SEISMIC ANALYSIS OF WATER SUPPLY SYSTEMS BY EARTHQUAKE SCENARIO SIMULATION

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ABSTRACT**:** In the past decade, scenario simulation has played a more and more important role in urban earthquake hazard mitigation and emergency response. Both public and private sectors can be enhanced in terms of their seismic preparedness and operation if adequate implementation of seismic scenario simulation can be employed. Regarding water utilities, system-wide retrofit and emergency planning can be conducted to reduce the likely damage and losses prior to the occurrence of a devastating earthquake. Post-earthquake repair personnel and material dispatching, temporary water supply for affected people, emergency water supply for hospitals and fire fighting, strategies for restoration and recovery can all benefit from scenario-based analyses. In this research work, efforts were made to study and integrate pivotal technologies essential to the earthquake damage and serviceability analysis of water systems, such as seismic hazard analysis, empirical formulae for pipe repair rates, hydraulic analysis of water network system in terms of pressurized pipe flow simulation, hydraulic models for various types of pipe damages, and Monte Carlo method for the performance analysis of large and complicated systems. The water system in Yi-lan County, Taiwan was selected as a test bed for the demonstration of its seismic serviceability analysis under an M7.1 earthquake scenario.

KEYWORDS: water system, post-earthquake performance, scenario simulation

1. INTRODUCTION

Water systems are one of the most essential infrastructures in modern societies. The disruption of water supply following earthquakes may cause serious inconvenience to the daily life of people in the disastrous areas. Medical caring, sanitation, fire-fighting and so forth may be seriously affected, too. It is very important to facilitate water utilities with a seismic scenario simulation tool for help estimate the likely service disruption following earthquakes. Such tool will benefit the efforts to improve preparedness, robustness, and resilience of water systems in a quantitative approach. In the past years, Shinozuka et al. (1981), Ballantyne et al. (1990) and Markov et al. (1994) have made pioneer studies in this topic. Recently, software called GIRAFFE (Graphical Iterative Response Analysis for Flow Following Earthquakes) has been developed at Cornell University (2008). It was successfully adopted as a decision support tool for hazard mitigation and emergency response by the Los Angele Department of Water and Power. It employs EPANET as the engine for hydraulic computation. EPANET is public computer codes released by the Environmental Protection Agency, U.S., especially for the solution of pressurized pipe flow problem (Rossman, 2000).

Similar to GIRAFFE, a technology for assessing the post-earthquake performance of water systems has been developed at NCREE (Liu et al., 2010 & 2011). It consists of several steps, as depicted in Figure 1. (1) estimate the seismic hazards (ground shaking and failure) of where the interested water network system locates, (2) simulate the locations of pipe damages according to the hazards and pipe repair rates (numbers of repairs per unit pipe length caused by ground shaking and deformation, respectively), (3) classify the properties of each pipe damage (whether a break or a leak, and what which model of pipe leak if it is a leak; the probability model for pipe damages employed by GIRAFFE was adopted here), (4) modify the hydraulic model of the water network system to take into account the pipe damages, (5) execute EPANET and take out the water supply nodes affected by negative pressure from the solution. Details of these steps will be explained in the following sections.

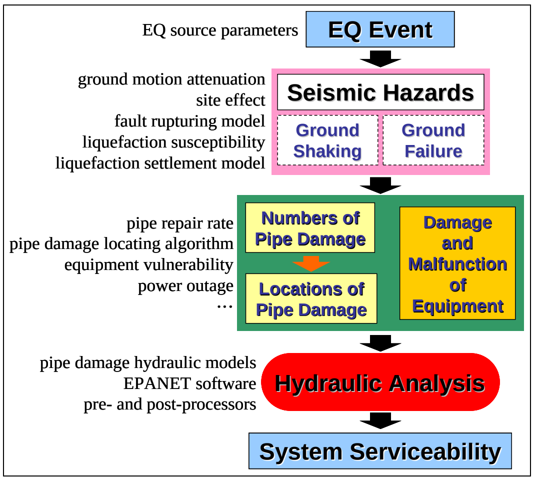

Figure 1 Flowchart for the serviceability assessment of water systems following earthquakes

2. PIPE DAMAGE MODELING

Repair rate (RR) is defined as the number of repairs (or damages) per unit pipe length (km). It is widely employed to indicate pipe fragility under seismic effects. Numerous investigations have been made to express the relationship between pipe repair rate and earthquake-induced ground shaking (e.g. peak ground acceleration, PGA) or ground failure (e.g. permanent ground displacement, PGD). The pipe material and diameter affect its repair rate, too. The empirical formulae for pipe repair rates have been proposed by the authors, which read (Liu et al., 2011):

$$RR = C \cdot RR_0$$

$$RR_0 = \max[RR_{PGA}, RR_{PGD_{Fault}}] + RR_{PGD_{Liq}} \cdot p_{Liq}$$

where

$$RR_{PGA} = 6.5756 \times 10^{-3} \cdot (PGA - 100)^{0.878}$$
$$RR_{PGD} = 0.6445 \cdot PGD^{0.728}$$

where RR_0 is the standard pipe repair rate, C is an adjustment coefficient and is a function of pipe material and diameter, PGA and PGD are in cm/sec^2 and cm, respectively. The terms PGD_{Fault}, PGD_{Liq} and p_{Liq} represent the fault rupturing and soil liquefaction-induced PGDs, and the probability of occurrence of soil liquefaction, respectively.

Conventionally, a stationary Poisson process is widely used to simulate the damage locations along a pipe. In this study, an approach based on the expected number of damages of pipes was otherwise proposed. From Figure 2, let the length of a typical pipe segment be L. Assume there are a total of N pipes in the water pipe network under study. Let all pipes be broken down into segments of constant length L from their beginning nodes (the length of the last segment of each pipe may not equal L), and be denoted as (i, j), where i refers to pipe i $(i = 1,..., N)$ and j refers to its j-th segment. The expected number of pipe damage of any pipe segment (i, j) can be decided according to the segment length and the corresponding pipe repair rate. Denote this number as e_{ij}. Starting with the origin of the number line, if all the expected numbers of pipe damage $e_{11}, e_{12}, ..., e_{21}, e_{22}, ..., e_{NJ_N}$ (where J_N refers to the last segment of pipe N) can be sequentially accumulated as (e_{11}), $(e_{11}+e_{12})$, $(e_{11}+e_{12}+e_{13})$, ..., $(e_{11}+e_{12}+...+e_{NJ_N})$ and denoted on the number line, then the interval $[0, E_R]$, where E_R equals to the summation of all the expected numbers of pipe damage, consists of as many sub-intervals as the number of all pipe segments with lengths $e_{11}, e_{12}, ..., e_{21}, e_{22}, ..., e_{NJ_N}$. This also means that there exists a one-on-one mapping between any real-number within $[0, E_R]$ and a specific pipe segment.

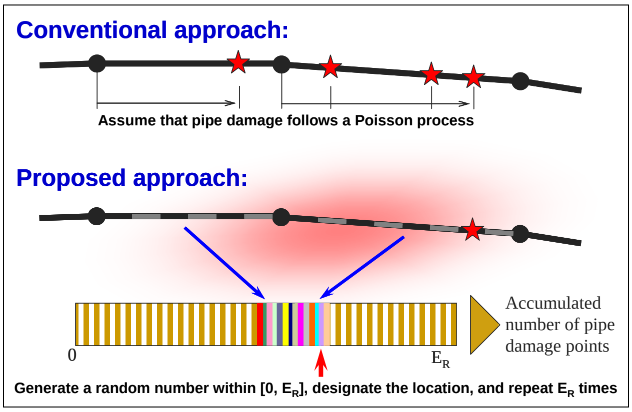

Figure 2 Comparison between the conventional and the proposed approaches for simulating pipe damage locations probabilistically

To simulate a location of damage along the pipe, first, an arbitrary number between 0 and E_R can be generated using a random number generator that follows uniform distribution. It will refer to one single segment, say e_{nm}, along the axis of number line. Finally, the midpoint of the m-th segment of the n-th pipe is designated as a pipe damage location. The same process can be repeated E_R times to determine all pipe damage locations.

The hydraulic models for pipe damages proposed in GIRAFFE (Cornell University, 2008) were adopted in this study. This model includes pipe break and various types of pipe leaks, and the probability that each will occur in various pipe materials, and also the hydraulic models and parameters for each type of pipe damage. Following their findings from water pipelines and their damages in past earthquakes in the U.S., water pipe materials could be classified into 5 types: cast iron, ductile iron, jointed concrete, riveted steel and welded steel. Furthermore, there are five different types of pipe leaks, namely the annular disengagement, round crack, longitudinal crack, local loss of pipe wall, and local tear of pipe wall at welded slip joint, as illustrated in Figure 3.

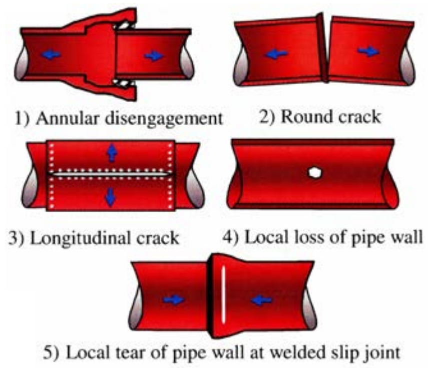

Figure 3 Schematic diagrams of the 5 types of pipe leaks (Cornell University, 2008)

GIRAFFE further proposed the hydraulic models for pipe breaks and leaks, respectively. A pipe break and its hydraulic model can be depicted as the left schematic diagram in Figure 4. At each of the broken ends, a reservoir and a short pipe with a check valve are needed being added to mimic the mechanism of water flowing into the atmosphere. To take into account the effect of a pipe break in simulation, several steps to modify the hydraulic model of the broken water system should be taken. They are: (1) Decide the location and elevation of pipe break point, (2) Remove the original link (pipe segment), (3) Add two new nodes A and B at the location of pipe break point, (4) Add two new links connecting the original pipe segment ends to A and B, respectively, (5) Add two new nodes A' and B' with the elevation of pipe break point and designate them as reservoirs, and finally (6) Add two new links connecting A-A' and B-B' and specify them with one-way check valves.

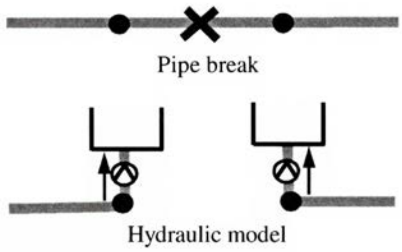

Figure 4 Hydraulic model for a pipe break (Cornell University, 2008)

On the other hand, a pipe leak and its hydraulic model could be depicted as the right schematic diagram in Figure 5. A pipe leak is hydraulically equivalent to a sprinkler with a specific discharge coefficient and an orifice size. This sprinkler is further proven to be equivalent to a fictitious pipe linking the original pipe and an added reservoir. A check valve is designated to the fictitious pipe ensuring that water flows from the leaking pipe to the reservoir. The steps to modify the hydraulic model of the leaking water system could be summarized as follows: (1) Decide the location and elevation of pipe leak point, (2) Remove the original link (pipe segment), (3) Add a new node A at the location of pipe leak point, (4) Add two new links connecting the original pipe segment ends to A, (5) Add a new node A' with the elevation of pipe leak point and designate it as a reservoir, and finally (6) Add a new link connecting A and A' and specify it as a fictitious pipe with a diameter of corresponding pipe leak model, and also specify it with a one-way check valve.

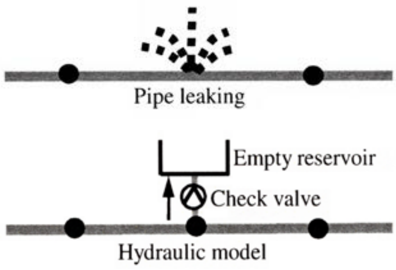

Figure 5 Hydraulic model for a pipe leak (Cornell University, 2008)

3. HYDRAULIC ANALYSIS AND NEGATIVE PRESSURE ISSUE

Figure 6 depicts the schematic diagram of a simplified water network. A water network system usually consists of tanks, reservoirs, pumps, valves and numerous pipes and nodes. The hydraulics of such a system can be assumed as pressurized pipe flows, and can be solved by using two sets of equations (Rossman, 2000). Let there be N nodes, NF fixed nodes (e.g. tanks and reservoirs) and K pipes in a water network, then the first set prescribe the difference of water head at the ends of each pipe and read:

$$H_i - H_j = h_{ij} = r \cdot Q_{ij}^n + m \cdot Q_{ij}^2$$

where H , h , Q , r , n and m are the nodal head, head loss, flow rate, resistance coefficient, flow exponent and minor loss coefficient, respectively. The most widely used empirical formulae for the pipe resistance coefficient are the Darcy-Weisbach, Hazen-Williams or Chezy-Manning equation, all of which employ flow rate and various pipe parameters. The second set prescribes the balance of flow at each node and read:

$$\sum_j Q_{ij} - D_i = 0$$

where D_i is the demand at node i. By using these two sets of equations, the pipe flow can be solved in terms of the water heads H_i at N nodes and the pipe flow rate Q_{ij} (from node j to node i) in K pipes.

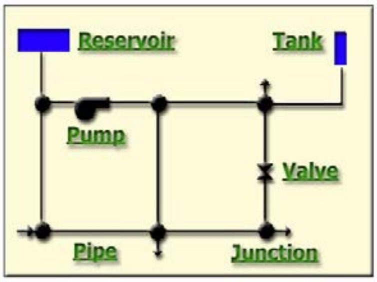

Figure 6 The schematic diagram of a simplified hydraulic network (Rossman, 2000)

The procedure for assessing the post-earthquake performance of a water system is illustrated in the flowchart in Figure 7, which reads:

(1) Read the input file for the hydraulic analysis of the interested water system. This file is usually prepared by the water utilities and is compatible with the employed analysis software in terms of data formatting. All attributes of the components in the water system (e.g. reservoirs, tanks, pumps, nodes and pipes) are defined in the file.
(2) Simulate the pipeline damage of the water system based on an earthquake scenario. A pre-processor has been developed in this study to decide the locations and attributes of pipe breaks and leaks in the pipeline network in a probabilistic way, and then to modify the input file according to the simulated pipeline damage. It takes into account the seismic hazard and the pipe repair rate, and the pipe damage models Proposed in GIRAFFE (Cornell University, 2008) were employed.
(3) Check the connectivity of all nodes to the system with simulated pipeline damage. Remove the disconnected nodes by further modifying the input file.
(4) Perform hydraulic analysis using EPANET.
(5) Check the pressure at all nodes from the result of Step (4) and, following the approach proposed by Ballantyne et al. (1990) to eliminate the negative pressure and summarize the water supply by excluding the demands (supplies) at nodes of negative pressure.

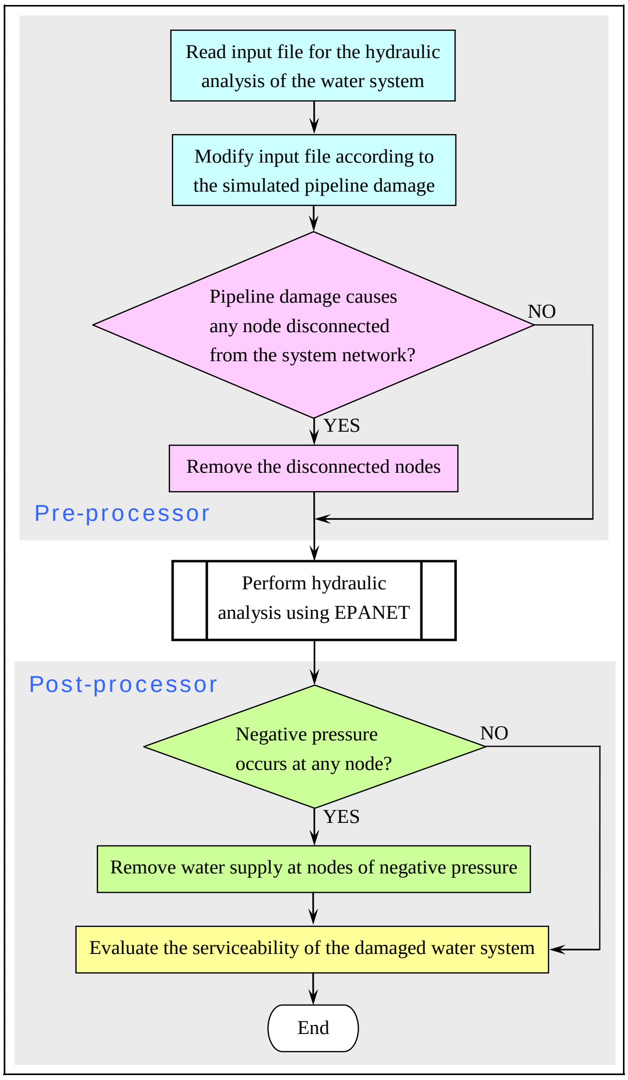

Figure 7 Flowchart for assessing post-earthquake performance of a water system

While performing hydraulic analysis of a water network with pipe damage, it is likely to predict negative pressure at some nodes. Negative pressure is generated due to the assumption that the pipe flows are always full and pressurized. However, water pipelines are not air-tight, especially when they are damaged. As a result, hydraulic analysis of a damaged water network tends toward overestimating its ability to convey water. Elimination of negative pressure under such circumstance is therefore advised. In this study, the approach proposed by Ballantyne et al. (1990), which assumes that no water will flow through negative pressure nodes, was employed in Step 5 of the assessment procedure.

4. CASE STUDY

The off-shore of eastern coast is one of the most earthquake-prone areas in Taiwan region. In this study, the water system in Yi-lan County, one of the three counties in East Taiwan, was chosen as the test bed for the implementation of the proposed ESLE technology. The water system in Yi-lan County is operated by the Eighth Branch of the Taiwan Water Corporation. Its service area is 814 kilometer square. The total pipe length is approximately 2,600 km. The system serves 150,500 customers or 427,000 people, with an average supply of 162,395 CMD (2010). The major pipes include PVC pipes (63%), ductile iron pipes (26%), HIWP (high-impact PVC) pipes (6%) and cast iron pipes (1%). The entire system is simplified as a hydraulic node-and-link network, depicted in Figure 8, with a total of 358 nodes and 439 links.

Consider an earthquake occurring off-shore Yi-lan County. The earthquake magnitude is 7.1, the epicenter locates at the coordinates of $(121.88^{\circ}E,\ 24.28^{\circ}N)$ and the focal depth is 20km. Assume that the source mechanism is a horizontal line source of 84.2km with north-south orientation. The ground shaking and ground failure induced by this scenario earthquake can be simulated by TELES and be illustrated as Figure 9.

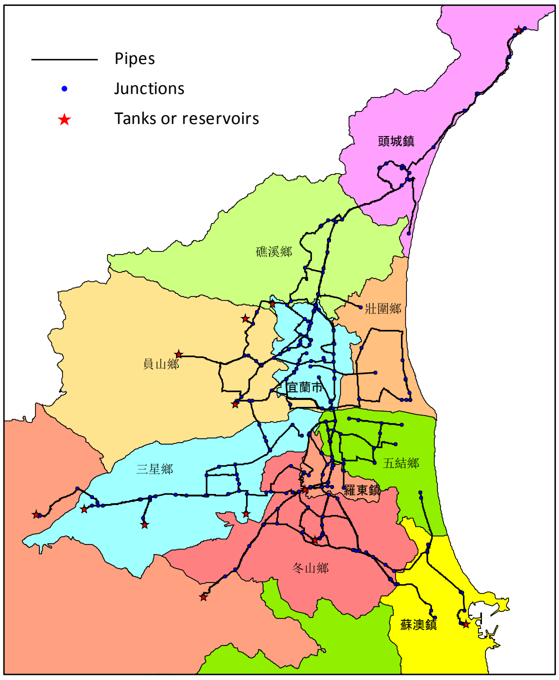

Figure 8 The water system in Yi-lan County

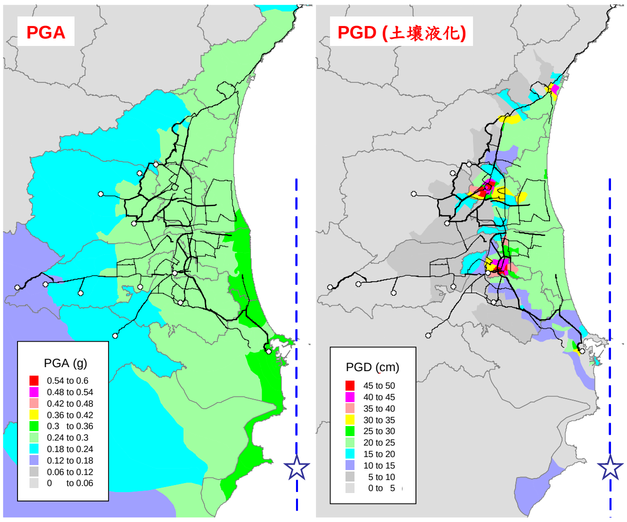

Figure 9 Simulated distribution of PGA (left) and liquefaction-induced PGD (right) in Yi-lan County under the M7.1 scenario earthquake

The Monte Carlo method was employed to estimate the average post-earthquake serviceability of the system. One hundred times of simulation were performed, and the pipe breaks and leaks due to ground shaking and failure were decided according to a random process in each run. The simulation results are depicted in Figure 10. Here, the serviceability index (SI), defined as the ratio of flow at demand nodes after and before an earthquake, is used to quantify the system's ability to meet the demand in each town. Under this scenario, the worst reduction in SI occurs in Tou-cheng (0.3521), while the other two worst reductions occur in Zhuangwei (0.5091) and Jiao-xi (0.5430), respectively.

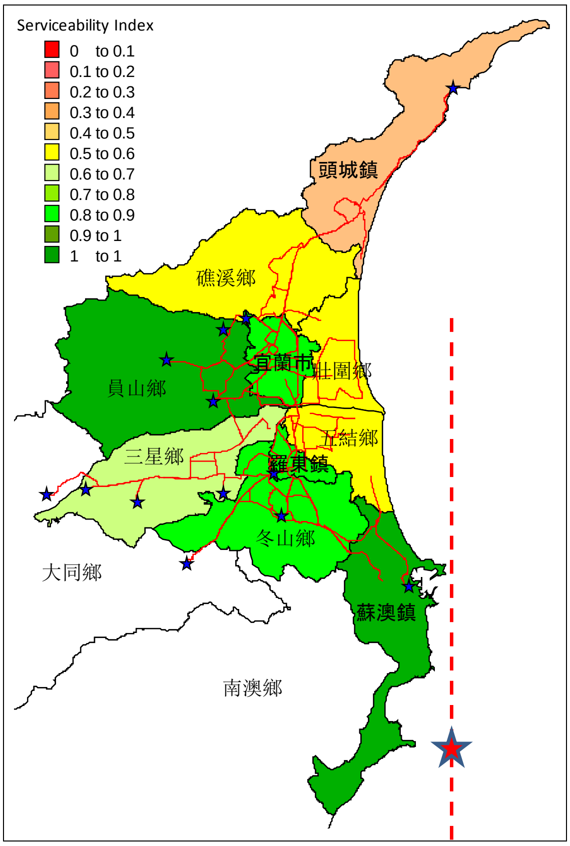

Figure 10 The simulated serviceability of Yi-lan's water system under the M7.1 scenario earthquake

5. CONCLUDING REMARKS

A technology for assessing the seismic performance of water systems has been developed. Key issues including models of strong motion attenuation and pipe repair rate, and the pipe damage model have explained. Particularly, a new approach for the simulation of pipe damage locations based on the expected number of damages of pipe segment has been proposed. The water network system in Yi-lan County, Taiwan was employed as a test bed for case study. A major earthquake occurring off-shore was considered. The post-earthquake performance of the system in terms of the serviceability index (SI) of each service area was simulated.

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