6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch, New Zealand

Toward Seismic Resilient Horizontal Infrastructure Networks

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ABSTRACT

The challenges to creating seismic resilient horizontal infrastructure networks are exemplified using water systems and their four subsystems, namely supply, treatment, transmission, and distribution. The resilience of each subsystem is critical for providing water delivery, quality, quantity, fire protection, and functionality services, all necessary to supporting community resilience. The paper outlines some concepts for developing seismic resilient pipe networks at component and system level. The paper stresses how strategies for creating seismic resilient pipe networks could be greatly improved by reviewing case studies of actual water system network performance and recovery in past earthquakes. There is a need for system case histories documenting service losses and restoration strategies to improve knowledge on resilient horizontal infrastructure networks supporting community resilience goals.

Introduction

Resilient performance of horizontal infrastructure systems during seismic events is critical to the resilience of the communities they serve. The seismic resilience of horizontal infrastructure is dependent upon the amount of service losses sustained as a consequence of an earthquake event and the time required to re-establish the services. Given the lack of universally accepted standards or interpretation of infrastructure resilience (Barnes, et al 2012) this paper proposes and uses the following definition with specific reference to infrastructure seismic resilience: *A resilient infrastructure network is designed and constructed to accommodate earthquake damage with ability to continue providing services or limit service outage times tolerable for community recovery efforts.* This definition underpins the need for robustness and reliability of complex infrastructure systems. An important distinction is made between the terms robust (or resistant) and resilient. Robust describes the resisting of change or the effects of disturbance as compared to resilience describing the adaptation to the impact (Barnes, et al 2012).

This paper focuses on water networks, but the concepts discussed can be regarded as examples for the extension and similar application to other horizontal infrastructure systems. The main purposes for water systems and the key subsystems and components are briefly summarized. The paper enforces two key notions: 1) water system resilience cannot be measured only by the amount and time of service lost, but also by how it helps to improve overall community resilience; and 2) the importance of and concepts for enhancing the resilience of horizontal infrastructure at the network level. These two key notions are operatively translated by,

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1. Introducing service categories against which the system resilience should be measured, namely, Water Delivery, Quality, Quantity, Fire Protection, and Functionality.
2. Making explicit how the earthquake-induced physical damage to different subsystems might inhibit the resilience with respect to the aforementioned five service categories.

Case studies from Los Angeles and Christchurch are introduced to exemplify the aforementioned concepts and extract learning from past earthquakes on best practice for resilient infrastructure systems. Building on the cases and the authors' experiences, concepts to implement resilient networks in existing built-out subsystems are finally described, including the importance of enhancing the robustness at component level (e.g., by the use of pipeline materials and joints known to resist earthquake damages) in high-risk areas or in strategic parts of the network.

Water Systems

Water systems are lifelines essential to modern industry and for public health in all urbanized areas. Water is the lifeblood of every city and the provision of potable water supplies is expected as a norm in most modernized economies. Water supply and sanitation are among the most basic human needs and access to reliable potable water is a key measure of human well-being. The main purpose of establishing and maintaining a water system is to ensure a safe and reliable water supply. Water systems generally serve the following functions:

1. Providing potable water supply for domestic, commercial, and industrial uses; including critical services, emergency operations and evacuation centres, and other lifeline systems.
2. Providing potable or non-potable water supply for cleaning, flushing, cooling, firefighting, irrigation, recreation, and environmental quality.

Water systems are made up of the subsystems described in Table 1. The purpose for segregating the systems is to develop a general hierarchical understanding for the relative importance of the major systemic functions in order to more easily assess the overall water system serviceability and resiliency. The division between the subsystems shown in Table 1 is not always clear; and some water systems might not include all the subsystems in Table 1. In general more advanced water systems have more distinct subsystems. Table 1 also identifies typical facilities or components making up the different subsystems. Furthermore, Table 1 correlates the subsystems with the corresponding component level taxonomy proposed by the Syner-G project (Pitilakis et al. 2014).

Characterizing Subsystem Performance and Post-Earthquake Services

Characterizing subsystems and earthquake performance

Water subsystems generally operate in series flowing from the raw water supply to the treatment, transmission, and then distribution subsystem. The raw water supply subsystem may include multiple sources. The treatment subsystem may also have components interlinked within the other subsystems. The transmission and distribution subsystems may have multiple lines interconnecting complex pipeline networks. Earthquake-induced transient or permanent ground deformations can damage components within the water subsystems to a different degree and extent depending on the level of robustness (i.e. resistance or flexibility) built into each specific component. However, the water systems' earthquake performance is not only dependent on the seismic robustness of each component from which it is made, but also on the systemic design, layout, and inter-links of each subsystem identified in Table 1. The seismic performance of the raw water supply, treatment, transmission, and distribution subsystems all have a direct effect on the ability of a water system to provide the post-earthquake services.

Table 1: Major water subsystems.

Subsystems	Description	Typical Facilities/Components	Syner-G Taxonomy
Raw Water Supply Systems	Systems providing raw water for local storage or treatment including local catchment, groundwater, rivers, natural and manmade lakes and reservoirs, aqueducts.	Reservoirs, pump stations, wells, pipelines, canals, tunnels, dams, levees, desalination and wastewater treatment plants are sources.	WSS01 – Water source
Treatment Systems	Systems for treating and disinfecting water to make it potable for safe use by customers.	Treatment plants, filtration systems, settling basins, chlorination stations, and other chemical stations (fluoridation, hypo-chlorination, chloramine, etc.).	WSS02 – Water treatment plant
Transmission Systems	Systems for conveying raw or treated water. Raw water transmission systems convey water from a local supply or storage source to a treatment point. Treated water transmission systems, often referred to as trunk line systems, convey water from a treatment or potable storage point to a distribution area.	Medium to large diameter pipes, tunnels, reservoirs and tanks, pumping stations, valves and regulating stations.	WSS03 – Pumping station WSS04 – Storage tank WSS05 – Pipeline WSS06 – Tunnel WSS07 – Canal WSS08 – SCADA system
Distribution Systems	Networks for distributing water to domestic, commercial, business, industrial, and other customers.	All pumping stations, regulating stations, tanks and reservoirs, valves, and piping not defined as part of other subsystems forming a network from connections at the transmission systems to points of service.	WSS03 – Pumping station WSS04 – Storage tank WSS05 – Pipeline WSS06 – Tunnel WSS07 – Canal WSS08 – SCADA system

Characterizing Water System Services

Table 2: Water service categories (Davis, 2014).

Service Categories	Description
Water Delivery	The system is able to distribute water to customer service connections, but water delivered may not meet quality standards, pre-event volumes, fire flow requirements, or pre-event functionality.
Quality	The water quality at service connections meets pre-event standards. Potable water meets health standards, including minimum pressure requirements to ensure contaminants do not leach into the system.
Quantity	Water flow to customer service connections meets pre-event volumes (water rationing removed).
Fire Protection	System is able to provide pressure and flow of a suitable magnitude and duration to fight fires.
Functionality	The system functions are performed at pre-event reliability, including pressure (operational constraints resulting from the earthquake are removed/resolved).

Table 2 summarizes the five service categories normally provided by water systems using common network topology (Davis, 2014). Water system resilience is dictated by all five service categories and how they interact with the regional community. Operability is not a service but defined as the cumulative restoration of all service categories in Table 2 except functionality (Davis, 2014b). Once system operability is achieved the system is able to completely service customers to their pre-earthquake levels; whereas functionality service describes the ability of a system to reliably perform. Operability is a measure of the system's ability to support community resilience and functionality is a measure of system resilience. Community dependence on water for survival does not allow a water system's resilience to be defined independently from community resilience. Additionally, water system resilience cannot be measured only by the amount and time of service lost, but also by how it helps to improve community resilience.

Table 3 presents a matrix relating impacts to the water service categories, which may result when damage is inflicted to the different water subsystems. Damages to different subsystems, no matter how severe, do not necessarily induce a loss in services. There are many variables dictating service losses. For example, expected service losses may include all listed in Table 2 when the distribution subsystem is severely damaged; however if distribution system damage is limited to a few pipe leaks, then possibly service losses are limited to minor functionality. In contrast, few damages but at critical locations in the raw water supply, treatment, or transmission subsystems can cause significant service losses in all categories. Detailed descriptions of the complicated interactions between subsystem damages and service losses are beyond the scope of this paper.

Table 3: Matrix of potential impacts on water services due to damages in different subsystems.

Service	**Damage to Subsystem**			
	Raw Water Supply	Treatment	Transmission	Distribution
Delivery	✓	✓	✓	×
Quality	✓	×	✓	×
Quantity	✓	✓*	✓	×
Fire Protection	✓	✓*	✓	✓
Functionality	•	•	•	•

*If treatment component is critical node; e.g. treatment plant without bypass or flow through capability

Impact on service from damage to subsystem (does not indicate extent of service losses)

• Service reduction → depending on system capabilities.

✓ Possible service loss → depending on water system topology.

× Service loss → expected service losses in some locations.

Learning from Earthquake Experiences

Davis et al. (2012) describe the Los Angeles water system performance in the 1994 M_w 6.7 Northridge Earthquake. In summary, there were 14 repairs to the raw water supply conduits, 60+ repairs to transmission pipes, 1013 repairs to distribution pipes, 200+ service connection repairs, 7 damaged distribution tanks with another having a damaged drain line, 4 damaged transmission reservoirs (1 roof, 3 liners), temporary suspension of half the treatment plant service and other incidental damage. In addition, water supply wells and some large transmission and small distribution pump stations were temporarily unusable due to power outage. Figure 1 shows the 1994 earthquake service losses and restoration times. The services were calculated as the ratio of customers receiving the service after the earthquake to those with the service before the earthquake. The raw water supply subsystem performance impacted all services in Table 2 except quality. The treatment subsystem performance mainly impacted functionality services. The transmission and distribution subsystem performances impacted all Table 2 services.

The water delivery service dropped to about 78%, with 22% of all Los Angeles customers receiving no water shortly after the earthquake due to water leaking from broken transmission and distribution pipes. The quantity and fire protection services dropped to a low of about 72% after the earthquake. The quality service dropped immediately to zero because a water purification notice was issued across the entire city within 3 hours after the earthquake. As shown in Figure 1, the water delivery service was restored to 100% at about 7 days, quantity and fire services at about 8.5 to 9 days, and quality service at 12 days after the earthquake. The Los Angeles water system achieved complete operability in 12 days, which was entirely governed by water quality service restorations. The functionality service restoration is calculated using the methodology described by Davis (2014a) for the supply, treatment, transmission, and distribution subsystems. The functionality service initially dropped to about 34% and rapidly increased to about 60% once critical repairs were completed a few days after the earthquake and was 95%

restored within 3 years. It took 6 years to return functionality to 99% after completing a number of tank and reservoir repairs and replacements. Functionality was completely restored after about 9 years.

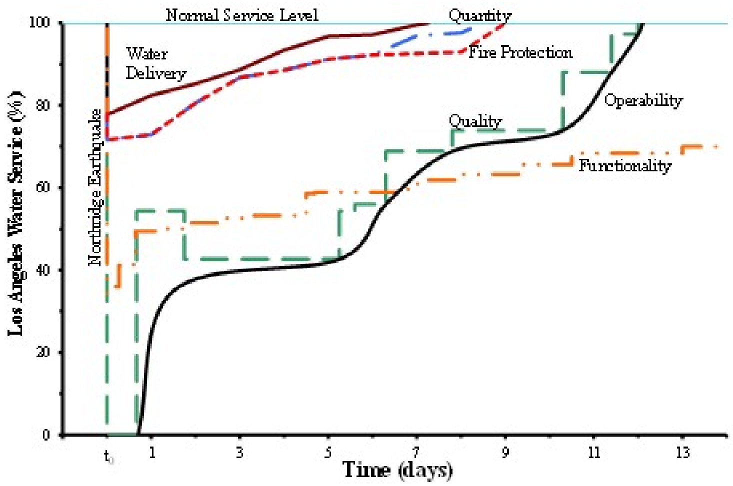

Figure 1: LA water system service restorations following the 1994 Northridge earthquake.

TCLEE (2015) describes damages to the Christchurch water system during the 2010-2011 Canterbury Earthquake sequence. The sequence consisted of multiple earthquakes ranging from M_w 5.8 to 7.1. This paper only details the Feb. 22, 2011 M_w 6.2 earthquake. The water system sustained damage to more than 20 groundwater wells, 20 tanks were damaged to different degrees from complete loss (2) to minor damage remaining operable (10), and there were over 1,600 pipe repairs. Some pump stations were damaged from liquefaction and others were inoperable due to power service loss. Wells were temporarily out of service due to power outage. The main office building had to be evacuated and set up in a local library. Over 200,000 of the nearly 400,000 residents were without water for several days after the earthquake and it took over 30 days to restore water to everyone. An estimated 55% of water was being lost due to system leakages three weeks after the earthquake. Christchurch water is not normally treated (i.e. no treatment subsystem). To maintain public health, boil water notices were issued across the city for over 6 weeks and portable chlorination stations were used. Water conservation was implemented in summer 2011/2012 due to continued supply problems. Water system repairs and upgrades continue at the present time. The water system was nearly recovered from the Sept. 2010 earthquake when the Feb. 2011 earthquake struck. Recovery from the Feb. 22, 2011 earthquake was lengthier and not complete when the June 13, 2011 earthquakes struck. Similarly, the Dec. 23, 2011 earthquakes further impacted system performance.

The water supply, transmission, and distribution subsystems performances impacted all Table 2 services. Due to water quality problems a temporary treatment subsystem had to be installed and utilized for about 9 months. Unfortunately the earthquake impacts on the Christchurch water system have not been thoroughly analysed similar to Figure 1 to understand service losses and recoveries from any of the earthquakes in the sequence. This is a missed opportunity to improve our understanding of the complex interactions between water system resilience, service categories, and community resilience from this important case study. In depth service restoration studies from Christchurch will clearly show differing situations from those in Los Angeles and expose additional important water service restoration characteristics useful for improving systems worldwide. Investigating systems, which have suffered significant earthquake impacts and utilized different restoration strategies in a wide range of earthquake scenarios can improve our understanding of damage effects to the different subsystems and move toward seismic resilient horizontal infrastructure networks.

Concepts for Pipe Network Seismic Improvements

Most water systems were built over the last century before any significant water system seismic design criteria was developed. Water system components such as dams, reservoirs, tanks, building structures, etc., built within the past 50 years should have been designed for some level of earthquake performance. Older components may have been upgraded to some level of seismic performance. Technologies have long existed to improve these components to meet selected performance criteria and should be utilized to develop resilient systems.

The remaining challenge to creating resilient horizontal networks lies in improving the pipelines. At present and with few exceptions, water pipelines are not designed or constructed for seismic forces. Exceptions exist in Japan where they have been installing seismic resistant pipes for the past 40 years. Some critical supply and transmission lines outside of Japan have been upgraded to be more seismically robust (e.g., Balir, 2014). Distribution subsystems are normally not seismically designed or upgraded, even though: (1) distribution pipe aggregates to the greatest total assets within the system, and (2) the total system resilience depends on the resilience of all subsystems. Technologies now exist to upgrade pipes for seismic robustness in a cost-effective manner. To aid in developing seismically resilient networks, the following sections provide some useful easy to implement strategies and concepts.

Strategies for improving pipe network resilience

This section outlines strategies useful for water agencies providing services to large cities, smaller cities and towns, and rural communities to develop seismic resilient horizontal pipe networks.

- Identify the earthquake hazards including potential for strong shaking, fault rupture, liquefaction induced ground movements, differential settlement, landslides, tsunami and other local aspects. Permanent ground deformations often have the greatest impacts on system performance and these locations can inform prioritization for asset expenditures.
- Analyze the network component fragilities against the earthquake hazards and assess potential damage. A focus on design detailing can reduce fragility. Systemic details such as adding isolation valves and connection redundancies increase post-event operability. These often result in significant step improvements in resilience and can be accomplished with little or no cost.
- Determine how components if damaged will impact system performance and compare to targeted performance objectives. The identification of expected verses targeted performance aids in prioritizing improvements.
- Identify consequences from inability to provide the Table 2 water services when the

community needs them following an event. This includes identifying critical facilities and needs, such as hospitals, emergency operation centers, emergency shelters, and firefighting, with target service performance levels. The earthquake geotechnical hazards identified above cannot be assessed along pipelines with great precision and even areas of low hazard can encounter problems leading to network damage. If a pipeline is critical to community resilience the importance should influence the need for seismic robustness.

- Recognize the material cost is usually a relatively small portion of the total project cost. Benefits from selecting a certain pipe-type should be assessed from project and lifecycle costs. Great seismic benefit can be achieved for a small cost increase to each project; proper assessment in support of community resilience can show cost effectiveness.
- Develop guidelines, policies and plans helpful for incremental seismic network improvements. Include looped pipe systems, redundancy, material stockpiles, isolation capabilities, and organizational resilience strategies.

Concept for Developing Seismic Resilient Pipe Networks

A seismic resilient network should target water provision to critical areas and locations when needed by the community for disaster recovery. All subsystems in Table 1 should incorporate seismic resilient network concepts. Seismic resilience can be cost-effectively incorporated into pipe networks utilizing some key concepts to build robustness.

1. First, identify pipe materials and joint types, which provide adequate seismic resistance for the local service area.
2. Next, within the network identify critical and important pipes using risk-based methodologies and incorporating community resilience needs.

Pipes can be classified based on their seismic importance and selection criteria is based on criticality and expected ground behaviour (ALA, 2005). Pipe materials and types for consideration include earthquake resistant ductile iron pipes (ERDIP), fused polyethylene pipes, polyvinyl chloride pipes, welded steel pipes, among others. These seismically robust pipes can be obtained relatively easily worldwide, but require proper design and construction quality control to ensure appropriate earthquake performance. ERDIP has had excellent performance over the past 40 years in Japan (Kaneko et al, 2013). More recently the excellent performance of medium and high-density polyethylene pipes (MDPE and HDPE) has been shown in Christchurch, NZ (Giovinazzi et al, 2011; O'Rourke et al, 2014). ERDIP and HDPE are highly robust and easy to utilize in water systems when the materials adequately meet all design requirements. Other pipe materials may require specific analysis to assess seismic robustness on a case-by-case basis. There currently is an increased interest to develop seismically robust pipes in a portion of the pipe industry, which is expected to lead to new cost-effective and easy to install products.

Developing a seismic resilient network must start with an overall vision of what the entire system could look like in the future. System specific strategies must be created to move the vision into a plan (e.g., Davis, 2014). Using the current subsystem networks, develop a layout for long-term seismic improvement build-out including seismic hazards, pipe importance, and grid dimensions consistent with fire department equipment capabilities to relay water. Once the plan is initiated, the water system can provide increased community resilience at local levels in very short periods of time, possibly in the order of months to years. For example, reliable potable water distribution can be achieved for critical hospitals by installing only a few seismic robust pipes in vulnerable areas within an existing redundant network.

Seismically robust pipes need to be incorporated into the on-going asset management and pipe replacement programs. Dramatic gains in network resilience can be achieved simply by including seismic risk as part of asset prioritization, pre-identifying which lines are most important for developing a resilient network, and using proper materials during replacement.

Not all damage can be prevented when an earthquake strikes and not all needed improvements can be completed in short timeframes. As a result, some water service outages will inevitably occur following a major earthquake. Knowing this, it is essential to prepare plans:

- Emergency water plan (EWP) linked to known vulnerabilities within the system. The EWP must include the ability to obtain alternative water sources, other from the network, for all customers, including fire departments, during entire outage durations.
- Restoration plan to recover post-earthquake services within an acceptable timeframe. Establish restoration goals with community input to meet their resilience needs.

Conclusions

Water systems are made up of four subsystems: supply, treatment, transmission, and distribution. The seismic design of each subsystem is critical to supporting community resilience. Each of these subsystems plays an important role in providing water delivery, quality, quantity, fire protection, and functionality services (Davis, 2014). A number of strategies for improving resilience of existing built-out systems were identified. Based on these strategies and the target to support community resilience, concepts for developing seismic resilient pipe networks were outlined. Strategies for creating seismic resilient pipe networks can be greatly improved by reviewing case studies of actual water system network performance and recovery in past earthquakes. There is a significant need for tracking the loss and restoration of the core service categories in order to move toward seismic resilient horizontal infrastructure networks.

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