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

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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.

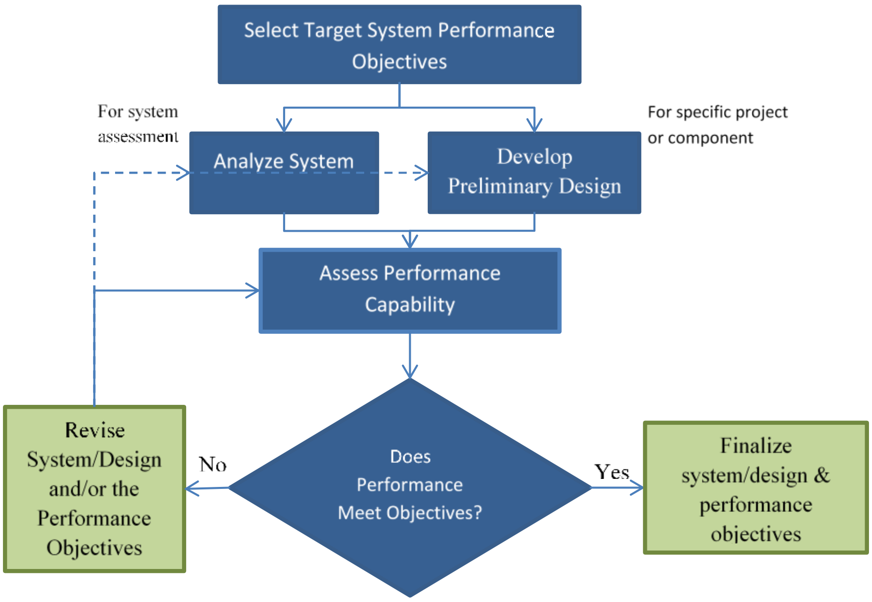

Figure 1. Performance based seismic design flow diagram (revised from [5]).

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.

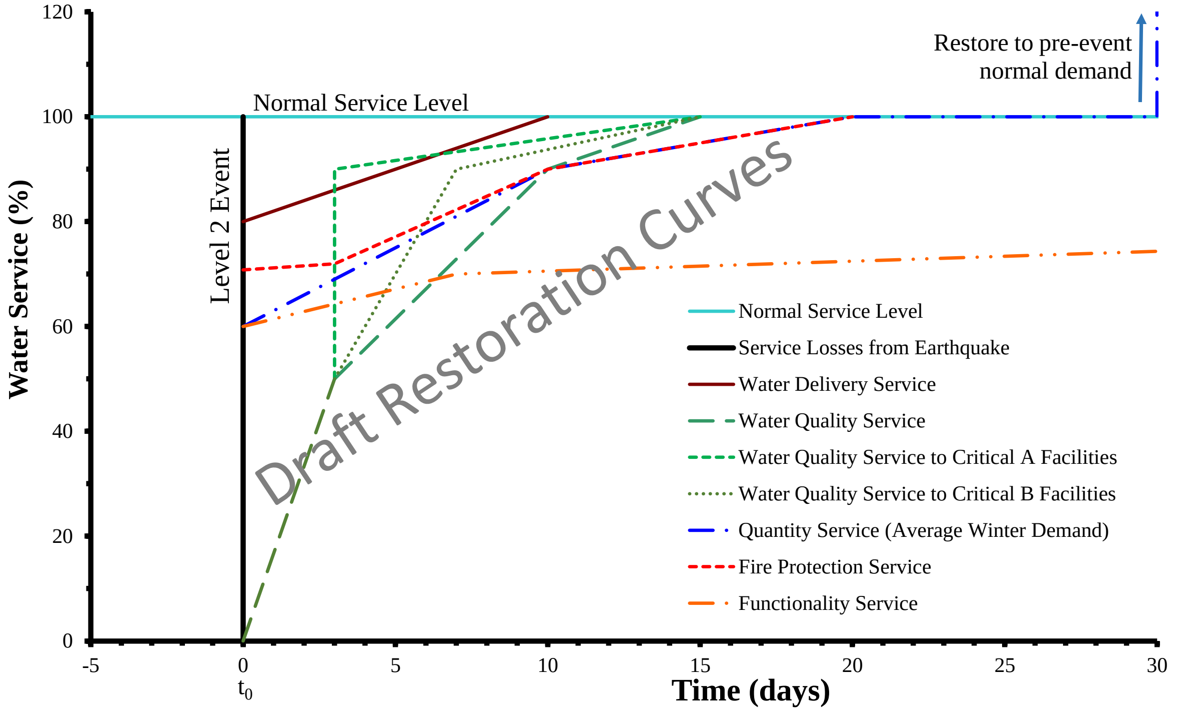

Figure 2. Draft service restoration curves for Level 2 events.

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.

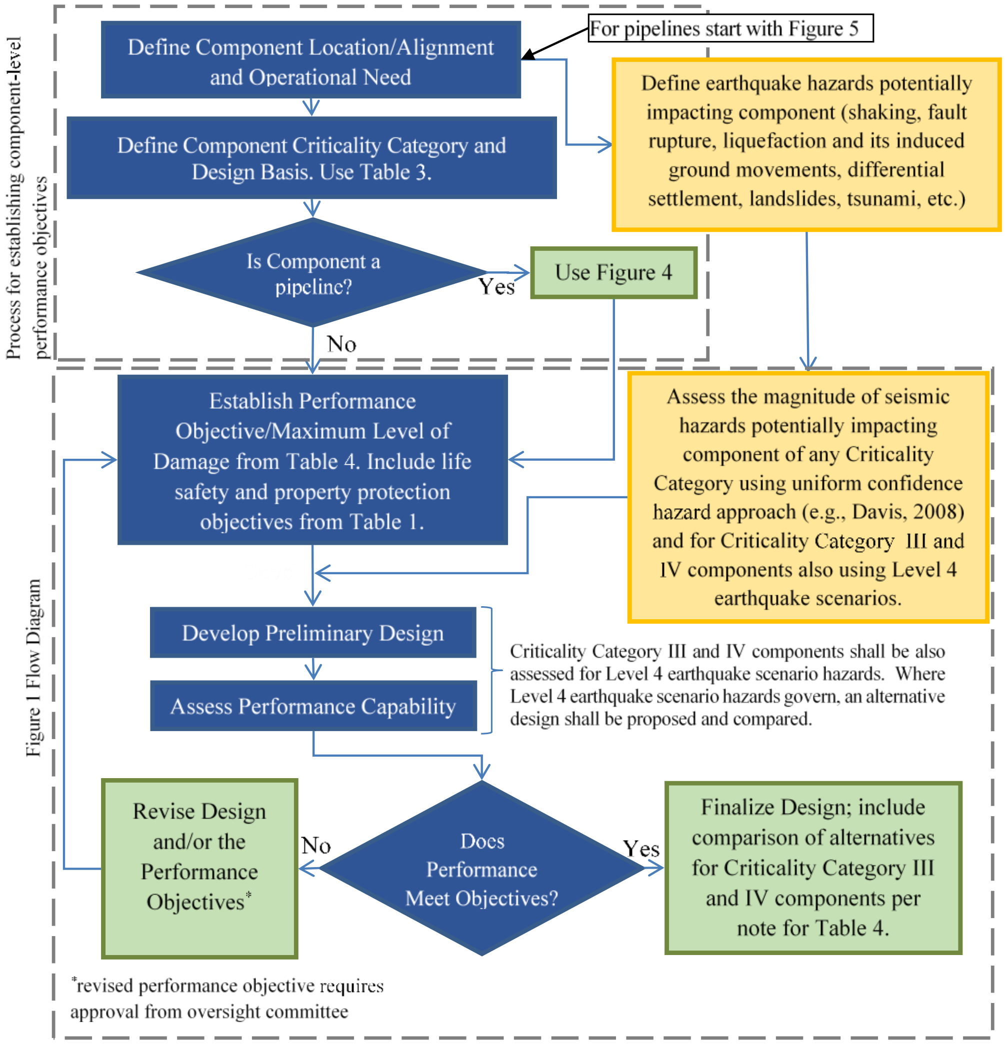

Figure 3. Component design flow diagram.

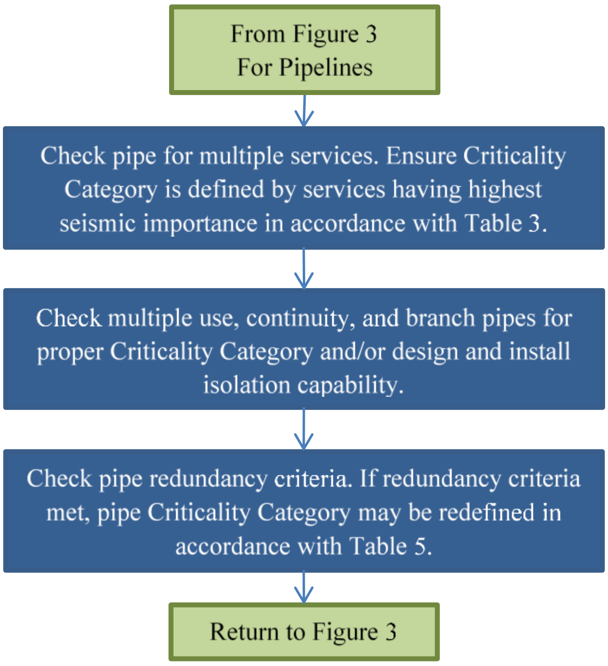

Figure 4. Pipeline component partial flow diagram for establishing performance objectives.

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	Criticality Category II	Criticality Category III	Criticality Category 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
Hazard Return Period (yrs) 975	High	Moderate to High	Moderate	Minor to Moderate
Hazard Return Period (yrs) 475	Moderate to High	Moderate	Minor to Moderate	Minor
Hazard Return Period (yrs) 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].

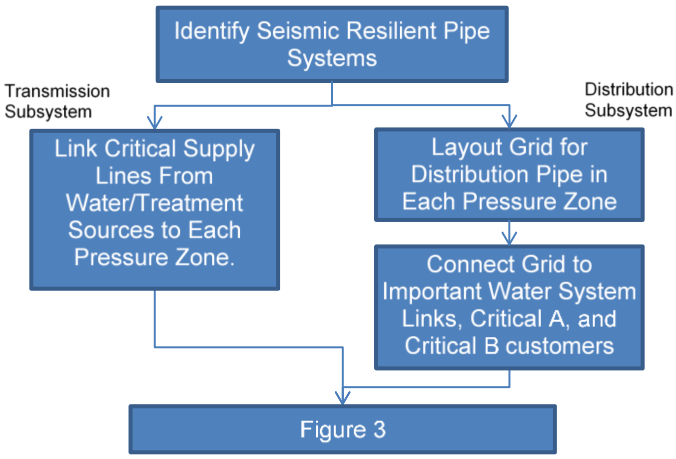

Figure 5. Work flow process for developing a seismic resilient pipe network.

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.

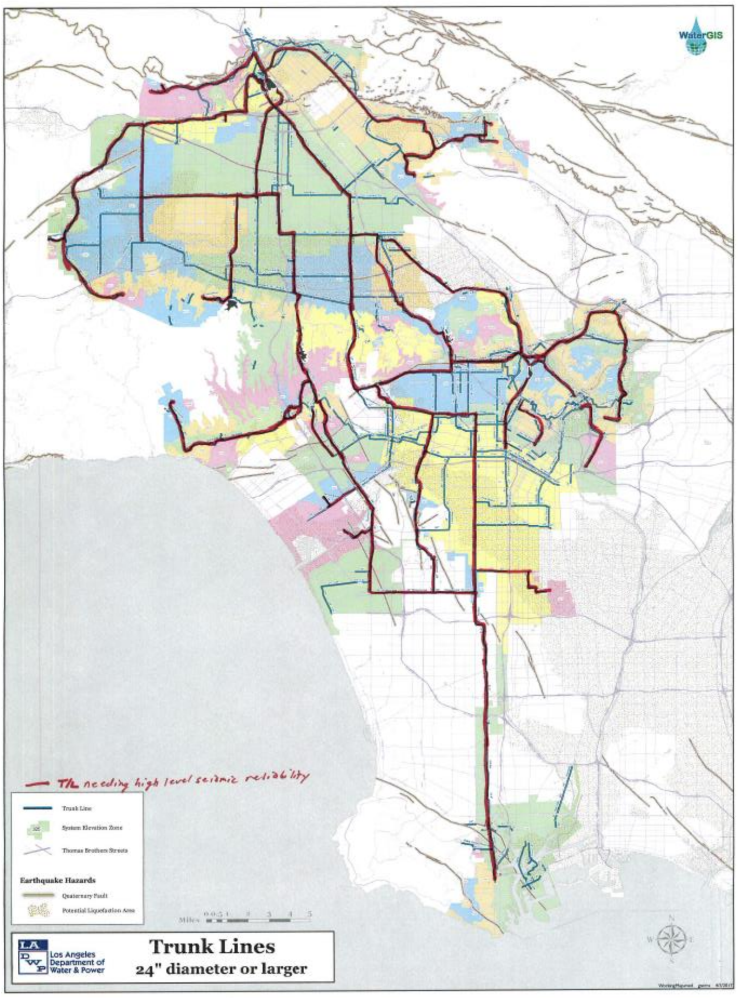

Figure 6. Draft LADWP Resilient Transmission Pipe Network (red lines are seismic reliable pipes with Criticality Category IV, blue lines are pipes with other Criticality Categories).

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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