Mitigation of Potential Impacts of Seismic Events on a Regional Water Distribution System

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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.

Part 1 – Assessment of Vulnerable Existing Pipelines: 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.

<u>Part 2 – Mitigation Measures for Existing Pipelines</u>: 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

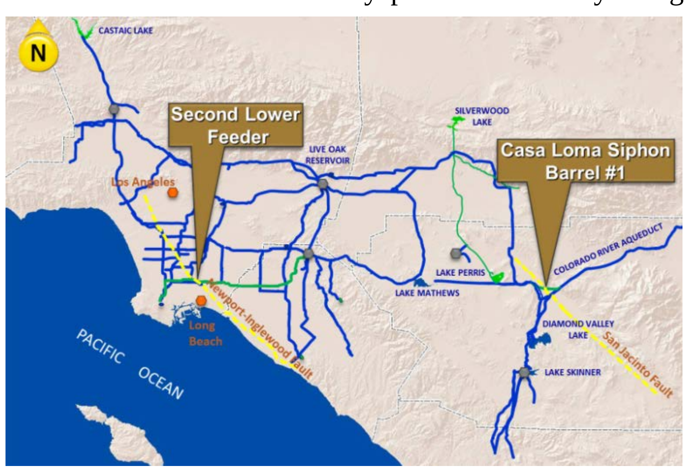

Figure 2: Location Map for Case Studies

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

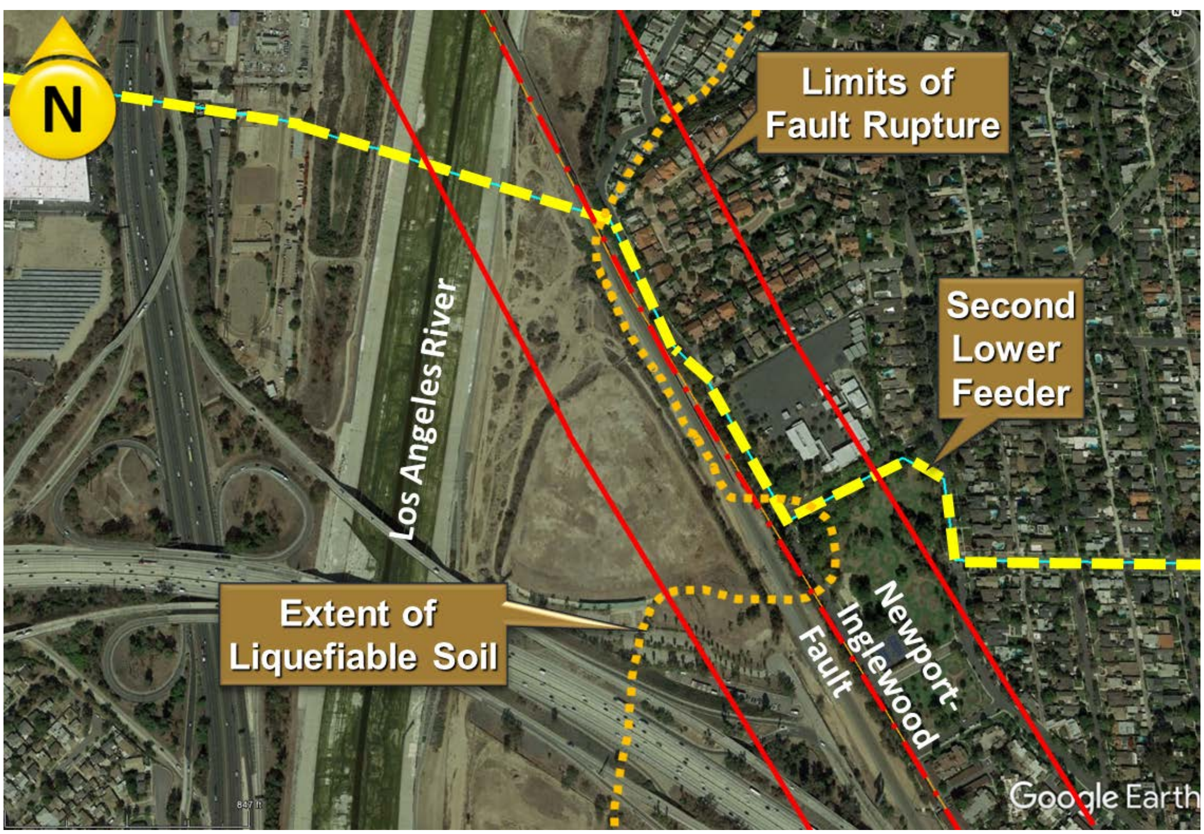

Figure 3: Second Lower Feeder Fault Crossing

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

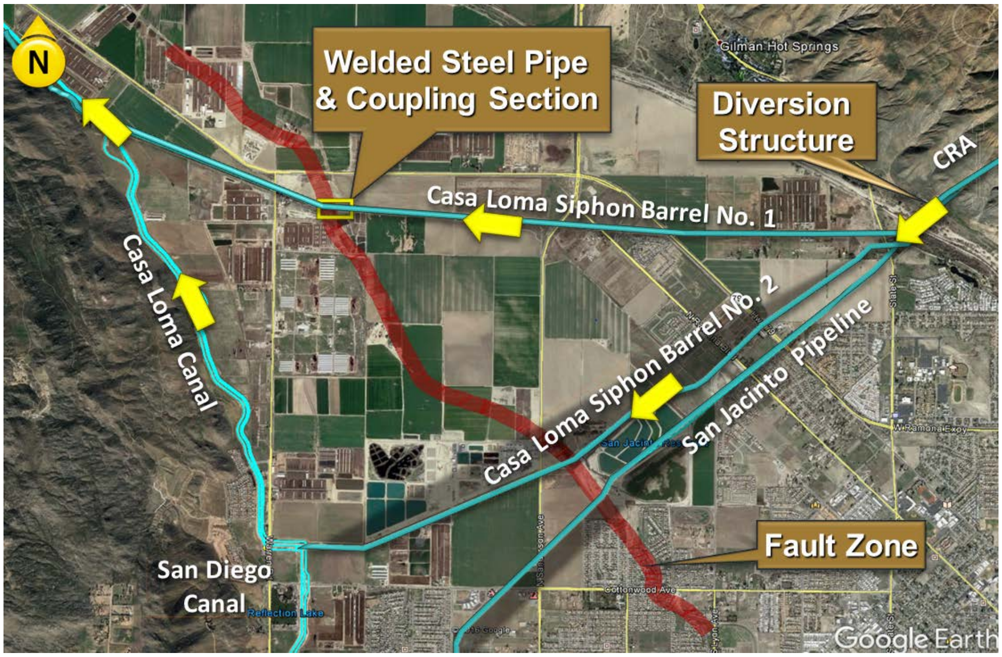

Figure 4: Casa Loma Location Map

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

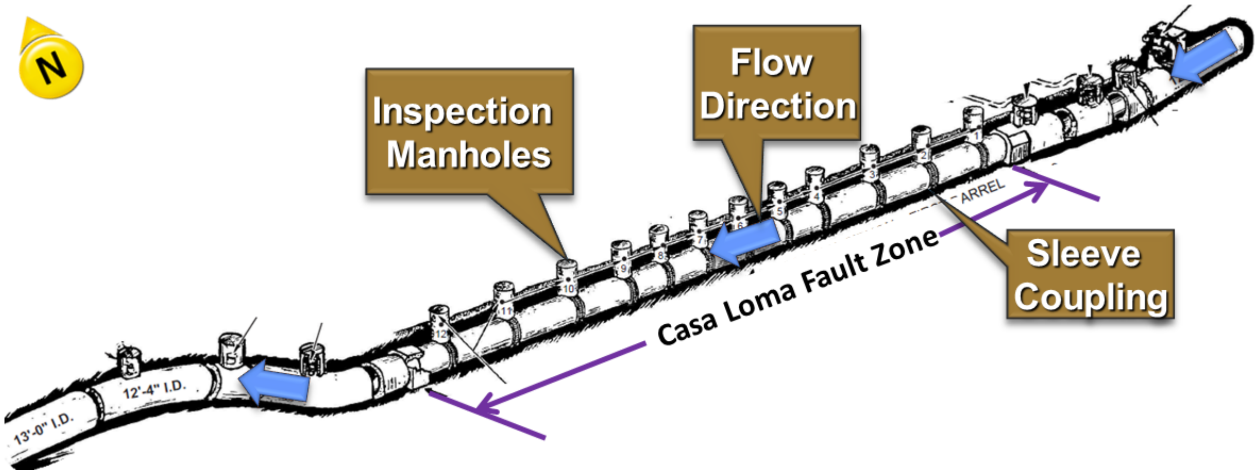

Figure 5: Casa Loma Siphon Barrel No. 1

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 streng-thening 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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