SEISMIC CONSIDERATIONS

Seismic Considerations for Water Distribution Resiliency in California

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The California Aqueduct system was developed in the 1960s to store water and distribute it to 29 urban and agricultural water suppliers in Northern, Central and Southern California

Water and the apparent ease in which it is conveyed is the foundation of California's urban communities, and water distribution systems are essential lifelines for their survival. These systems are vitally important to respond and recover from significant natural disasters including wildfires and earthquakes. California ratepayers have approved significant investment in the last decade to improve urban water systems' seismic survivability, primarily focusing on water storage and conveyance system vulnerabilities. In 2014, results from new seismic hazard forecasting tools were released which estimate that California is at greater risk than previously thought for large seismic events, specifically in Southern California. Concurrently, the cities of San Francisco, Los Angeles, Oakland and Berkeley have joined the 100 Resilient Cities program, an international movement to make urban communities more resilient. Urban resiliency is defined by this program as "the capacity of individuals, communities, institutions, businesses and systems within a city to survive, adapt and grow no matter what kinds of chronic stresses and acute shocks they experience."[1] Large-magnitude seismic events such as the 2004 Java (Indonesia) and 2011 Tohoku (Japan) earthquakes were acute shocks to urban communities with devastating impacts. California is now investigating potential impacts it may suffer as a result of a large seismic event.

CALIFORNIA'S WATER SYSTEM

In the last century, a network of reservoirs, canals and aqueducts has been developed by federal, state and local agencies to supply potable water to the growing metropolitan communities extending from the San Francisco Bay Area to San Diego. As the communities grew, so did the network of distribution systems.

As shown in Figure 1, these communities receive water through a system of canals and aqueducts that bring water from storage reservoirs located in the Sierra Nevada Mountains or from the Colorado River in the eastern and northern part of the state. These conveyances cross a number of known active faults including the San Andreas, Calaveras and Hayward Faults as well as a significant number of parallel faults. Water is also conveyed through an aqueduct that crosses the seismically vulnerable Sacramento-San Joaquin Delta, founded on a deposit of soft, compressible organic and potentially

Figure 1. California's Water Distribution Systems. Source: Lauder 2014

liquefiable loose and cohesion-less granular soils. These conveyance systems are at significant risk for disruption due to fault movement and seismically-induced ground failures, including ground settlement, lateral slope instability and liquefaction, and flow failures.

The growth of California's urban communities has also put the growing areas themselves at significant risk. For example, the cities of Northridge and Hollywood were areas developed alongside previously unknown faults. Also, portions of the Marina District in San Francisco, which experienced damage during the 1989 Loma Prieta earthquake, were developed on reclaimed land. Land reclamation activities can expand development onto areas with deep, soft and compressible soils or landfill the area by placing loose fills with high liquefaction potential; either activity can amplify seismic ground motions.

NEW UNDERSTANDING OF SEISMIC HAZARDS

In 1971, the San Fernando earthquake registered 6.6 on the Richter scale. It took 65 lives, injured 2,000 people, caused an estimated $505 million in damage and abruptly brought into focus the vulnerability of California's infrastructure to handle moderate seismic events (defined by magnitudes of 6.5 to 7.0).

Since then, efforts have been made to develop methods to understand and forecast seismic hazards. The 2014 Working Group on California Earthquake Probabilities (Southern California Earthquake Center), using the Third California Earthquake Rupture Forecast Model (UCERF3), forecasted that the probability for moderate seismic events in California is lower than previously predicted.[2] However, the probability for large (greater than magnitude 7.0) seismic events occurring in the next 30 years is believed to be significantly greater. These studies were conducted after the 2011 Tohoku earthquake in Northern Japan (9.0 magnitude) and the 1999 Chi-Chi earthquake in Taiwan (7.6 magnitude); two quakes that changed the understanding of large seismic events.

New studies have also found that Northern California's Hayward and Calaveras Faults, which extend through the cities of San Jose, Fremont, Oakland and Berkeley, are believed to be continuous and able to generate a large 7.3 magnitude earthquake.[3] In addition, the probability of a magnitude 7.8 seismic event on the San Andreas Fault in Southern California is now believed to be approximately 50 percent greater than previously believed.

Recognition of increased seismic risk is not just limited to California. Seismologists now believe that seismic risk is greater for both Oregon and Washington. The Cascadia Subduction Zone that extends along the West Coast from Northern California to Victoria Island is very similar to the subduction zones in Indonesia and Japan that recently experienced large seismic events. The Cascadia Subduction Zone is currently estimated as being able to generate magnitude 9.0 seismic events; therefore, Oregon and Washington are also assessing their infrastructure vulnerabilities.

Southern California contains 20 million people, and the City of Los Angeles has been ranked by a major reinsurance company as having the fourth-highest seismic risks in the world after Tokyo, Jakarta and Manila. Los Angeles gets 88 percent of its water from outside its region, and all of its water must cross the San Andreas Fault. If a large-magnitude seismic event occurs, it is projected to damage all of the city's aqueducts and take an estimated 18 months to restore the system. The Los Angeles Department of Public Works (LADPW) has an estimated six months of local storage capacity. LADPW also manages over 7,000 miles of pipelines; some of this distribution system is 100 years old.

- Cardno 2015

INFRASTRUCTURE PERFORMANCE HISTORY

In 1994, a 6.7 magnitude Northridge earthquake caused significant damage to the Los Angeles regional water supply system. According to O'Rouke and Toprak, the strong ground shaking "caused damage at 15 locations in the three transmission systems providing water from Northern California, 74 locations in water trunk lines (nominal pipe diameter > 600 mm), and 1,013 locations in the Los Angeles Department of Water and Power (LADWP) distribution pipeline network".[4] Figure 2 is an Associated Press photograph showing disruption of the gas and water systems in the Northridge earthquake.

A study by Eidinger and Davis in 2012, for the Water Research Foundation, looked at damage to water infrastructure from four different earthquakes:

- 2010 Chili earthquake (magnitude 8.8)
- 2010 Christchurch, New Zealand, earthquake (magnitude 7.3)
- 2011 Christchurch, New Zealand, earthquake (magnitude 6.1)
- 2011 Tohoku earthquake (magnitude 9.0)

The authors found that the bulk of the total earthquake damage to water systems, and the resulting water outages to customers, was due to the failure of hundreds to thousands of smaller diameter distribution pipes in zones of infirm ground.[5] They also found that existing buried pipe infrastructure remains highly susceptible to damage due to earthquake-caused ground failures (liquefaction, landslide, surface faulting and other effects). Another factor affecting water distribution systems included the loss of large diameter distribution pipelines mainly due to pipe joint slippage, damage to water treatment systems, and loss of power to pumping facilities. By way of comparison, the moderate 6.0 magnitude 2014 South Napa earthquake that occurred in Northern California caused 144 small-diameter water main breaks and damage to only one large diameter water distribution pipeline.

With the current understanding of water system performance and seismic susceptibility of their systems, the West Coast metropolitan areas recognize they must focus on water system resiliency, telecommunication and emergency response infrastructure.

CAUSES OF PIPE FAILURES

California's local water distribution systems are complex. They have been constructed over the last century using varying materials and construction techniques, and many of these systems are approaching the end of their design life. Seismically-induced ground movement applies additional axial and compressional forces on a pipeline, prompting large stresses that can cause pipe splitting, bursting or collapse (material failure), or inducing soil/pipe movement that results in shearing or pipe joint pullout. Pipe distress, as a result of seismically-induced ground movement, can be grouped into three broad categories:

- Lateral Offset
  - Transverse offset (shearing or connection failure) due to fault rupture (vertical and/or horizontal)
  - Offset from rigid fixed connection (connection to bridge abutments or other structures)
- Lengthening and Rotation
  - Oblique fault offset elongating (pulling) the pipe
  - Settlement induced pipe sag
  - Flotation/heave
  - Lateral earth movement (lateral spreading or slope failure)
- Compression
  - Pipe displacement into fixed point (pipe bend or structure penetration)

Structural factors that could have an impact on pipeline performance during seismic events include:

- Age of materials (fatigue and corrosion)
- Material type (strength)
- Pipe joint type and spacing (mechanical connection or welded)
- Trench installation method (configuration and backfill)
- Depth of installation (applied loading)
- Supporting soil conditions (applied loading)

Seismic ground factors that could have significant effects on the integrity of pipelines include:

- **Fault offset.** The magnitude of ground movement due to fault offset depends on the specific site conditions and fault characteristics. Ground displacement can be abrupt when crossing the actual fault plane with lateral or vertical offset ranging from a few inches to tens of feet in a relatively short distance. Ground displacements can be less abrupt in areas where the faults are overlain by a soil. Fault offset can propagate through a thin overburden soil, or as the overburden soil layer thickens, the displacements occur with the shearing of the soil. In areas where the faults are overlain by deep soil deposits, near surface ground deformations may be relatively minor.
- **Dynamic slope instability (landslide) in natural and manmade slopes.** In general, seismically-induced slope instability is a function of intensity of ground shaking, slope geometry (heights and inclination) and the composition and strength of the earthen materials within the slope.
- **Dynamic densification and/or liquefaction induced settlement.** Dynamic densification can occur in loose, dry and relatively clean coarse-grained (cohesion-less) soils, which results in particle redistribution (densification) from strong ground shaking. Liquefaction can occur in loose, saturated and relatively clean cohesion-less soils where strong ground shaking induces an increase in pore water pressures within the soil deposit. Dissipation of the pore pressures result in densification of the soil deposit. Strong ground shaking can induce large excess pore pressures that can result in an associated loss of soil strength. The loss of strength can result in lateral slope movement, discussed later. The amount of settlement is a function of the ground motion magnitude and both the density and thickness of the cohesion-less deposit, among other factors.
- **Ground lurching and associated ground cracking.** Ground lurching occurs adjacent to a steep vertical slope face that shifts (“lurches”) toward the unsupported vertical face during shaking. This can result in surface cracking adjacent to the slope and/or slope failure.
- **Lateral slope movement due to liquefaction (lateral spreading).** Strong ground motion can result in development of large pore pressures with an accompanying strength loss. Based upon the site geometry, the strength loss may induce lateral slope movement ranging from a few inches to many feet, commonly referred to as a flow failure. Liquefaction-induced slope movement can occur in gently sloping ground toward a free face, such as a creek or channel.
- **Soil-structure interaction.** When a structure’s response or movement doesn’t match the soil’s response to seismic shaking, facilities supported by or connected to the structures can get damaged.

SYSTEM RESILIENCE BY PREVENTING PIPE FAILURES

In order for water distribution system pipes to be functional after a seismic event, the pipe needs to be able to accommodate movement. Depending on structural factors or seismic ground factors at a given location, this capacity for movement can range from a few inches to several feet. However, preventing all pipe failures is not realistic nor achievable. The goal of a resilient water system is to maintain acceptable distribution capacity immediately after an event by limiting the number of breaks, avoiding breaks at key locations and restoring damaged infrastructure and water services to full capacity quickly.

The City of San Francisco is evaluating deployment of a system of above-ground pipelines to quickly restore both water and natural gas services. The East Bay Municipal Utility District (EBMUD) recently installed a deformable vault on the Mokolume Aqueduct that will expand with lateral movement.[6] The City of Los Angeles is focusing on upgrading pipelines in the most vulnerable areas (for instance, using high-density polyethylene pipe for its aqueduct where it crosses the San Andreas Fault) and using more resistant pipe material (for instance, importing technology from Japan for more earthquake-resistant pipe).

In highly active seismic areas, or areas where seismic forces are considered more severe, these pipe types can be used in conjunction with mechanical isolation joints capable of accommodating offset, rotation and lengthening. Another technique for accommodating movement is use of geotechnical or geostructural improvements. Such measures can include designing a trench and trench backfill configuration to allow the pipe to move within the trench backfill and designing isolation vaults or structures that can deform and accommodate movement. Ground improvement techniques, such as compaction grouting, densification and soil modification, can also be performed to reduce the magnitude of offset and settlement in order to protect against damage due to liquefaction. However, use of specialized pipe types or geostructural improvements can add significant costs to installation of water distribution systems, so specific studies need to be performed to demonstrate the benefits. Nevertheless, these techniques have proven effective in reducing the number of pipe failures, and ground improvement is a sound mitigation technique.

Upgrading California's pipeline distribution system is currently in the pilot study phase with the cities of Los Angeles, San Francisco and Palo Alto installing earthquake-resistant ductile iron pipe (ERDIP). Manufactured by Kobata Corporation and imported from Japan, this segmental type of pipe incorporates a joint locking mechanism to prevent pipe separation. Joint locking technology was initially developed in Japan in the 1980s and is part of Japanese industry standards. Observations made after the 1995 Kobe earthquake found that pipes with joint locking mechanisms were not damaged in the earthquake, which led to the development of Kobata's current joint locking mechanism design. In their 2012 study, Eidinger and Davis did not find any evidence of ERDIP breaks from the 2011 Tohoku earthquake.[7]

As shown in Figure 3, the pipe is a segmented design that provides flexibility, allowing up to 1 percent axial movement and up to 8 degrees rotation to deal with the strains associated with earthquakes, landslides and temperature changes. The pipe lengths bolt together via a rubber flange with its zinc-coated lengths forming an interlinking system that will rotate, flex and not pull apart under pressure. The locking joint design allows the pipe to move with the soil until the locking joint is engaged, which then mobilizes the next segment of pipe like a chain allowing the pipe to deflect with the soil. Due to the increased cost of the ERDIP over standard replacement pipe, installation of the pipe is being limited to strategic pilot projects critical to the city's water system and located in areas with high seismic risk. This includes a pilot project where 6,500 feet of ERDIP will be installed in streets surrounding the Northridge Hospital Medical Facility. This area is especially significant, as it is close to the epicenter of the 1994 Northridge earthquake. The project is expected to be completed in December 2015. Upgrade of the entire Los Angeles system is planned to be completed over the next 20 to 30 years.

SYSTEM RESILIENCE THROUGH ADAPTIVE MANAGEMENT

It is anticipated that a large seismic event will cause severe delivery system disruptions. Figure 4 highlights four critical locations where Los Angeles Basin conveyance systems cross the San Andreas Fault. The potential loss of water supply aqueducts would be catastrophic for San Diego, Los Angeles and other communities, resulting in complete cutoff from their existing water supplies. Outages of up to 18 months have been forecast while existing local water storage capacity is estimated to be limited to six months.

In response, San Diego developed its Emergency Water Storage Project that includes enlarging and strengthening the Olivenhain and San Vicente dams and related pipelines and pump stations, specifically to increase the resilience of its water system. The improvements at Olivenhain Dam also include a pump storage project to generate electricity that offsets the cost of the program.

Los Angeles, San Francisco and EBMUD have upgraded and expanded their water storage and pumping facilities. EBMUD has retrofitted its Mokolume Aqueduct to have locations of controlled breaks, should it experience severe offsets, and has planned local storage with sufficient capacity to endure during the time needed for restoration of service.[8]

Additionally, alternative water use technologies are being explored. The City of San Diego has invested in a micro filtration and treatment pilot program to treat its tertiary treated wastewater for reuse as potable water. Once the process is approved, the treated water will be pumped back into the reservoirs for fresh water blending to augment the water supply. California cities are also evaluating the use of recycled water and possible desalination of sea water for use in emergency response firefighting to save potable water supplies.

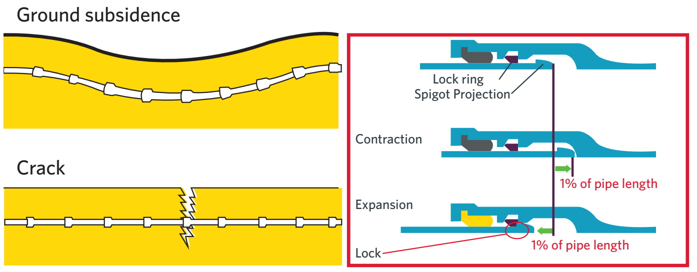

Figure 3. ERDIP Locking Joint Design.
Source: Haddaway 2015/Kabota Corporation

CURRENT CALIFORNIA INVESTMENT

Water agencies in California have begun to invest billions of dollars to evaluate and begin improving the seismic resiliency of their water supply, storage and distribution facilities. For example:

- San Francisco: In 2001, the San Francisco Public Utilities Commission initiated the Water System Improvement Program (WSIP) to increase water supply reliability, delivery reliability and seismic reliability. The $4.5 billion program includes about 40 regional projects designed to reduce risk from seismic events and to improve system reliability by providing redundancy for facilities that convey water from the Sierra Nevada to the Bay Area. This also includes about 40 projects within San Francisco designed to enhance reliable water deliveries, update outmoded equipment and rehabilitate aging infrastructure to withstand seismic events. It is one of the largest water infrastructure programs in the country and is about 90 percent complete.
- Oakland: Seismic resiliency has been a top priority for EBMUD since 1994 when the utility adopted a 10-year, $189 million Seismic Improvement Program (SIP) for its water distribution system.[9] EBMUD's seismic improvement efforts have continued since the completion of the SIP, including the investment of $39 million into seismic improvements of the Mokelumne Aqueduct.
- Los Angeles: In December 2014, Los Angeles Mayor Eric Garcetti announced a plan called Resilience by Design, aimed at reducing the city's earthquake vulnerabilities.[10] The goal is to be proactive with respect to seismic design. The plan embraces fortification of the city's water supply, including:
  - Development of an alternative system for firefighting
  - Fortification of the Los Angeles Aqueduct crossing the San Andreas Fault
  - Fortification of other aqueducts crossing the San Andreas
  - Fortification of water storage (seismic resiliency of LADWP dams)
  - Increase in local water sources (stormwater capture, water conservation, water recycling and remediation of contamination in the San Fernando Basin groundwater)
  - Development of a network of resilient pipelines
  - Development of a statewide seismic resilience bond measure

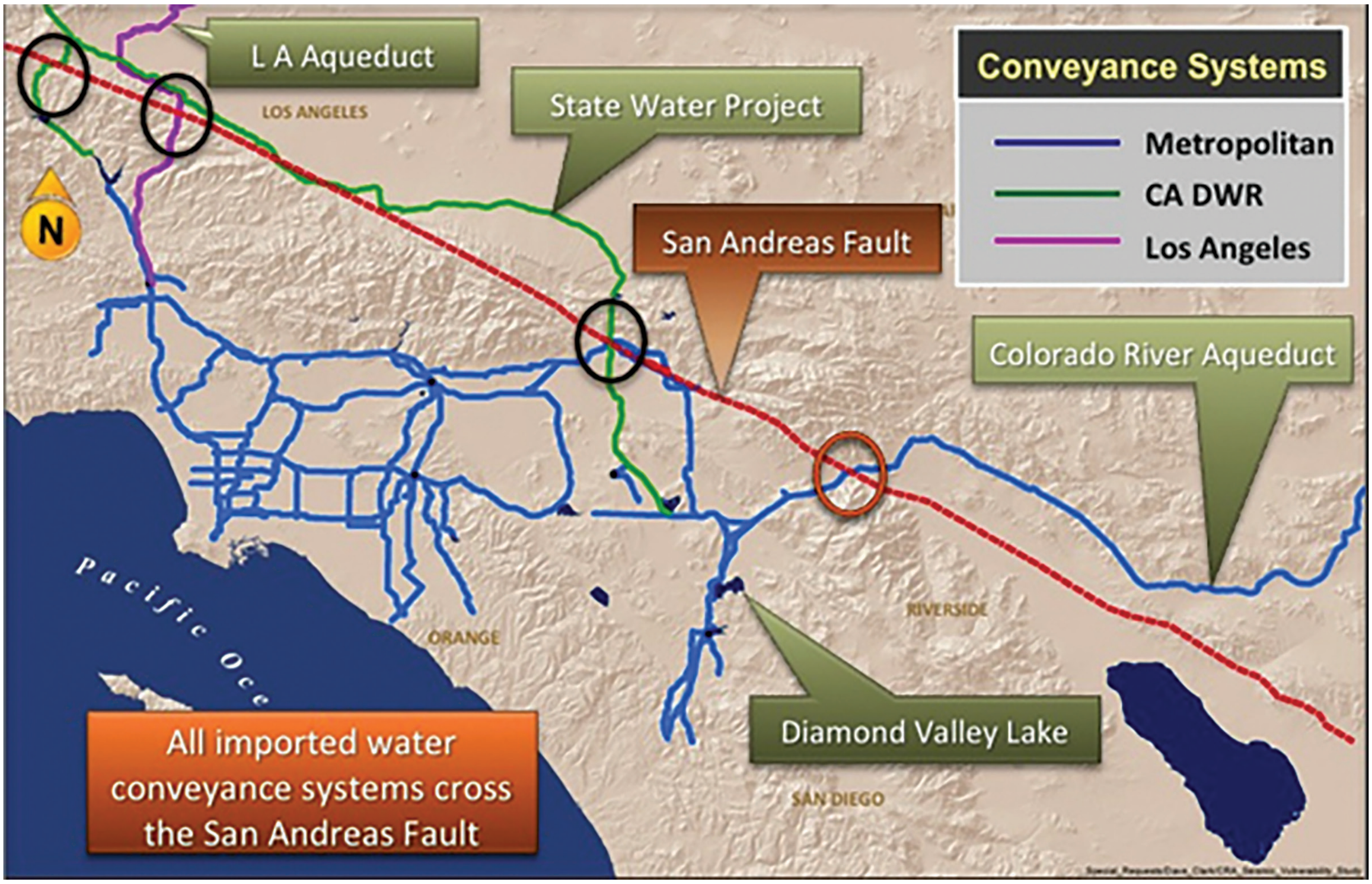

Figure 4: Aqueduct Fault Crossings. Source: Totten 2014

CALIFORNIA'S FUTURE

Communities in California are dependent on aqueducts and pipelines to provide clean, potable water. Pressures due to long-term drought make limited fresh water sources even more valuable. Growing populations increase reliance (and dependence) on pipelines. A resilient water distribution system is critical for people living in a seismically active area. California utilities and government entities have recognized this need for resilience, and water resiliency projects are underway statewide.

Although funding is not limitless and system upgrades often must take place over the course of years, renewed focus on resiliency, adaptive management and construction of strategic projects is resulting in considerable progress. While we cannot predict earthquakes and the associated damages, it is recognized that large-magnitude earthquakes will occur in the future and challenge California's pipeline systems. Because these water supply systems are critical infrastructure, the systems must survive earthquakes, or must be capable of being restored quickly in the aftermath of earthquakes. This will enable urban areas to survive and continue to thrive.

As summed up by Councilmember Mitchell Englander, who represents the Los Angeles 12th District that includes Northridge, on the 21st anniversary of the Northridge earthquake, "There is no life without water, and access to clean, potable water after a major earthquake will make the critical difference in how many lives are saved and how quickly our City rebounds."[11]

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