Performance Analysis of Water Systems under Hazardous Conditions

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ABSTRACT

The performance analysis of water systems is very important to urban disaster mitigation. It will benefit the task of preparedness and emergency response through a more practical and more quantitative approach. In this research work, an overview of hydraulics of water system has been provided. A methodology for such implementation based on scenario simulation and hydraulic analysis has been developed. The water system of Taipei Water Department was selected as a test bed for case study. Its serviceability following a major earthquake around Taipei metropolitan area has been quantified.

INTRODUCTION

Service disruption of water supply systems following natural or man-made hazards may cause serious inconvenience to the daily life of people in disastrous areas. Medical caring, sanitation, fire-fighting may be seriously affected. Huge secondary loss caused by business discontinuity is inevitable, too. Due to the difficulties raised by repairing the damage in buried water pipelines, the time needed for the recovery of water supply is much longer than that for, says, electricity or telecommunication. It is desired to facilitate water utility managers and operators with a comprehensive simulation tool for estimating the likely service disruption under hazardous conditions. Measures could be taken then to improve the preparedness and emergency response more appropriately. In this research work, an approach to establish such implementation based on scenario simulation and hydraulic analysis will be discussed and demonstrated.

HYDRAULICS OF A WATER SYSTEM

A water system is a system of engineered hydrologic and hydraulic components which provide water supply. A water supply system typically includes: (1) The watershed or geographic area that collects the water; (2) A raw water collection point where the water accumulates, such as a lake, a river, or groundwater from an underground aquifer; (3) Water purification facilities; (4) Water storage facilities such as reservoirs or water tanks; (5) Water pressurizing components such as pumping stations; (6) A pipe network with switching valves for the distribution of water to consumers and other usage points (such as fire hydrants) (Wiki encyclopedia).

A water system can be conceptually represented as a network consisting of nodes and links see Figure 1. The nodes can be categorized into three types, i.e. reservoirs, tanks, and pipe junctions. The reservoirs and tanks feed water into the water network. Some of the junctions feed water to consumers, and are therefore specified with a value of demand indicating the amount of water needed by the consumers. Also, the links can be categorized into two types, i.e. water pipes and pumps. Generally, the valves inside a water pipe network are specified at a pipe segment and treated as one of its property.

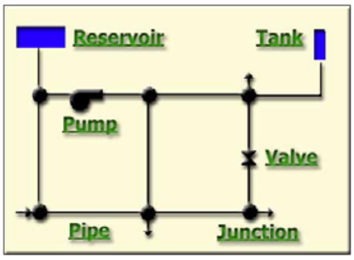

Figure 1. Schematic diagram of a simplified water system (courtesy: U.S. Environmental Protection Agency website).

Consider a water network with m junctions and n pipes. The hydraulic problem of the water network is that, given the initial water heads at all reservoirs and tanks, how to solve the head of each junction and the flow at each pipe, such that the pumps can drive the water network to meet the required amount of water (flow) from each of the demanding junction. Basically, these m + n unknowns can be solved by the equation of continuity at each junction combined with the flow headloss relation in each pipe. It is worth mentioning that the software called EPANET is a famous and very power computer program for the simulation of hydraulic and water quality behavior within a pressurized pipe network (Rossman 2000). It is developed and maintained by the U.S. Environmental Protection Agency and, best of all, the computer codes are free and well documented. It has been widely adopted by commercial packages, e.g. WaterCAD and MIKE NET, as the hydraulic engine.

AFFECTION OF HAZARDS TO A WATER SYSTEM

By all means, natural or man-made hazards may damage the facilities and buried pipelines of a water system directly. Earthquake is one of the most damaging natural forces to water systems. Ground failures and strong motions are the most common causes of damage during an earthquake. Inundation of equipment (mostly the booster pumping stations and wells), loss of power and communications, damage of pressure vessels (chlorine cylinders, etc.), damage of conveying pipes through a structurally weakened bridge are also very common and may happen for various natural or human causes.

Hazards may affect the serviceability of a water system in another way. For example, flooding and debris flow in the catchment areas may increase the turbidity of raw water of a reservoir and halt the water treatment plants. This is very common in Taiwan during typhoon season. One of the worst experiences is the case of Aere typhoon in 2004. The typhoon brought catastrophic rainfall to the catchment of Shihmen reservoir and dramatically escalated reservoir turbidity. Water supply to more than 3.2 million people in the Tauyuan area was suspended for 17 days (Chen et al., 2009)! Sometimes, the raw water may be polluted, or the pipe flows may be contaminated due to the break or leak of buried pipelines through waste storing sites. In such case, it is the quality of pipe flow to be concerned.

Sometimes, the damage or loss of functionality of components in a water system could be associated with a node in the network. To analyze the performance of the system hydraulically, this node should be removed directly, and the ends of pipes connecting to this node can be treated as open to the atmosphere by assigning a new node, actually an empty reservoir, at each of the pipe end. Otherwise, for pipe damage, there are two ways to deal with. One is to treat as a pipe break, and the other is to treat as a pipe leak. The hydraulic models for both pipe breaks and pipe leaks are discussed below.

HYDRAULIC MODELS FOR PIPE DAMAGES

A pipe break and its hydraulic model could be depicted as the schematic diagrams at the left side of Figure 2. At each of the broken ends, a reservoir and a short pipe with a check valve are needed being added to mimic the mechanism for water flowing into the atmosphere. To take into account the effect of a pipe break in simulation, several steps for modifying the hydraulic model of the associated water system have to be carried out. 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, respectively.

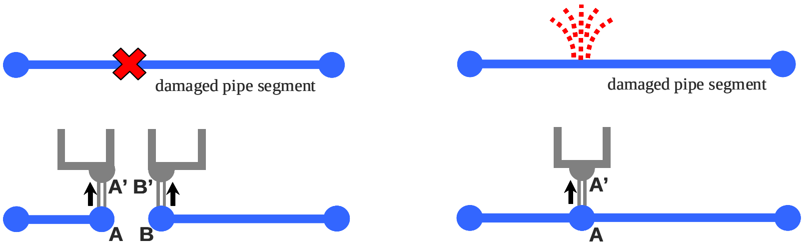

Figure 2. The pipe damage and hydraulic model for a pipe break (left) and a pipe leak (right).

Otherwise, a pipe leak and its hydraulic model could be depicted as the schematic diagrams at the right side of Figure 2. 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 (Shi 2006, Wang 2006). A check valve is designated to the fictitious pipe to ensure that water flows from the leaking pipe to the reservoir. The corresponding steps for modifying the hydraulic model of the associated water system could be summarized as: (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.

METHODOLOGY FOR QUANTITATIVE PERFORMANCE ANALYSIS OF WATER SYSTEMS UNDER HAZARDOUS CONDITIONS

There are two approaches to specify the status of damage of a water system, namely the deterministic approach and the probabilistic approach. The deterministic approach is to decide exactly what and how the components of a water system are damaged, based on either the field data collected after a hazardous condition or based on merely an assumption. On the other hand, the probabilistic approach is to decide the status of damage of a water system based on a scenario as well as a set of analytical or empirical formulae specifying the vulnerability of the components. Usually, fragility curves (which specify the probability of occurrence a damage state at a intensity of hazard) are employed to describe the vulnerability of various kinds of equipment, while pipe repair rate equations (which specify the numbers of repairs or damages per unit pipe length at a intensity of hazard) are employed to describe the vulnerability of various kinds of pipelines.

Once the deterministic approach is to follow, i.e. the overall status of damage of a water system is given precisely; this information can be used to modify the hydraulic model of the water system straight forwardly. However, once the deterministic approach is to follow, i.e. only the scenario (distribution of intensity of hazard) and component vulnerability formulae are given, it is advised to specify the status of damage of a water system through the Monte Carlo simulation, which avoids theoretical difficulty to deal with the problem analytically. One benefit to employ the Monte Carlo simulation is that the uncertainties within the parameters of the whole can be investigated easily (Liu, 2009a).

Furthermore, an algorithm is needed to simulate the locations of pipe damage that statistically follows the repair rate equations for pipelines. Conventionally, the algorithm based on the assumption that the occurrence of damage along a pipeline follows the stationary Poisson process is widely employed (Shi 2006, Wang 2006). Recently, a new approach based on the expected number of damages of each pipe is newly proposed by the author (Liu, 2009b). It possesses several merits over the Poisson process approach. Firstly, it allows a varying repair rate along a pipe, which has been divided into shorter pipe segments in advance. Secondly, the probability a pipe segment is designated as being damaged is rigorously consistent with its expected number of damages. Finally, the number of generated locations is guaranteed the same as the expected number of damages.

Finally, the procedure of performance analysis of a damaged water system is illustrated as the flowchart in Figure 3. It reads:

1. Read the input file for hydraulic analysis of the interested water network 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 equipment and pipe damages based on the hazardous condition. A preprocessor has to be developed to modify the input file to make it hydraulically equivalent to the damaged water system.
3. Check the connectivity of all nodes to the network system with simulated pipe 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 summarize the water supply by eliminating the demands at nodes of negative pressure.

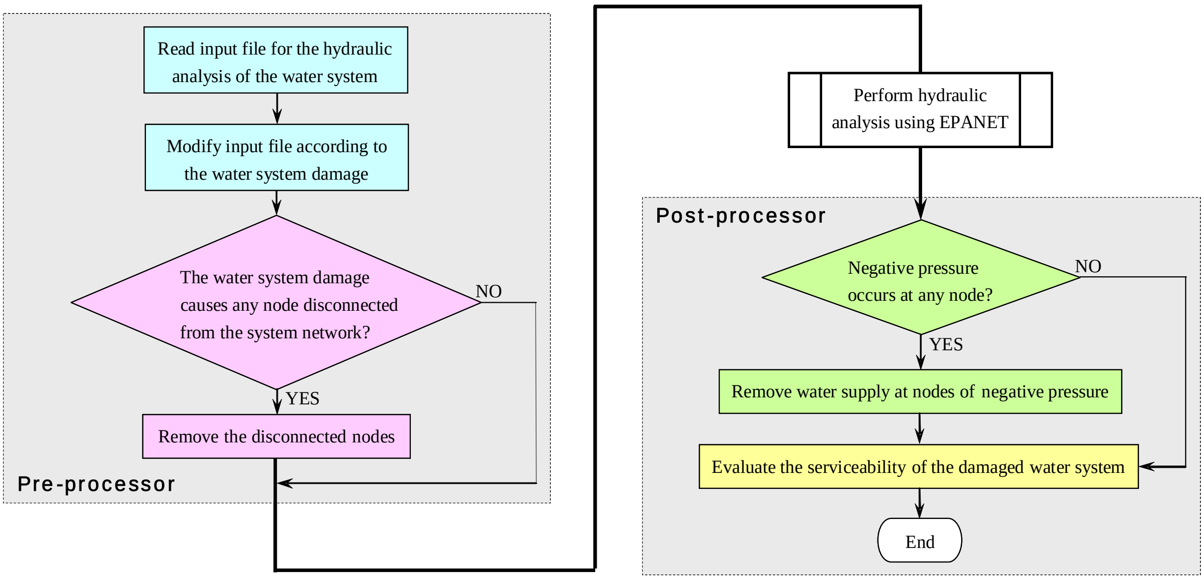

Figure 3. The flowchart for performance analysis of a water system.

EXAMPLE: SEISMIC SCENARIO OF TAIPEI WATER SYSTEM WITH PIPE DAMAGE

The water system of the Taipei metropolitan area has been selected as a test bed for case study. This water system is operated by the Taipei Water Department (TWD). It provides service to the Taipei City as well as four other cities of the Taipei County. It has a service region of 434 square kilometer separated into 10 service areas, and serves water to 1.51 million customers or 3.85 million people. The daily water supply is around 2.5 million tons.

An M7.5 earthquake scenario associated with the Hsincheng fault is assumed here. Analysis through a 100-time Monte Carlo approach has been conducted. The simulated serviceability index (SI, the ratio of flow at demand nodes before and after an earthquake) for each service area is depicted in Figure 4. The SI values vary between 0.44 and 0.92.

SUMMARY

An overview of hydraulics of water system has been provided. A methodology for such implementation based on scenario simulation and hydraulic analysis has been developed. The water system of Taipei Water Department was selected as a test bed for case study. Its serviceability following two most likely major earthquakes around Taipei metropolitan area has been quantified.

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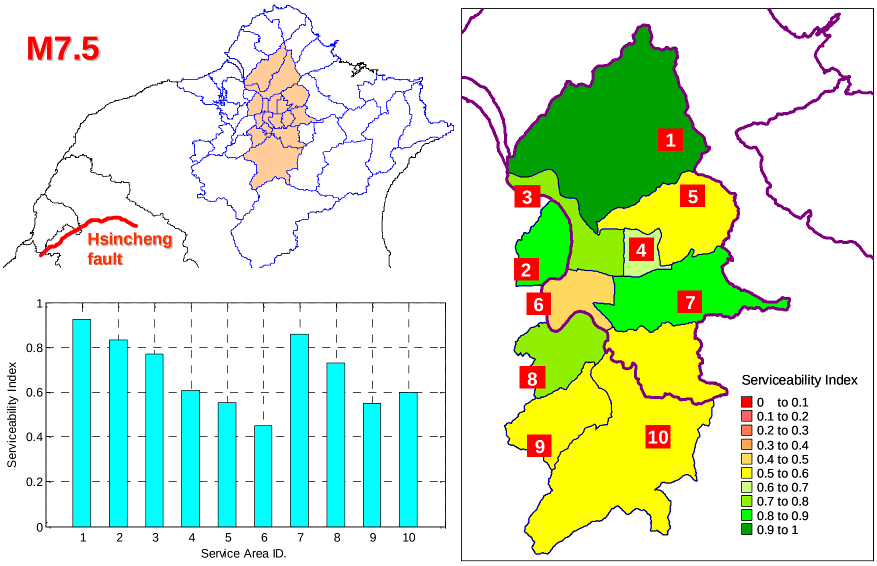

Figure 4. The simulated distribution of SI value for the TWD water system following the considered M7.5 earthquake associated with the Hsincheng active fault.

REFERENCES

1. Chen, S.-H., Jong, C.-G. and Lin, C.-C. 2009. “Strategy of Shihmen Reservoir High Turbidity,” Proc. 6th Taiwan-US-Japan Workshop on Water System Seismic Practices, (Technical Report NCREE 09-019, National Center for Research on Earthquake Engineering, Taipei, pp.49-59), Taipei, Taiwan.
2. Liu, G.-Y. and Hung, H.-Y. 2009a. “Seismic Performance Simulation of Water Systems Considering Uncertainties in Ground Motions and Pipeline Damages,” Proc. 10th Int. Confer. Struct. Safety and Reliability (ICOSSAR 2009), Paper No. 709, Osaka, Japan.
3. Liu, G.-Y. and Hung, H.-Y. 2009b. “Hydraulic Performance Analysis of Water Systems under Major Earthquakes,” Proc. 6th Taiwan-US-Japan Workshop on Water System Seismic Practices, (Technical Report NCREE 09-019, National Center for Research on Earthquake Engineering, Taipei, pp.152-162), Taipei, Taiwan.
4. Rossman, L. A. 2000. EPANET 2 User’s Manual, EPA, Cincinnati, OH.
5. Shi, P., O’Rourke, T. D. and Wang, Y. 2006. Simulation of Earthquake Water Supply Performance, Proc. 8th U.S. Nat. Confer. Earthquake Eng., Paper No. 1295, San Francisco, CA.
6. Wang, Y. 2006. Seismic Performance Evaluation of Water Supply Systems, Ph.D. Dissertation, Cornell University, Ithaca, NY.