Seismic Practices to Improve Water System Resilience

C.A. Davis[1]

[1] *Geotechnical Engineering Manager, Department of Water and Power, Los Angeles, California.*
Email: Craig.Davis@ladwp.com

ABSTRACT :

The seismic resiliency of a water system dictates the seismic resiliency of an entire urban region. As a result, it is critical for water systems to rapidly recover from earthquake impacts. Unfortunately, most water systems are not designed or constructed to withstand earthquake forces. As a result, there is a strong need for water systems to manage seismic programs and implement seismic practices. The purpose of a water system seismic program is to ensure the safe provision of water following an earthquake. This purpose is realized through six goals, described in the paper, intended to make resilient water systems through reduced failure probability, reduced consequences from failures, and reduced time to recovery. This paper summarizes practices implemented by operational Water Systems worldwide to improve their seismic resilience and identifies several areas of needed advancement in this young field of practice. The information is useful for other infrastructure systems.

KEYWORDS: Water System, seismic improvement practices, resilient, seismic program management

1. INTRODUCTION

The seismic resiliency of an urban region (i.e., the ability to recover from an earthquake with least amount of negative impacts) in many, if not all, locations worldwide is directly related to the seismic resiliency of the local water systems. A recent study on the potential impacts of a San Andreas Fault magnitude 7.8 earthquake in Southern California identified water related issues to dominate the regions' ability to recover from the scenario earthquake (Jones et. al., 2008). The major water related concerns include storage, supply transmission, water system damages, coordinating regional emergency response, emergency assistance (i.e., mutual aid, inter-system connections, etc.), fire following earthquake and limited water to extinguish, water supply for critical facilities, long restoration and recovery times (some areas will take up to 6 months to restore water service), restoration materials, and the short and long term economic impacts resulting from interrupted water service. The total estimated economic loss from this scenario exceeds $200 billion. More than half the business interruption losses are from the loss of water services; combined with fire losses, the water related economic impacts account for nearly half (just under $1 billion) of all the losses. The water related issues exposed in this study generally apply to other urban centers around the world, and are repeatedly experienced when disastrous earthquakes occur, such as the 1995 Hyogo Ken Nunbu Earthquake in Kobe, Japan, and the 2008 Wenchuan Earthquake in China's Sichuan Province. The problem is amplified realizing that most water systems are not designed to withstand earthquake forces.

In the past few decades there has been a movement, mostly among the largest water systems in the most highly seismically regions of the United States and Japan, to improve water system seismic performances. For the most part, the practice of preparing a water system to properly operate after an earthquake initiated following the 1971 San Fernando earthquake in Los Angeles, California and has progressed relatively slowly, evidenced by the fact that most water have not evaluated their ability to perform after an earthquake. The focus has been mainly on strengthening specific components (tank, pump station, purification plant, pipe segment, etc.) within the system to withstand earthquake effects without significant consideration on how the system as a whole may perform. More recently a systems approach has been incorporated into solving the problem.

This paper summarizes practices implemented, and other practices identified as needing to be implemented, by operational Water Systems worldwide to improve their seismic resilience. Water system seismic resilience is the ability of a water system to recover from an earthquake while mitigating and containing earthquake effects with minimal social disruption. Waterworks organizations globally are found to have similar seismic improvement interests and deal with similar problems in implementing seismic programs. The information presented herein was collected by the author through experiences in working on water system seismic improvements (e.g., Lund and Davis, 2005) with significant influences by waterworks organizations in the United States and Japan derived from presentations, discussions, interactions, and requests for information through a series of workshops sponsored by the American Water Works Association Research Foundation and the Japan Water Works Association (AWWARF 2003, 2007; JWWA 2001, 2005). Waterworks organizations in Great Britain, Taiwan, Central America and other countries as well as other engineering associations have influenced the understanding of worldwide water system seismic practices described herein. This paper does not attempt to quantify water system resilience, but instead focuses on practical applications implemented by operating waterworks organizations intending to improve seismic resilience. The paper also identifies several areas of needed advancement. The information presented is useful to other infrastructure systems.

2. WATER SYSTEM SEISMIC PROGRAM PURPOSE AND GOALS

The purpose of a water system seismic program is to ensure the safe provision of water following an earthquake. This purpose is realized through the following goals:

- Providing adequate post-earthquake water supply throughout service area,
- Reducing earthquake damage to facilities,
- Ensuring minimum level system functionality and rapid system recovery,
- Achieving a rapid emergency response,
- Accomplishing a well planned, cost-effective, and publicly responsible seismic program to ensure public safety, and
- Continually developing and improving earthquake disaster prevention capabilities.

Within these goals reside the characteristics of resilience: reduced failure probability, reduced consequences from failures, and reduced time to recovery. There are many facets associated with fulfilling each goal, only some of which will be reviewed herein, including common global problems encountered when attempting to implement water system seismic programs. The following sections provide an overview of items to consider for each goal. The goals and their descriptions are not in any priority order nor considered independent; they must be accomplished in an integrated approach to develop a water system that can perform adequately following earthquakes. The items used to describe each goal are grouped only due to their affinity and natural relationship with a particular goal, but in many cases the items serve to support all the goals.

2.1. Providing adequate post-earthquake water supply throughout service area

In order to meet the purpose of a water system seismic program, an adequate post-earthquake water supply must be provided throughout the service area. Generally the term “adequate” means that a minimum supply is available to meet critical sanitation, public health, and fire fighting needs in relation to rational criteria usually determined in relation to performance criteria. Performance criteria is described in later sections of this paper. The supply adequacy may not be the same in different portions of the service area (i.e., total area served), and may vary with different water systems. Water demands for normal business operations are generally not of concern immediately following a seismic event, but are an important part of the total urban resiliency and therefore must be met as soon as possible after the minimum critical supply needs are met. Also, the supply may be provided in non-conventional ways (i.e., not necessarily using the existing pipe distribution network).

Many different strategies may be implemented to accomplish this goal. However, all strategies must include a forecast of expected water outage times. The outage forecast may not be the same in different parts of the service area, and must consider potential damage to the distribution network and supply transmissions, seismic vulnerability of purification/treatment and storage facilities, and expected performance levels for different potential earthquake scenarios. From the forecast outage time, an estimate can be made of the needed post-earthquake water supply accounting for the supply source outage time, water loss through broken pipes and damaged facilities, water usage in different parts of service area, and critical facility needs. Strategies for helping to assure water availability throughout the service area include:

- Installing infrastructure to isolate and/or store water for post-earthquake usage in order to assure water availability throughout system. This may include isolating pipes for use as underground emergency storage tanks similar to the Kobe Waterworks Bureau large capacity transmission main (Matsushita, 1999) and/or installing separate emergency water storage tanks and cisterns, accessible within a limited distance from every point within service area, as is done in many Japanese Cities.
- Isolate tanks and reservoirs to keep from draining.
- Evaluate reliability of water supply from sources (i.e., wholesale agencies, aqueducts, storage reservoirs, etc.) and improve as necessary.
- Prepare for mobile water deliveries and temporary water supply systems.
- Develop and install emergency backup connections to other water systems (inter-system connections).

Many times the strategies are formulated in collaboration with fire departments, hospitals, and other emergency response organizations dependant upon water. It is important to discuss strategies with user organizations and communities to help determine the overall best approach. For example, it may not always be best for firefighting or long term recovery to automatically isolate water in storage facilities to keep water from leaking out of damaged pipes; this may have too severe an impact on firefighting or pipe repair times. Additionally, it is important to coordinate with the costumers for emergency preparedness and supply needs. The customers must understand that the water utility may not be able to help all customers immediately after an earthquake disaster; the community must have minimum self-sufficiency capability without system water supplies. As an example, Southern California is advising residents to store one gallon of water per person per day for 14 days in preparation for a large event on the San Andreas fault (Jones et. al., 2008).

Alternative post-earthquake water deliveries, such as bottled water, portable tanks, water trucks, distribution facilities, etc., may be utilized to reduce impacts from lack of stored emergency water. These alternate delivery forms are typically required in some areas immediately after a seismic event and should be planned as part of the overall supply strategy to ensure adequate supplies, distribution facilities, and personnel are available.

Post-earthquake system operation requirements need to be established using system performance as a priority, instead of focusing on individual components. Critical aspects include limiting water loss from damaged facilities and preventing secondary disaster impacts (e.g., fire, disease, etc.) following an earthquake. Further, the identification of system needs regarding post-disaster potable and non-potable water supplies (drinking and sanitation vs. firefighting) must be made. Broken pipes require the water to be considered non-potable and damaged treatment facilities limit the ability to treat raw water. Decisions must be made on the appropriateness of providing non-potable water in the distribution system. Generally, providing non-potable water to support firefighting is acceptable, but water purification notices are issued.

2.2. Reducing earthquake damage to facilities

All existing water system facilities and components, including dams, reservoirs, tanks, purification plants, pumping stations, maintenance buildings, office buildings, pipelines, etc., should be evaluated and where necessary strengthened and upgraded to provide the seismic resistance necessary to meet the seismic program goals. In addition, any new facility should include seismic resistant design. Seismic evaluations for any facility should include impacts from transient and permanent ground movements. Methods used to reduce earthquake damage to the previously described facilities are beyond the scope of this paper.

Pipelines having poor earthquake resistance generally include old pipes and those susceptible to corrosion. Cast iron pipes exist in many modern water systems, but is known to be one of the most vulnerable to earthquake damage. Replacing old and vulnerable pipes with more seismically resistant and corrosion resistant pipes reduces damage and can improve post-earthquake network performance. Inadequate maintenance reduces integrity and increases a facilities' vulnerability to earthquake damage. Therefore, providing adequate and continued maintenance for pipelines and other facilities helps safeguard against seismic damage. Installation of corrosion protection systems extends facility life and helps reduce earthquake damage. Designing pipeline connections to structures, and incorporating flexible joint connections, also reduces earthquake damage.

2.3. Ensuring minimum level system functionality and rapid system recovery

The minimum functioning level a system can operate to meet the seismic program goals is established through defined performance criteria. Performance criteria describes the intended operational performance level the water system is expected to achieve in a post-earthquake disaster situation and is established by defining a target performance level for a hazard level. For example, a performance criteria may define a water system to provide 50% of all service within four days and 100% after thirty days following a magnitude 6.5 earthquake on a specified local fault. The criteria may include probability relationships; the above example could specify having an 80% reliability. A survey conducted by the author to determine what types of performance criteria have been established by waterworks organizations (AWWARF, 2007) revealed a wide range of practical implementation, and established criteria depends mostly on local preference. Recently the Japan Water Works Association has established performance criteria that are being implemented in many waterworks organizations in that Country with a goal of returning the water system to full service within 30 days following an earthquake.

In order to assess if a water system can meet the defined performance criteria, the system, along with the geologic hazards (landslides, liquefaction, fault movement, etc.), must be modeled. An evaluation using the model can assess the potential earthquake damage and resulting system response. Analysis results can be compared to determine if the system meets the performance criteria, and if not which portions of the service area requires improvements. Modeling can range from very crude assessments and estimates focused on small portions of a water system to very complex evaluations. Most evaluations are limited in extent and complexity. However, some water systems (e.g., East Bay Municipal Utility District, Oakland, California) have performed analyses of primary transmission pipes for their seismic improvement program. The Los Angeles Department of Water and Power is currently working with Cornell University to develop state-of-the-art capabilities to model all facilities, including distribution pipe, which can be applied to any water system (Davis et. al., 2007).

Water system seismic vulnerabilities can be identified through evaluations and inspections. Results of modeling and vulnerability assessments will aid in preparing damage estimates. Damage estimates are useful for determining the expected cost and time to make post-earthquake repairs. Geographic Information Systems and fragility relationships are useful tools for making estimates. Some waterworks organizations find it useful to have results presented in terms of a probability of damage and with an estimate of the probability for continued operation resulting from the estimated damage. An estimate of overall community and customer impacts from water system damage and supply outage, along with total post-disaster community recovery, is very useful to help understand and justify needed system improvements and reconstruction to meet performance criteria. Mitigation strategies to reduce component damage and effects on system functionality include:

- Provide seismic resistant power supply (normal and backup).
- Implement block distribution system.
- Provide system redundancy to expected damage areas.
    - Water storage (as much as possible)
    - Supply and distribution pipelines
    - Utilize multiple water supply sources/points
- Provide isolation capabilities within the system, consider installing remote valve operations.
- Ensure continued and uninterrupted system operation in lightly damaged and undamaged regions.

The last item deals with the concept that, at least in some water systems, localized damage may provide a wider impact and limit the ability to supply water in areas having little to no earthquake damage. Overall resiliency is increased when the number of impacted customers is reduced. As a result, it is best, and easiest to manage, when the water service outages are limited to the earthquake damage region. As an alternative to mitigating damage, crews can be maintained to repair damage following an event, as described in the following section.

The time required for total system recovery is reduced by mitigating the known seismic vulnerabilities. Prior to mitigating, concerns related to known vulnerabilities should be incorporated into emergency response plans. This could include stockpiling specific repair supplies and deploying inspection teams following an event. System recovery time is reduced with increased damage assessment capabilities; therefore, the developing and incorporating of real-time damage assessment capabilities can greatly reduce system recovery time.

The model evaluation and system component field inspections should be revisited periodically and compared with new knowledge gained since last system evaluation and inspection.

2.4. Achieving a rapid emergency response

Employing an adequate number of well trained crews is one of the most critical aspects for achieving a rapid emergency response. A crew is defined herein as an individual staff employee and includes people who work in all the professional and non-professional trades, in the office and in the field, needed to plan, analyze, design, construct, operate, and maintain a water system. The crew size and training needed is dependent upon the water system size and the vulnerabilities. A resilient water system must at least maintain adequate crews to perform normal operation and maintenance under non-emergency conditions. This provides a minimum number of crews to respond to a disaster and also helps maintain the system, which as explained above helps reduce earthquake damage. On-the-job training (i.e., knowing your job) under normal operations is the best way to provide the minimum preparedness level for making emergency repairs. Additional training for emergency preparedness procedures and how to handle specific vulnerabilities is also critical for rapid system recovery.

In addition to normal crews, a forecast of the crews needed to ensure adequate response and recovery is needed. This forecast can be made using results of damage estimates explained in the previous section by estimating the time needed to repair the damages and the total time to complete repairs needed to achieve the performance criteria. If the crews maintained for normal operations are not adequate to achieve the performance criteria, additional crews may be necessary, or seismic improvements must be performed to reduce the emergency crew size. The emergency crew size must account for limited staff availability immediately after an earthquake. It is generally difficult to justify sustaining additional crews in preparation for an emergency. Therefore, many waterworks organizations rely on mutual aid and mutual assistance from other organizations; this requires agreements to be made in advance. Some organizations develop community support groups and train them for system operations assistance. However, experience shows that outside assistance does not provide the same repair efficiencies as existing staff, due to the assistance being unfamiliar with the damaged system and the need to have existing crews help lead the assisting crews. Emergency crew size requirements are useful for justifying the need to maintain adequately sized crews for normal operations. Similar estimates and justifications can be made for materials and equipment. A system repair and operation plan can assist crews in preparing for expected damage. This plan should include the stockpiling of materials, supplies, and equipment; establishing contracts for materials, equipment and construction support; and establishing sites to disperse material stocks, personnel, and equipment throughout the service area.

Emergency preparedness and response plans are also a critical component for achieving a rapid emergency response. It is beyond the scope of this paper to thoroughly describe details of emergency preparedness and response plans, but some aspects include:

- Coordinate emergency support with other cities and water utilities
- Incorporate community emergency planning
- Establish a mutual aid scheme (formal and informal relations with other organizations)
- Coordinate post-earthquake response with municipal department and emergency service agencies (e.g., fire, police, city, county, state agencies)
- Prepare to provide food and water rations to repair crews
- Develop damage assessment teams (with pre-assigned reporting location)
- Prepare plans for communicating damage assessment and dispatching crews to damaged facilities
- Prepare plans for communicating water system problems to the community in a disaster

The emergency preparedness and response plans should also provide for periodic disaster prevention training, in collaboration with other cities and agencies, and annual emergency drills including mutual assistance. Further, vulnerability assessment tools, described in the previous section, in combination with real-time earthquake parameter and damage assessment data can be utilized to simulate emergency drills for "real-time" emergency response planning. These tools can also assist in focusing post-earthquake activities.

2.5. Accomplishing a well planned, cost-effective, and publicly responsible seismic program to ensure public safety

Developing and managing a seismic program is essential to creating a resilient water system. There are many aspects of a seismic program, described throughout this paper, that must be consistently managed. This section focuses mostly on managing and administering a seismic program. An important governing aspect is to establish seismic program objectives and relate the objectives to performance criteria. Possibly the most important aspect for ensuring the seismic program can be accomplished is to establish a management strategy for implementing the seismic program. The management strategy must include cost, schedule, resources, prioritization schemes, and other management concepts in addition to realistic goals, in relation to priorities, for what can be implemented and when. The seismic program also needs a risk management structure to provide a way to systematically manage the uncertainty in the seismic program and the earthquake impacts on water system operations to increase the likelihood of meeting the performance criteria. Matsushita (2003) provides a very good overview and risk management approach.

After vulnerability studies have been performed and mitigation strategies have been identified, as described in previous sections, cost-benefit analyses should be performed. Cost-benefit analyses compare estimated costs for infrastructure improvements with cost savings for making the infrastructure improvements. It is important to identify the true damage costs resulting to the community if improvements were not made. Consideration of community impacts is important for justifying mitigation alternatives because in many cases the benefit when only considering the infrastructure does not justify the mitigation cost. Using a critical supply transmission pipe as an example: A single transmission pipe, providing all emergency water to a large urban area, passes through a highly liquefiable site and with a high level of certainty is expected to sustain great damage in a design earthquake scenario; The cost to reroute the pipe is \$500,000 and the cost to repair the earthquake induced pipe damage is \$30,000. From this it is clear the mitigation is not warranted when considering only the infrastructure (no one can justify spending \$500,000 today to save \$30,000 in the future). However, following the earthquake the pipe repair will take at least four weeks to complete and without the pipeline the large urban area will loose all water storage within one day, with no other source of replenishment; thus, the area has no significant ability to sustain sanitation, public health, or fight fires following a major urban disaster for at least one month. Community impact estimates include the probability of a conflagration destroying \$100,000,000 in structures and killing 100 people if the pipe is out of service and no serious conflagration or death if the pipe remains in service. Including the community impact costs clearly justify the pipe mitigation. This hypothetical example shows how cost-benefit analyses can provide an economic justification for improvements to managers, elected officials, community leaders, customers, and others while showing the water organization is trying to be fiscally responsible. Cost-benefit analysis is also a useful tool for comparing mitigation alternatives.

As a part of selecting mitigation strategies to implement, a cost loaded schedule must also be developed to determine the timeframe the improvements will be completed. The seismic program manager can use this to achieve a multi-year fiscal commitment (e.g., 10 year financial plan) with adequate funding for the program. Lack of commitment from all stakeholders will likely result in the inability to implement the improvements needed to make a resilient water system. All those involved must understand that a proper seismic improvement program requires a major investment over long periods of time. For example, the East Bay Municipal Utility District (EBMUB) in Oakland, California recently completed a 10-year program, Kobe Waterworks Bureau (KWB) is progressing with their program that initiated over ten years ago, and the Los Angeles Department of Water and Power (LADWP) has a nearly continuous program where seismic improvements have been implemented for at least the past thirty years and will continue in the foreseeable future (Lund & Davis, 2005). These organizations implement their programs using different budgeting methods. The LADWP incorporates components of their seismic improvements into their over all capital budget, EBMUB created a separate section to manage and implement their 10-year Seismic Improvement Program, KWB seems to incorporate aspects of both methods to implement their program. Proper program management includes infrastructure and post-earthquake response and recovery costs. Program funding may come from bond sales, water revenue, government grants and subsidies, insurance, taxes, and other sources.

In developing and implementing a seismic program it is important to communicate with customers, and the public. Inform customers of seismic issues including risk of earthquake damage, true costs of improvements, damage costs to system and community, and all system benefits from improvements. Get their input and understand the customer's needs and interests. Gain customer support and acceptance of projects and programs and keep appraised of social changes and demands. Prior to working with the community, communicate seismic issues with managers, politicians, elected officials, board members, and other decision makers. Keep them appraised of progress, important issues as they arise, and community input.

Establish a plan for performing work to improve facilities and system performance (design, construction, emergency response, etc.). As part of the plan prioritize seismic improvements to be made and coordinate with other system improvements and upgrades (e.g., deteriorating facilities, water quality improvements, etc.). Incorporate a multihazard approach by coordinating seismic issues with needs for other hazards (e.g., flood, security, wind, water quality, etc.). Gain multiple benefits where possible.

2.6. Continually developing and improving earthquake disaster prevention capabilities

Water system seismic practices encompass developing fields that are not yet fully understood. As a result, it is important for waterworks organizations to encourage education, training, and knowledge exchange through:

- Learning from past earthquake experiences,
- Learning from other water organization experiences,
- Networking with others who are working on water system seismic aspects,
- Training managers, engineers, operators, and field personnel on seismic issues,
- Providing staff development.

It is equally important for waterworks organizations to perform engineering development and research activities related to water system seismic performance. In this regard, practicing water utility organizations must: (1) foster the transfer of information between organizations in their own and in different countries in the development of water system seismic practices, and (2) interact with academic researchers who are familiar with waterworks industry practices to foster the learning and discussion of water system practitioners, and to also provide an opportunity for academic researchers to learn from practitioners and identify where industry research is needed. One of the most valuable and practical activities that can easily be performed is the development of case studies from past earthquakes on:

- Actual past water system performances
- How utilities responded to their disaster prevention plans
- How crews are dispatched and respond to damaged facilities
- Mitigation measures taken by utilities after the earthquake
- Utilities and collaboration

Earthquake issues have a lot in common with issues related to other disasters. Therefore, earthquake disaster prevention capabilities can be greatly enhanced by applying knowledge learned from other disasters, management systems, and risk assessments other than earthquakes. Through the studies, identify potential vulnerabilities and improvements needed as a result of lessons learned from earthquakes and other disasters affecting water systems.

Developing water system seismic guidelines and goals also helps improve earthquake disaster prevention capabilities by documenting, for use by others, current state-of-the-practice. The American Lifeline Alliance (2005) and Japan Water Works Association (1997) are excellent examples. Through work in developing and the use of these types of guidelines additional knowledge gaps are exposed, furthering the improvement process.

3. CONCLUSION

Water system seismic programs require very broad approaches and the inclusion and integration of many different components including, management, risk analysis, numerous engineering fields, geology, seismology, technical research, emergency preparedness and response, socio-economic issues, financial, community involvement and development, working knowledge of specific water operations and field crews, and so on. All of these aspects must be incorporated into practice to develop a resilient system that can rapidly recover from a disaster. Methods used by operating organizations around the world were presented in this paper to provide guidance on how to develop a resilient water system. Many aspects identified herein are relatively new to water system seismic programs and need further research and development to improve their implementation.

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