INTEGRATED SEISMIC RESILIENCE STRATEGY FOR THE METROPOLITAN WATER DISTRICT OF SOUTHERN CALIFORNIA

D. Clark¹ and G. de Lamare²

ABSTRACT

The Metropolitan Water District of Southern California (Metropolitan) owns and operates a complex water conveyance, storage, treatment, and distribution system that covers 5,200 square miles in a seismically active region and is depended upon to provide approximately one-half of the water needed by its 19 million residents. Metropolitan has developed a comprehensive Seismic Resilience Strategy (SRS) to prepare for and respond to significant seismic events. Metropolitan’s multi-faceted SRS involves coordination within Metropolitan as well as coordination with other owners of imported water conveyance systems that cross the Southern San Andreas Fault. The coordination within Metropolitan focuses on enhancing operational flexibility; diversifying water resources; providing adequate emergency water supplies; identifying and addressing infrastructure and system vulnerabilities; and developing effective emergency response capabilities. The coordination outside Metropolitan is through a multi-agency task force which involves the California Department of Water Resources (DWR) and the Los Angeles Department of Water and Power (LADWP). Metropolitan’s SRS also includes a reporting component to increase transparency and accountability. Each year, Metropolitan’s Board of Directors is updated on recent seismic resilience achievements and near-term goals.

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Introduction

The Metropolitan Water District of Southern California (Metropolitan) was created by the legislature of the State of California in 1928 for the purpose of constructing and operating the Colorado River Aqueduct (CRA) that serves Southern California’s coastal plain. The 242-mile CRA system was placed into service in the early 1940’s and then, over the seven succeeding decades, Metropolitan expanded the system to include five regional water treatment plants, nine reservoirs, 16 hydroelectric plants, 7 pumping plants and an additional 830 miles of large diameter pipelines and tunnels. On average, Metropolitan delivers approximately 1.7 billion gallons of treated and untreated water per day to 26 member agencies within Los Angeles, Orange, Riverside, San Bernardino, San Diego, and Ventura Counties to supplement local supplies.

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Metropolitan’s service area covers 5,200 square miles in a seismically active region and the seismic risk posed to its infrastructure is significant (See Figure 1).

From its inception, Metropolitan has been committed to minimizing interruptions to water deliveries following major seismic events by being proactive in system planning, facility design, and in developing emergency response capabilities. Metropolitan has also enhanced seismic resilience efforts by applying lessons learned from major seismic events.

**Post 1906 San Francisco and 1933 Long Beach Earthquakes (1930-1970)**

The majority of Metropolitan’s conveyance and distribution system was constructed between the 1930’s and the 1970’s. Despite having no provisions within design codes, Metropolitan took proactive measures to address seismic resilience in design of the CRA. Metropolitan geologists and engineers took into account the ground shaking and deformation that had occurred along the San Andreas Fault system during the 1857 Fort Tejon earthquake and lessons learned from 1906 San Francisco earthquakes, and supplemented their understanding of regional active faults through geologic mapping and analysis of stereo aerial photographs. This led to the aqueduct being designed to cross active faults near the ground surface in inverted siphons and cross at right angles to the fault traces [1][2]. The designers also opted for a flexible siphon design in fault regions rather than rigid monolithic concrete construction used elsewhere on the CRA, and provided extra hydraulic grade at three siphons crossing active faults. These provisions minimize the adverse effects of seismically induced ground movements and simplify access for repairs.

Figure 1. Metropolitan’s service area and known earthquake faults
Post 1971 San Fernando Earthquake (1971-1990)

Following the San Fernando Earthquake, Metropolitan formed an Earthquake Committee to investigate its structures damaged by this event and recommend enhanced seismic design criteria to mitigate seismic risk for potential future events. Metropolitan also adopted its Emergency Response Plan and established a formal Emergency Response Organization (ERO).

Post 1989 Loma Prieta and 1994 Northridge Earthquake (1990-2010)

During this period, Metropolitan greatly enhanced seismic resilience by updating its seismic design criteria, strengthening dozens of at-risk structures, performing special seismic risk assessments, and enhancing emergency response capabilities.

Post 2010 Chile, 2011 New Zealand and 2011 Japan Earthquakes (2010-Present)

The recent earthquakes in Chile, New Zealand, and Japan demonstrated the importance of seismic resilience. Metropolitan re-assessed its existing programs and then implemented a more integrated, comprehensive approach to seismic resilience which is described below.

Metropolitan’s Comprehensive, Integrated Seismic Resilience Strategy

Metropolitan’s SRS (see Figure 2) is a multi-faceted approach that involves coordination among key areas within Metropolitan as well as coordination with other owners of imported water conveyance systems that cross the Southern San Andreas Fault.

![Figure 2. SRS Structure and High Level Goals](image)

As shown in the figure, the coordination within Metropolitan focuses on planning, engineering/design, operations/emergency response, and reporting. The coordination outside
Metropolitan is through a multi-agency Task Force focused on the unique seismic vulnerabilities of Southern California’s imported water supplies.

The purpose of Metropolitan’s SRS is to ensure that Metropolitan can restore water deliveries to its member agencies as soon as possible after a seismic event through system flexibility, a diversified supply portfolio, and emergency storage; by minimizing damage to infrastructure; and by maintaining a robust emergency response and recovery organization. This integrated, comprehensive approach will ensure long-term efforts remain effective and focused, program achievements and goals are clearly communicated to the Board, and member agencies have more clarity regarding projected regional seismic performance to enhance local facility and emergency response planning efforts.

Planning

The planning component develops diversified water resources, enhances system flexibility and provides emergency water storage through Metropolitan’s Integrated Water Resources Plan (IRP). The goal of Metropolitan’s IRP is to develop a diverse water supply portfolio that will be able to maintain a reliable water supply under any conditions, including a major seismic event.

Diversified Water Supply Portfolio

Metropolitan’s planning initiatives, including three Integrated Water Resource Plan (IRP) Updates provide policy framework guidelines and resource targets for Metropolitan to ensure regional water supply reliability and additional resiliency during seismic events. Metropolitan’s strategy is to maintain rather than increase traditional levels of imported water supplies, and sustain continued growth in the region through the development of local resources and conservation. The ability to draw upon an ever more diverse water supply portfolio results in greater resilience to the potential impacts of seismic events on Southern California’s water supply infrastructure.

System Flexibility

Water supply reliability and water demand-driven projects increase Metropolitan’s system flexibility to deliver water to its member agencies and improve seismic resilience. For example, the construction of Diamond Valley Lake (DVL) and the Inland Feeder pipeline significantly increased water supply reliability by nearly doubling the ability to store imported water supplies within the Metropolitan service area. These projects also increased the flexibility of the system to maintain deliveries under adverse conditions. In addition, seismic resilience was increased as the storage was purposely located within the major fault lines that cross the SWP, CRA, and LAA, and a significant amount of storage in DVL is dedicated to emergency storage.

Emergency Storage

Over the past two decades, Metropolitan has developed a large regional storage portfolio which includes both dry year and emergency storage capacity. Storage generally takes two forms: surface reservoirs and groundwater basin storage. Emergency storage requirements are based on...
the potential of a major earthquake damaging the aqueducts that transport Southern California’s imported water supplies (SWP, CRA, and LAA). The adopted criteria currently assume that damage from such an event could render the aqueducts out of service for six months. Therefore, Metropolitan has based its planning on a 100 percent reduction in these imported supplies for a period of six months.

Under the emergency criteria, retail demand will be met through Metropolitan and DWR’s surface storage and local production (e.g. groundwater basins). The total amount of storage available for Metropolitan’s emergency needs, which includes DVL, and Lake Mathews and Lake Skinner, is 319,200 acre-feet. In addition, the amount of emergency storage available to Metropolitan in DWR’s reservoirs, which include Lake Perris, Castaic, Silverwood, and Pyramid Lakes, provide another 354,300 acre-feet of emergency storage.

**Engineering**

The engineering component addresses design concepts, vulnerability studies, and seismic resilience projects implemented though a Capital Improvement Program (CIP). The engineering component includes the Seismic Upgrade Program, special seismic assessments, Safety of Dams Seismic Monitoring Program, and pipeline seismic resilience enhancements. These efforts are all aimed at improving the seismic resilience of the treatment and distribution systems through facility upgrades and operational flexibility improvements.

**Seismic Upgrade Program**

In general terms, the purpose of the Seismic Upgrade Program for water delivery infrastructure is to prevent seismic damage in probable events and limit damage in extreme events in order to minimize water delivery interruptions. For occupied structures, the program’s purpose is to ensure life safety and critical functions. The Seismic Upgrade Program applies a systematic approach to evaluate structures that were constructed in accordance with earlier codes, and where necessary, upgrade those existing structures identified to have seismic deficiencies. The criteria applied to the seismic evaluation incorporate current code provisions and industry standards, and also addresses seismic issues unique to Metropolitan. In general, a structure is upgraded to maintain seismic performance level that is comparable to that of a new facility.

Over the past two decades, this program was primarily aimed at improving the seismic resilience of above ground facilities and structures constructed prior to 1990. To date all preliminary assessments of 311 pre-1990 structures have been completed. 195 structures were found acceptable. Of the 116 identified as potentially deficient, 86 have either been upgraded or are currently in various phases of design or construction.

In 2017, the scope of the Seismic Upgrade Program was expanded to further improve the seismic resilience of the water delivery system and now includes the following: fully and partially buried structures; seismic anchorage and bracing of non-structural components (equipment, pipes, ducts, etc.); and structures designed and constructed prior to the adoption of UBC1997.
Special Seismic Assessments

Seismic vulnerability assessments evaluate the potential impacts of credible earthquake scenarios to Metropolitan’s individual facilities and/or the system as a whole. For these studies, staff review current and readily available seismic hazard data from reputable public, academic, state and federal sources, as well as input from geotechnical consultants, to screen each facility or system (e.g., the CRA) for its level of exposure to seismic hazards (i.e., surface displacement, ground shaking, liquefaction and landslides) during a major seismic event. The potential damage to Metropolitan’s facilities and the time to repair key system components to restore service are estimated based on the level of exposure to seismic hazards during a major seismic event. These studies then evaluate the impact of the damage on Metropolitan’s water delivery capability and identify areas with limited or no backup capability to provide water while the facility is out of service for repairs. Improvements that could reduce the loss of service and/or reduce the time to restore service are then identified and prioritized.

Findings from the seismic vulnerability studies can lead to capital improvements to strengthen facilities, improve system flexibility, and/or provide input into Metropolitan’s emergency response planning to improve the seismic resilience of Metropolitan’s system. To date, Metropolitan has completed over ten seismic vulnerability studies.

System flexibility studies are used to identify 1) the impacts of regional facility outages on water deliveries to member agencies, 2) areas with limited flexibility to deliver water during an outage, and 3) options to improve system flexibility (e.g., interconnections with other agencies, local resource development, isolation valves). The process involves postulating Metropolitan and DWR facility outages, assigning a reasonable duration to the outage based on past experience, and evaluating the impact of the assumed outage on water deliveries.

The results of these studies benefit member agencies’ efforts to improve local system reliability in the event of a planned or unplanned Metropolitan facility outages; joint efforts of Metropolitan and its member agencies in evaluating the reliability benefits of potential projects; and Metropolitan’s efforts to identify options to improve operational flexibility.

Safety of Dams Seismic Monitoring and Assessment Program

Metropolitan owns and operates 20 dam and reservoir facilities that are under the jurisdiction of the California Department of Water Resources, Division of Safety of Dams (DSOD). The seismic resilience of these dams is ensured by a robust and proactive comprehensive dam safety management strategy managed by Metropolitan’s Safety of Dams Team. The core responsibilities of the Safety of Dams Team are to perform inspections, interpret and analyze collected surveillance and monitoring data, evaluate dam structures and appurtenant works, report findings, and function as Metropolitan’s liaison with DSOD.

Pipeline Seismic Resilience Enhancements

Metropolitan’s pipelines are exposed to a number of geohazards of varying risk, including fault zone crossings, permanent ground deformation from causes such as liquefaction or landslides,
and ground shaking during seismic events. Although Metropolitan’s pipelines have always been constructed in conformance with standards of practice at the time of design, there were no code requirements to address seismic risk nor, until recently, were there many mitigation options for large diameter pipelines.

Recently, however, seismic resistant pipelines, such as earthquake resistant ductile iron pipelines with special seismic resistant joints, are becoming more available in diameters that are suitable for use by Metropolitan. As a result, Metropolitan is now formalizing a strategy to achieve significant improvement in overall distribution system resilience over time. This approach takes advantage of the latest seismicity data, modern computer modeling techniques, recently developed seismic resistant products, extensive industry research, and updated codes.

The seismic resilience strategy for pipelines has three components:

**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 is focusing on the most vulnerable pipelines to determine the need and priority of future seismic mitigation as well as seeking to integrate seismic mitigation along with planned rehabilitation programs for aging pipelines to minimize costs. This approach is currently being taken under its PCCP Rehabilitation Program. It is anticipated that there will be relatively few cases where it will be cost-effective to upgrade a pipeline solely to enhance seismic resilience.

Vulnerability assessments of pipelines within the distribution system follow the same multi-step approach used for traditional seismic risk assessments. The initial steps entail gathering available geologic, seismologic, and geodetic data and identifying seismic hazards, such as fault zone crossings, liquefaction zones, and landslide hazards along a pipeline route. Three simulated earthquake scenarios are considered in the evaluation to perform a system wide hazard assessment: a frequent seismic event, a moderate event, and a severe event. The hazard assessment provides a bounded solution that includes an expected probable and maximum probable damage for each earthquake scenario.

The resulting damage to the pipeline due to the three simulated seismic scenarios provides an insight into the corresponding consequences of disruption. These consequences include life-safety impacts, delivery impacts, and societal/environmental impacts.

A preliminary screening is then performed to identify the most vulnerable pipelines that warrant further analysis. 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.
For those pipelines that do not meet the performance objectives, mitigation measures are recommended. The order and timing of projects to mitigate risks as part of the overall pipeline rehabilitation strategy are determined considering the overall capital improvement plan.

**Part 2 – Mitigation Measures for Existing Pipelines:** Where mitigation is recommended to minimize the consequences of service disruption, the general design goals are to design pipe segments and joints that can withstand projected vertical and horizontal movement. In most cases, a simplified analysis will provide sufficient insight into seismic performance; however, in some cases, it may be necessary to analyze the pipeline and connecting structures using a more comprehensive computer model.

Continuous welded steel pipe with adequate wall thickness and joint welds is expected to perform well under significant ground shaking. Specialized earthquake resistant joints are one option. Where these joints cannot achieve acceptable seismic performance, other options may include providing continuity across the joint(s), 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.

**Part 3 – Design Guidelines for New Pipelines:** The guidelines for new pipelines will be similar in concept to existing pipelines and will be developed in conjunction with several new large-diameter pipeline projects that are planned over the next 5 to 10 years.

**Operations**

The operations component ensures Metropolitan is prepared to respond to all types of emergencies, including earthquakes, so impacts to water deliveries are minimized and interrupted deliveries are restored quickly. This is achieved through its Emergency Management and Business Continuity Operating Policy. This involves IT Disaster Recovery, Business Continuity and Emergency Response operations components. This paper focuses only on the emergency response operations component due to specific steps taken in this area to increase seismic resilience.

**Emergency Response Organization**

Metropolitan maintains a dedicated Emergency Operations Center (EOC) that can be activated at any time to manage Metropolitan’s response to a large disaster, including seismic events. The EOC is equipped with multiple modes of communications and coordinates directly with Metropolitan’s Operations Control Center (OCC) and Security Watch Center (SWC), as well as with numerous external agencies. For example, the EOC would coordinate with DWR and LADWP in the event that one or more aqueducts are damaged by an earthquake on the San Andreas Fault as further explained in the next section.
Metropolitan also has Incident Command Centers (ICCs) located at various sites in the district. These ICCs can also be activated anytime to manage localized emergencies, and coordinate directly with the EOC during a major disaster. Metropolitan also has Damage Assessment Teams (DAT) that can be called upon by the ICCs to conduct investigations at the incident site. The DATs consist of engineers who can assess damage and initiate engineering responses, including recommendations for short-term repair or work-around and potential designs for permanent, long-term repair.

Metropolitan’s emergency response structure follows the National Incident Management System (NIMS) and the State of California's Standardized Emergency Management System (SEMS).

**Emergency Response Training Exercises**

In addition to training emergency response staff on NIMS procedures, Metropolitan regularly conducts emergency exercises which have often been based upon a postulated seismic event. Examples include: “Resilient Grid” (2017), “Desert Shake” (2015), and “Golden Guardian”. (2012). These regular exercises, as well as monthly radio and communications tests with member agencies and other outside agencies, allow Metropolitan to continually improve its readiness.

**Emergency Response Construction Capabilities**

Metropolitan maintains the capability to perform rapid repair of damaged facilities and components such as large pipelines for up to two simultaneous repairs by the La Verne Shops. The Machine, Fabrication, Coatings, and Valve Shops are used extensively to support system-wide routine maintenance; to provide emergency services within Metropolitan, for its member agencies, and for the California Department of Water Resources (DWR); and to perform fee-for-service work that supports its member agencies and the State Water Project. The Fabrication Shop, specifically, can roll pipe on a 24-hour per day basis. In 2015, Metropolitan expanded the Fabrication Shop to enable the fabrication of two pipe sections up to 12 feet (3.7 meters) in diameter simultaneously, and has been developing standardized pipeline repair drawings and shoring drawings to expedite repair operations.

Metropolitan also maintain stocks and material on hand and has its own construction equipment and crews ready to mobilize if necessary. Pre-selected urgent repair contractors provide additional construction support, if needed, in case of an emergency. Maintaining manufacturing and construction capabilities in-house ensures that Metropolitan’s infrastructure is adequately maintained, continues to operate efficiently, and can be repaired quickly if damaged by seismic events.
Reporting

The reporting component involves documenting the SRS and annual reporting of near-term goals and recent accomplishments to Metropolitan’s Board of Directors. This component is aimed at facilitating internal knowledge transfer and increasing collaboration with Metropolitan’s member agencies regarding facility planning and emergency response planning efforts.

Seismic Resilience Water Supply Task Force

The Seismic Resilience Water Supply Task Force component involves Metropolitan’s collaboration with DWR and LADWP to address the unique seismic vulnerabilities of Southern California’s imported water supplies. The two primary objectives of this task force are to 1) enable the three agencies to coordinate emergency response efforts, and 2) identify practical mitigation options for reducing the magnitude and duration of disruptions to the region’s imported water supplies following a large earthquake on the San Andreas Fault.

Conclusions

Metropolitan’s strategy for seismic resilience has evolved over time and benefited from lessons learned from major seismic events. Metropolitan has made significant improvements in the overall seismic resilience of its water system over the past few decades in each of the following key areas: Operational flexibility, water resource diversity, emergency water storage capacity, seismic resilience of existing infrastructure, and emergency response capabilities. Metropolitan has also established a number of near-term goals to further enhance its defense-in-depth approach. The refined SRS approach will ensure long-term efforts remain focused and program goals are clearly communicated to the Board. Metropolitan’s multi-faceted SRS approach may also serve as a template for other water agencies serving within seismically active regions.

References