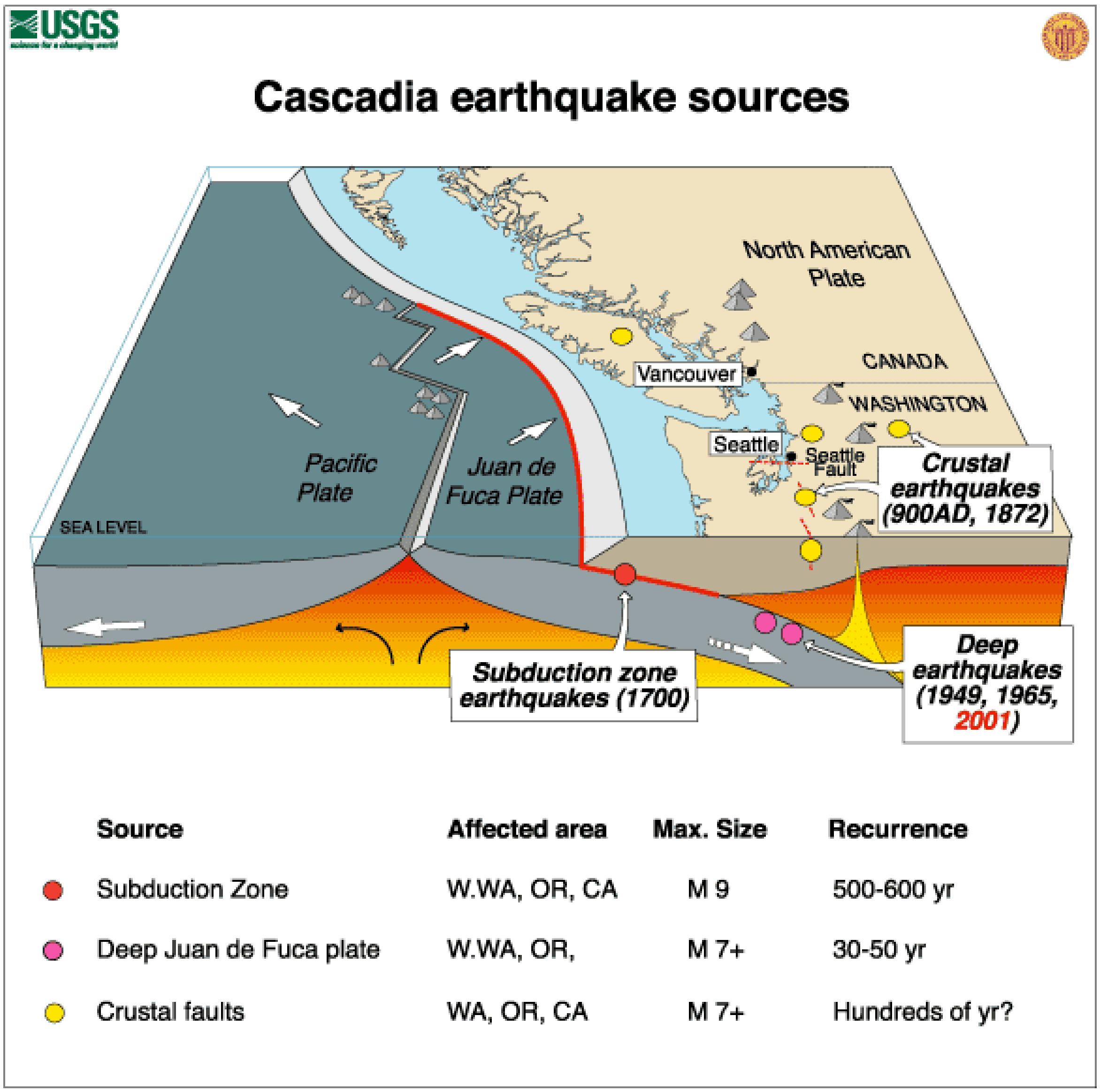

Figure 1. Puget Sound Earthquake Source Zones [2]

Every 25 to 30 years, M6.0 or greater earthquakes occur in the subducted Juan de Fuca Plate as it fractures below the Puget Sound region. Although these intraplate earthquakes can occur directly below SPU's service area, the hypocenters are typically 20 to 50 miles (30 to 80 kilometers) deep. In most areas, peak ground accelerations at the earth's surface are less than 0.2g. Although some SPU facilities were damaged during the 1949 M7.1, 1965 M6.5 and 2001 M7.1 Puget Sound earthquakes, water system operation was not significantly affected during either of these three earthquakes.

Crustal blocks within the North American Plate are being dragged northward by the Pacific Plate. These crustal blocks are colliding with a fixed portion of the North American Plate that lies in Canada. This compression has produced a complex set of shallow faults in Western Washington. One of these fault zones, the Seattle Fault zone, runs directly through Seattle and has produced earthquakes of M7.0 or greater in the Seattle area. These surface faults are capable of producing peak ground accelerations in excess of 0.6g. The determination that these surface faults are active only occurred in the last 25 to 30 years so most older facilities are not designed to resist these larger ground motions. Seismologists estimate there is a 0.05 probability of a M6.5 or larger Seattle Fault event in the next 50 years.

SEISMIC HAZARD ESTIMATION

SPU's facilities are spread over a larger geographical area. In addition to the probabilistic ground motions that are used by building codes, ground motions and seismic hazards were estimated for M7.0 Seattle Fault earthquake and M9.0 Cascadia Subduction earthquake scenarios.

The average of five NGA-West2 ground motion prediction equations were used to estimate ground motions for the Seattle Fault M 7.0 earthquake [3]. The BC Hyrdo ground motion prediction equation [4] was used to estimate ground motions for the M9 Cascadia Subduction earthquake.

Permanent ground displacements were estimated for liquefaction- and landslide-susceptible areas for both scenario earthquakes. These displacement estimates are used as input to pipeline damage algorithms developed by the American Lifelines Alliance [5]. The regional permanent ground displacement estimates are intended to produce averages over wide geographical areas and are not intended for site-specific analysis. The actual displacements at some sites may significantly differ from the regional estimates.

The liquefaction-susceptibility and soil units identified by the Washington State Department of Natural Resources [6] and the estimated ground shaking intensity and duration were used in conjunction with liquefaction displacement models to estimate the liquefaction displacements. Three components of liquefaction displacement were estimated [7]:

- PGD_h, the horizontal component due to lateral spread
- $PGD_{v\text{-}vol}$, the vertical component due to ground settlement and ejecta
- $PGD_{v\text{-}dev}$, the vertical component due to deviatoric strains cause by lateral displacement

The total permanent ground displacement from liquefaction was estimated as

$$PGD_{total} = \sqrt{[(\mathrm{PGD}_h)^2 + (\mathrm{PGD}_{\mathrm{v-vol}} + \mathrm{PGD}_{\mathrm{v-dev}})^2\,]} \quad (1)$$

The areal extent of liquefaction in a particular region was estimated as a function of the soil properties and ground shaking intensity. Shaking duration was considered by applying a magnitude scaling factor.

The factor of safety for landslides in Seattle under static conditions was estimated by Harp et al [8] in a previous study. Using a simplified sliding block model and assumed ranges of slope, the landslide probability was estimated as a function peak ground acceleration for each of the factor of safety ranges defined by Harp et. al. The Makdisi and Seed [9] relationships between the peak ground acceleration, $k_{y\text{-}max}$, the acceleration that triggers landsliding, k_y, and the earthquake magnitude was used to estimate permanent ground displacement from landslides [10].

FACILITY ASSESSMENT APPROACH AND FINDINGS

Over 100 SPU facilities were evaluated [11]. The facilities were evaluated with regards to expected post-earthquake functionality. The evaluation methodology was a function of the facility criticality. For most facilities, an ASCE 41-13 [12] Tier 1 assessment was conducted [13]. For many of the above ground reservoirs, pseudo static analyses were performed [14]. To address some structural issues that had been identified, detailed soil-structure interaction (SSI) analyses were performed for four of the below grade reinforced concrete terminal reservoirs [15-18].

Many of the simpler buildings were found to be seismically rugged even though they were designed and constructed before modern seismic codes were adopted. As expected, when there were deficiencies in the lateral force resisting system, they often involved inadequate detailing in the roof-to-wall connections and/or shear walls.

The reservoirs and tanks were more likely to have significant seismic concerns. Insufficient lateral strength and inadequate anchorage were common tank and reservoir deficiencies. The roof-to-wall connections were inadequate for many of the ground-supported concrete tanks.

Based on the SSI model findings, four below grade reservoirs were seismically upgraded. For all four reservoirs, the perimeter floor slabs were thickened to keep water loss from any cracking less than 100 gallons (380 liters) per minute. Wall sealants were used to control leakage from wall cracking in three of the reservoirs. In a fourth reservoir, the wall was thickened.

PIPELINE ASSESSMENT APPROACH AND FINDINGS

As Figure 2 shows, SPU’s transmission and distribution pipeline alignments are exposed to numerous seismic hazards. In addition to crossing several areas of unstable soils, the Cedar River transmission system traverses through the Seattle Fault zone as it travels north through Seattle. The Seattle Fault is a complex fault system that is approximately 50 miles (80 kilometers) long and as wide as five miles (eight kilometers) [19]. Uplift of up to 20 feet (six meters) may occur in the northern part of the Seattle Fault zone meters) may occur in the northern part of the Seattle Fault zone while three to ten feet (one to three meters) of surface displacement may occur in the southern portion of the zone. Similarly, the Tolt transmission system must traverse the Sound Whidbey Island Fault zone that is as wide as 12 miles (20 kilometers).

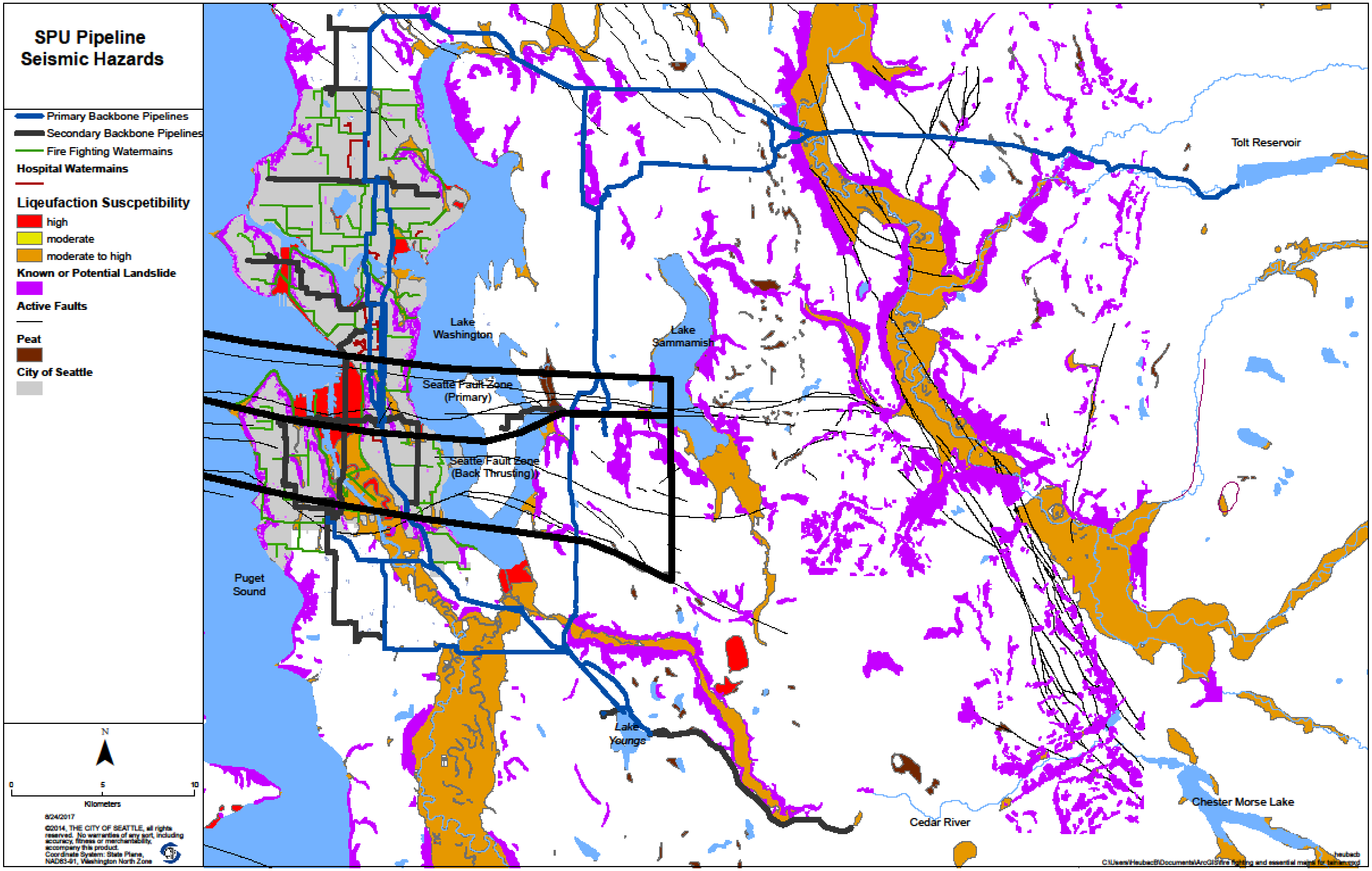

Figure 2. Seattle Public Utilities Pipeline Hazards

Distribution Pipelines

Two separate approaches were used to assess the distribution piping system and transmission piping system. The American Lifelines Alliance pipeline fragility models [5] were used to estimate distribution pipe breakage. These models take the form of

$$RR_{PGV} = K_1 \text{ X } 0.00187 \text{ X } PGV \tag{2}$$

and

$$RR_{PGD} = K_2 \text{ X } 1.06 \text{ X } PGD^{0.319} \tag{3}$$

where

RR_{PGV} = number of repairs per 1000 feet (305 meters) caused by seismic wave propagation effects

K_1 = constant dependent on the pipe material and joint system

PGV = the peak ground velocity expressed in inches per second

RR_{PGD} = number of repairs per 1000 feet (305 meters) caused by permanent ground displacement effects

K_2 = constant dependent on the pipe material and joint system

PGD = the permanent ground displacement expressed in inches

K_1 and K_2 range from 0.15 for ductile pipe to 1.4 for brittle pipe.

Peak ground velocities were estimated with the ground motion prediction equations referenced earlier [3 and 4]. The methodology described in the seismic hazards section was used to estimate the permanent ground displacements and areal extent of permanent ground displacement.

For the M9 Cascadia Subduction earthquake scenario, approximately 1400 pipe repairs are forecasted. In the M7 Seattle Fault scenario, approximately 2000 pipe repairs are forecasted. Figure 3 shows the repair rates for the Seattle Fault scenario. As the models suggest, the highest rates occur where permanent ground displacements are expected.

The models used to estimate distribution pipe are very approximate and do not show exact locations where pipe breakage is expected to occur. Instead, these models provide a gross estimate of the overall number of failures that might be expected.

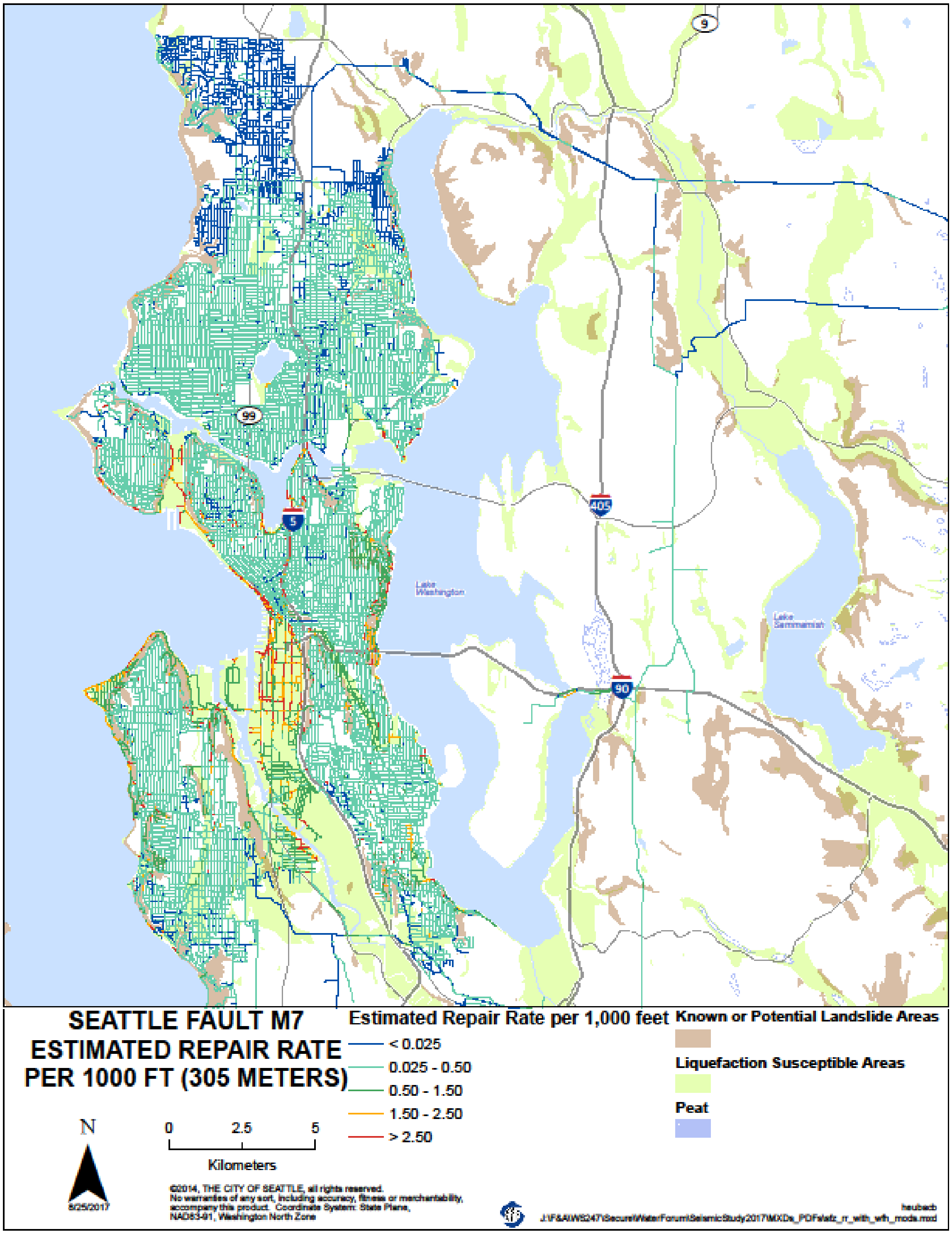

Figure 3. Estimated Distribution Pipeline Failure Rates for M7 Seattle Fault Earthquake

Transmission Pipelines

A more site-specific approach but still "high level" approach was used to evaluate transmission pipeline vulnerability. Previous findings from the 1990 Cygna report, SPU staff input and comparison of geotechnical hazard maps were used to identify those areas of most concern along the transmission pipeline alignments. For those sites believed to be most critical, available site specific geotechnical information was reviewed. Based on the transmission pipeline characteristics and the available geotechnical information, an expert panel estimated the pipeline performance for each of the three scenarios.

The assessment identified multiple locations along the Cedar River and Tolt transmission pipelines with potentially unstable soils. Additionally, the Cedar River transmission pipelines must cross the Seattle Fault zone and the Tolt transmission pipelines must cross the South Whidbey Island Fault zone.

The assessment concluded that under the M7.0 Seattle Fault scenario and M9 Cascadia Subduction Zone scenario, both transmission pipeline systems would likely suffer damage and would be unable to convey water into SPU's service areas. The transmission pipeline systems could be damaged in multiple areas and restoration could be difficult.

SYSTEM ASSESSMENT APPROACH

In order to develop a strategic mitigation approach, the facility and pipeline assessment results were applied to a system hydraulic model to estimate post-earthquake system performance. In addition to current system performance, the hydraulic model is being run for multiple mitigation approaches to determine the most-effective approaches that are consistent with SPU's post-earthquake performance goals.

In previous post-earthquake assessments, SPU has used a detailed EPANet system model to assess post-earthquake system performance. Because of all of the demands that a seismic event creates on the system, the full system model rapidly becomes unstable and has trouble converging. Consequently, a skeletonized model was used for this analysis. Instead of modeling every pipeline, the skeletonized model models most pressure zones with only a few nodes.

The FEMA Hazus [20] assumptions were used to estimate the severity of the pipeline failures. Breaks are defined to occur when a pipeline can no longer carry water. A leak is defined to occur when water is escaping from the pipeline but the pipeline can still convey flow. Permanent ground displacement failures were assumed to consist of 80% breaks and 20% leaks. Conversely, 20% of the wave propagation failures were assumed to be complete breaks and the other 80% were assumed to be pipeline leaks.

The individual flow rate through a break was estimated as the amount of flow that could be provided at the end of a 2000-foot (600 meters) open pipe that is supplied with water at 60 psi (400 kPa). The water flow through an average leak was estimated as the flow through a circumferential opening of 0.04 inches (1 millimeter) at 60 psi (400 kPa). These assumptions are based on the assumptions used by Kennedy/Jenks/Chilton in a study sponsored by the United States Geological Survey [21].

Because nearby pipeline failures will influence the volume of water that can be flow out of each failure, the effective volume of water that will be lost was reduced in each pressure zone once the failure rate exceeded one failure per 10,000 feet (3000 meters). The effective water loss was assumed to decrease exponentially below the water loss that would occur if all of the failures were independent.

Once the water loss for each pressure zone or node was estimated, the emitter coefficients were calculated and applied to the EPANet model. The emitter coefficients were calculated from the equation [22]

$$Q = Cp^{\gamma} \tag{4}$$

where

Q = the flow rate
C = the emitter coefficient
p = the pressure
γ = the pressure coefficient (assumed to be 0.5)

The results of the system analyses showed that much of SPU's direct service area would lose water pressure within 12 hours of either a M7 Seattle Fault or M9 Cascadia Subduction earthquake. It would likely take at least 2 months to restore minimal water service to all areas within the direct service area. It would likely take several years before pre-earthquake levels of service could be restored to the direct service area.

MITIGATION APPROACH

With input being provided by stakeholders such as SPU's ratepayers, the Fire Department and wholesale customers, SPU is currently establishing post-earthquake performance goals. The primary criteria the performance goals address are:

- Firefighting water availability immediately after a seismic event
- Maintaining and/or restoring water pressure within the distribution area and wholesale turnouts
- Mitigating life-safety risks

Given the number of vulnerable facilities, budgetary and workload realities make it unrealistic to immediately meet the performance goals. Consequently, one set of performance goals is being set for 20 years in the future and another set of performance goals is being established for 50 years in the future. The general approach SPU is taking is to over the short term, use isolation and control strategies, and emergency preparedness and response planning to mitigate the effects of facility damage on water system performance. As facilities are made more seismically rugged, overall facility seismic resiliency will gradually increase. In this regard, five mitigation strategies are being developed:

1. Construct a seismic resistant transmission pipeline from the Cedar River supply to Seattle that would be highly likely to survive a major earthquake so there would be at least minimal (fight fires and basic needs but not enough for landscaping or other non-critical uses) water flowing into town. The Cedar River system was chosen over the Tolt system because it is easier to supply water from the Cedar River system throughout the SPU service area than the Tolt system. This "seismic-resistant" transmission pipeline would be constructed over a 50-year time frame.

2. Install more isolation and control systems that would allow SPU to prevent pipe breakage from draining reservoirs and to allow SPU to isolate heavily damaged areas so the system could be restored faster. This mitigation measure will be implemented over a 10-year time frame and is intended to mitigate the failure effects of some of the current system facilities.
3. When new pipelines are installed or replaced in areas that are susceptible to permanent ground displacements, use earthquake-resistant pipe. Regardless of the known permanent ground displacement susceptibility, use earthquake-resistant pipe on all mains that necessary for fire fighting, serve critical facilities such as hospitals and facilities needed for emergency response, and pipelines that supply distribution tanks and large service areas. The estimated time frame to install earthquake-resistant pipelines in these situations is approximately 100 years.
4. Seismically retrofit the most critical facilities (tanks, pump stations, etc.). It is expected that less critical facilities will not be seismically upgraded, particularly those facilities with shorter remaining "useful" lives. The probability of the occurrence of a major earthquake before these facilities are replaced is relatively small and it is more cost-effective to use limited resource to address the seismic vulnerability of more critical facilities that have a bigger impact on system performance. These upgrades will be done over a 20- to 50-year time frame.
5. Improve emergency preparedness and response planning. Needed repair materials and resources will be identified and methods to obtain these materials and resources after an emergency will be identified. Strategies and resources needed to provide emergency drinking water after an earthquake will be augmented. These plans and procedures will be implemented over a 10-year time frame.

SUMMARY

Seismic vulnerabilities have been identified in the SPU water system. These vulnerabilities would likely lead to loss of water pressure in much of SPU's direct service area after a major earthquake. Restoration of minimal water service to all areas would likely take as long as two months. In order improve the seismic resiliency of the SPU water system, SPU plans to implement five mitigation approaches. Two of the approaches, using isolation and control measures and improving emergency preparedness and response to mitigate facility damage effects, are intended to improve system response in the short term. Over the longer term, constructing an earthquake-resistant transmission pipeline, replacing aging distribution watermains with earthquake-resistant mains and upgrading critical, seismically vulnerable facilities will increase the seismic resiliency and performance of the SPU water system.

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