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A software framework for assessing the resilience of drinking water systems to disasters with an example earthquake case study

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ABSTRACT

Water utilities are vulnerable to a wide variety of human-caused and natural disasters. The Water Network Tool for Resilience (WNTR) is a new open source Python™ package designed to help water utilities investigate resilience of water distribution systems to hazards and evaluate resilience-enhancing actions. In this paper, the WNTR modeling framework is presented and a case study is described that uses WNTR to simulate the effects of an earthquake on a water distribution system. The case study illustrates that the severity of damage is not only a function of system integrity and earthquake magnitude, but also of the available resources and repair strategies used to return the system to normal operating conditions. While earthquakes are particularly concerning since buried water distribution pipelines are highly susceptible to damage, the software framework can be applied to other types of hazards, including power outages and contamination incidents.

1. Introduction

Depending on their location and vulnerability, drinking water utilities are taking steps to enhance their resilience to earthquakes, floods, drought, hurricanes, winter storms, forest fires, tornadoes, contamination incidents, terrorist attacks, and other types of hazards (Critical Infrastructure Partnership Advisory Council, 2009; American National Standards Institute, 2010; US Environmental Protection Agency, 2014, 2015a, 2016). Resilience is defined by the National Academies of Science as “the ability to prepare and plan for, absorb, recover from, and successfully adapt to adverse events” (National Academy of Sciences, 2012). The ability to maintain drinking water service during and following such hazardous incidents is critical to ensure the well-being and continuity of daily life. Water system resilience is important not only for individuals, but also for hospitals, schools, nursing homes, fire stations, restaurants, and for other industries that rely on water.

Natural disasters and other types of hazards have resulted in different types of water service disruptions: pipe breaks and leaks; power outages; failure of reservoirs, tanks, pumps, treatment plants, and other infrastructure; reduced water quality; loss of access to facilities and supplies; as well as financial, social, environmental and human health consequences (Critical Infrastructure Partnership Advisory Council, 2009; Eldinger and Davis, 2012; US Environmental Protection Agency, 2015b). Following large disruptive incidents like earthquakes, affected communities have experienced power outages and water service outages lasting from hours to weeks. For example, the 1994 magnitude 6.7 Northridge Earthquake, located outside Los Angeles, California, damaged seven reservoirs, over 60 transmission mains, and 1000 distribution pipes. The quantity of water delivered was restored to pre-earthquake volumes after seven days, and the quality of water was restored and boil-water orders were lifted after 12 days. However, it took nine years to complete all repairs and restore full functionality of the water system (Davis, 2014). Even though evidence shows that seismic-resistant pipes have a high survival rate following an earthquake (Eldinger and Davis, 2012), these upgrades have not been widely implemented because of the high cost for pipe replacement.

General guidance is available on water system resilience to disasters (Critical Infrastructure Partnership Advisory Council, 2009; American National Standards Institute, 2010; US Environmental Protection Agency, 2014, 2015a, 2016); however, robust software tools to support utility-specific resilience assessment are not available. With such tools, water utilities could estimate potential

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damages to their system, understand the multitude of disruptions that could unfold over time, investigate redundancies, evaluate preparedness, and prioritize specific mitigation strategies, such as pipe replacement or adding redundancy to supply systems (American National Standards Institute, 2010; US Environmental Protection Agency, 2015b). Systems modeling tools have the potential to meet this need by combining disaster damage models with hydraulic and water quality models of water distribution systems. Additionally, systems modeling could incorporate changes in customer behavior during disasters (e.g., water usage), as well as utility response actions. This type of simulation approach could allow a water utility to design more effective mitigation activities before a disaster occurs.

This paper presents a comprehensive software framework for assessing the resilience of drinking water systems to disasters, including earthquakes. The software improves upon currently available capabilities by fully integrating hydraulic and water quality simulation, damage estimates and response actions, and resilience metrics into a single platform. This software is available as an open source software package called the Water Network Tool for Resilience (WNTR, pronounced *winter*). In the rest of this paper, the relevant literature is reviewed, the WNTR software framework is described in detail and then an earthquake case study is presented to demonstrate the capabilities in WNTR. While the case study focuses on earthquakes, the software framework is general and can be applied to a wide range of disruptive incidents and repair strategies.

2. Literature review

Existing hydraulic and water quality modeling software tools were not designed to handle sudden failures resulting in inadequate pressure or rapid changes in system operation. Moreover, they were not designed to handle situations when sections of a water system become isolated, tanks or reservoirs drain, or the system operational rules cannot be met. For example, commonly used demand-driven (DD) hydraulic simulators, like EPANET (Rossman, 2000), assume customer demands are always met even if the pressure is insufficient to provide the demand. In reality, disasters can lead to situations where pressure in the system is unusually low and customer demand would not be met.

Several alternatives to DD simulators have been discussed in the literature. Wagner et al. (1988) presented pressure-driven demand (PDD) hydraulic equations for water distribution systems in which the demand supplied to a node is a function of the pressure at that node. During low-pressure conditions, customers receive a fraction of their expected demand. PDD simulators include WaterNetGen (Muranho et al., 2012, 2014), which is an open source software tool, and WaterGEMS™ (Wu et al., 2008), which is a commercial software tool. Quasi-PDD simulators (or semi-PDD) run DD simulations in an iterative manner and nodes are switched between constant-demand nodes, zero-demand nodes, and (sometimes) emitters depending on the domain in which the pressure falls (Pathirana, 2011; Trifunovic, 2012; Yoo et al., 2016). When considering disaster scenarios, the difference between using DD and PDD simulation can be drastic (Laucelli et al., 2012).

After a large-scale disruption, water demand in the network can change dramatically. Structural damage and emergency operational changes can result in isolated sections of the network or low pressure conditions that reduce the amount of water delivered to customers. Policy changes, including do-not-drink orders, boil-water orders, or water conservation efforts, also decrease customer demand. When planning for an adequate drinking water supply during emergencies, water utilities need to account for the minimum acceptable water use per capita, the anticipated time scale of the disruption, the population impacted, and water quality standards that need to be upheld (US Environmental Protection Agency, 2011). If acceptable water volume and quality cannot be delivered, potable water alternatives would have to be considered. Customer behavior can also change during emergencies, either temporarily increasing demand (e.g., filling up bathtubs to stockpile water) or decreasing demand (e.g., relying on bottled water because of a lack of confidence in the delivered water). These changes in customer demand can impact resilience; for example, conservation might increase water availability for firefighting.

Several tools have been developed to estimate the hydraulic performance of a water distribution system after an earthquake (Markov et al., 1994; Shi and O'Rourke, 2008; Mani et al., 2013; Yoo et al., 2016). These tools use attenuation models and fragility curves developed by the American Lifeline Alliance to estimate network damage based on earthquake magnitude and location (American Lifelines Alliance, 2001a,b, 2005). Attenuation models calculate peak ground acceleration (PGA) and peak ground velocity (PGV) as a function of earthquake magnitude, location and depth. Fragility curves determine the probability of damage as a function of ground movement. These models are generally built on empirical data from recent earthquakes, which includes information such as the characteristics of damaged pipes and the measured PGA. The Graphical Interactive Serviceability Analysis of Life-Lines subjected to Earthquakes (GISALLE) tool quantifies water service availability after an earthquake and uses the Loma Prieta Earthquake as the basis for a stochastic parametric study (Markov et al., 1994). The Graphical Iterative Response Analysis for Flow Following Earthquakes (GIRAFFE) software builds upon GISALLE to include upgrades to the way low pressure conditions are handled when modeling pipe failure and includes a seismic wave model to estimate joint damage (Shi and O'Rourke, 2008). Mani et al. (2013) include pipe leak models developed by Shi et al. (2008), and use the Tehran water distribution network as a case study. The Reliability EVAluation model for Seismic hazard for water supply NETwork (REVAS.NET) tool includes earthquake attenuation models and probabilistic scenarios with different repair strategies (Yoo et al., 2016). Guidotti et al. (2016) extend previous work by including a general procedure for modeling resilience of critical network infrastructure. This work includes methods that account for dependencies between networks, such as the water distribution systems and the electric power network. The general procedure can be applied to a wide range of hazards and recovery actions. To date, these research efforts use quasi-PDD hydraulic simulations.

Several studies have simulated the damage to the Los Angeles Department of Water and Power caused by the 1994 Northridge Earthquake in California and the restoration activities that followed (Tabucchi, 2007; Shi and O'Rourke, 2008; Romero, 2009). These tools combine GIRAFFE with the capability to demonstrate restoration actions, such as sending crews to investigate, isolate, and repair pipe breaks. Other modeling tools were developed to help the East Bay Municipal Water District in Northern California manage earthquake response in real-time, prioritize transmission line upgrades, and assess interdependencies with the electricity sector (Irias et al., 2011). These tools combine real-time USGS ShakeMap data on ground movement after an earthquake (Wald et al., 2006) with a customized software tool to rapidly predict damage to specific water utility assets (Irias et al., 2011).

3. Modeling framework

The United States Environmental Protection Agency, in partnership with Sandia National Laboratories, developed WNTR to integrate critical aspects of resilience modeling for water