

Earthquake Vulnerability of Water Distribution Systems from Topology Perspective

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Abstract – Past earthquakes have demonstrated that water distribution systems (WDSs) suffered significant damage like buildings. System service ratio (serviceability) after earthquake is presented herein and calculated for hypothetical water distribution systems. GIRAFFE computer program was used to perform Monte-Carlo probabilistic simulations of the systems. Four different repair rates 0.2, 0.5, 2.0 and 4.0 were used in the analysis. Robustness and vulnerability of water distribution systems were evaluated with serviceability and system topology.

Keywords – Water Distribution System, Earthquake, Serviceability, Vulnerability, Topology

1. INTRODUCTION

Earthquakes are destructive for all structures. Ravage of earthquake on buildings or above ground structures is blatant but obscure for infrastructures. Piped infrastructures are one of the important components of infrastructure systems that's why they called as lifelines. Water distribution systems (WDSs) are one of the critical lifeline systems in urban areas. Past earthquakes have demonstrated that WDSs are vulnerable to earthquakes. The failure of a WDS not only impairs firefighting capacity, but also disrupts residential, commercial, and industrial activities, resulting huge economic losses. Hence, it is important to assess the seismic performance of a WDS [1]. Damage to lifelines not only results in physical impairment and cost of repair at specific locations, but also the losses of connectivity and potential for more widespread and serious losses of functionality throughout the network [2].

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Lifelines are configured as networks. A water distribution network consist of hydraulic apparatus (control valves, pumps, tanks, reservoirs etc.) as the nodes (or vertices) and pipes as the edges (or links) of the network. Post-earthquake serviceability of WDSs of some cities and hypothetical systems were studied in the literature. Javanbarg and Takada assess the seismic reliability of Osaka City after the 1995 Kobe earthquake using availability and serviceability indices [3]. Chou and others examined the serviceability of the Lan-Yan area in Taiwan after soil liquefaction by means of GIRAFFE software [4].

In this study, damage concepts of a WDS were investigated, pipe damage modeling and negative pressure treatment were described. Then Monte Carlo (MC) simulation technique in the pipe damage process was explained. As a case study, earthquake performance of nine hypothetical water distribution systems was examined.

Earthquake damage to buried pipelines can be attributed to transient ground deformation (TGD) or to permanent ground deformation (PGD) or both. TGD occurs as a result of wave propagation or ground shaking effects while PGD occurs as a result of surface faulting, liquefaction, landslides and differential settlement from consolidation of cohesionless soils. The relative magnitudes of TGD and PGD determine which will have the predominant influence on pipeline response [5]. The effects of TGD and PGD are evaluated for the components of above ground and underground facilities of WDS. The underground facilities performance under seismic loading is assessed by models for soil-structure interaction, including empirical models based on the observations from the past earthquakes, closed form analytical methods and numerical simulations such as finite element analysis. To account for uncertainty with respect to component or facility response, seismic behavior is frequently characterized by fragility curves that provide the probability of failure as a function of demand (Peak Ground Acceleration, Peak Ground Velocity etc.). Fragility curves can be derived from either the observations of past earthquakes or Monte Carlo techniques that have special capability in quantifying uncertainty [2]. PGD hazards are usually limited to small regions with high damage rates due to the large deformation imposed on pipelines. In contrast the TGD hazards typically affect the whole pipeline network, but lower damage rates [6]. In this study WDS damage is represented by only with pipe damages, earthquake effects on the other components of the WDS like pumping and storage facilities were not taken into consideration. Pipe damages were represented with repair rate (RR) (repairs/km).

2. MATERIAL AND METHODS

In a real WDS, water distributed along pipe but in the mathematical model pipe junctions are accepted as consumption points. A hydraulic network is a mathematical model of a WDS in which the physical components are represented as nodes and links. Pipes are links and junctions of the pipelines are nodes in the hydraulic network model. In the event of an earthquake a WDS may sustain various kinds of damage, previous research shows that buried pipelines in a WDS are the most vulnerable components [7].

In this study Graphical Iterative Response analysis for Flow Following Earthquakes (GIRAFFE) software and its methodology of pipe damage simulation and negative pressure elimination will be used. GIRAFFE is developed at Cornell University dedicating for the hydraulic analysis of the damaged water supply systems [8]. GIRAFFE works iteratively with the EPANET which is a computer program that performs extended period simulation of hydraulic and water quality behavior within pressurized pipe networks [9]. GIRAFFE groups pipe damages into two as break and leak.

A break is defined as the complete separation of a pipeline, such that no flow will pass between the two adjacent sections of the broken pipe. In case of the break, water flows from the two broken ends into the surrounding soil. In GIRAFFE the broken pipe is modeled by using the EPANET elements as a fictitious pipe and reservoir are attached at each broken end of the pipe, check valves ensure that water only flows from the broken pipe into the reservoirs which are fixed at atmospheric pressure to simulate the broken pipe being open to the atmosphere [8].

A leak is defined as a gap in pipe, such that water will continue to flow through the pipeline, while some loss of pressure and flow through the leak. In GIRAFFE leakage is simulated by a fictitious pipe open to the atmosphere, simulated as an empty reservoir with the same elevation as the leak location. A check valve constrains flow from the leaking pipe in one direction. The roughness and minor loss coefficients of the fictitious pipe are taken as infinite and 1, respectively, such that all energy loss from the leak is related to the minor loss [8]. Since a leak is modeled as a fictitious pipeline in hydraulic network analysis in GIRAFFE, the area of this pipeline should be calculated from the equivalent orifice diameter. GIRAFFE classifies leaks into five scenarios as annular disengagement, round crack, longitudinal crack, local loss of pipe wall and local tear of pipe wall which are frequent leak types for metallic pipes. Equivalent orifice area equations for each leak type can be found in the GIRAFFE manual [8]. Probabilities of the leak scenarios are dependent to the pipe material. In this study pipe material is accepted as ductile iron and default leak type probability values for this material in GIRAFFE are annular disengagement 80%, longitudinal crack 10% and local loss of pipe wall 10%; round crack and local tear of pipe wall type cracks are not expected for ductile iron pipes.

Hydraulic network analysis solves incompressible water flow in a pressurized pipeline network based on two principle laws: conservation of mass and conservation of energy. The conventional hydraulic network analysis algorithm does not differentiated positive and negative pressures and only uses the total head difference to drive water flow to satisfy demands. Commercial hydraulic network analysis software packages are designed for undamaged systems. The forced satisfaction of all demands may lead to the prediction of unrealistically high negative pressures at some nodes. Water distribution systems are not air tight so that their ability to support negative pressures is very limited [6].

In GIRAFFE, an isolation approach is applied to treat the negative pressures. This isolation approach works with EPANET hydraulic network engine iteratively. After hydraulic network analysis of the damaged system using EPANET engine, nodes with negative pressures are identified and isolated step by step, starting with the node of highest negative pressure. After each elimination, network connectivity is checked. If part of the system is isolated from the main system without water sources,

it is taken out of the system. Flow analysis and the elimination process continue until no negative pressure nodes exist in the system [8].

To simulate the earthquake performance of a WDS, pipe damage, including breaks and leaks, needs to be added in the network. Hydraulic simulation is then performed on the damaged network to predict the flow and pressure distributions. In GIRAFFE the pipeline break and leak models can be implemented into a hydraulic network both deterministically and probabilistically. The deterministic implementation specifies the number and location of leaks and breaks, and leak types, occurring in a pipeline network. This implementation can be used to simulate the performance of a WDS under a specific damage scenario. Whereas damage type and place has a probabilistic character even the RR of the pipes are known. The probabilistic implementation generates randomly distributed pipe damage in the system according to pipeline repair rate. Three normally distributed random numbers are used to determine the place of the damage, state of the damage (break or leak) and the leak type if it is a leak. In HAZUS [10] it is recommended that 80% and 20% of earthquake damage occurs as leaks and breaks, respectively, under seismic wave effects or TGD (percentages swap in case of PGD). With GIRAFFE, users have the ability to set the percentages of leaks and breaks to values other than the default settings of 80% and 20%, respectively [8].

The probabilistic implementation applied many times by using MC simulation to show the random character of damage. In GIRAFFE, number of MC simulations can be specified by user (MC Fixed Number) or automatically determined according to the user-specified convergence criteria (MC Flexible Number).

Reliability assessment of water networks comprises a complex, yet essential process. The seismic reliability of water networks is possible to be measured using different indices of physical nature or not, like vulnerability, connectivity, serviceability, maximum flow, redundancy and economic loss [7].

GIRAFFE uses the Seismic Serviceability as the performance indicator of the earthquake damaged water distribution network which is given in Eq. (1).

$$S_s = Q_T / Q_T^* \quad (1)$$

Where, S_s is the seismic serviceability, Q_T is the available demand and Q_T^* is the required demand. The serviceability can be calculated for each demand node and for the entire system. For deterministic simulation, the serviceability for each demand node is either 1 if this demand can be satisfied, or 0 if this demand node is isolated due to the negative pressure or connectivity problems. The serviceability for the entire system is the sum of the demands that can be satisfied over the sum of the total required demands. For probabilistic simulation, the system serviceability is reported in a matrix format. For each Monte Carlo simulation run, the serviceability is reported for each demand node and for the entire system [6].

Performance indicators of a damaged WDS will be examined by means of 9 hypothetical WDSs in this study. The basic hypothetical system consists of 51 pipes (edges), 36 pipe junctions (nodes, vertices) and a reservoir. Elevations of all junctions are 100 meters and lengths of all pipes are 400 meters. Demand from each node is uniform and 2 liters per second. Water surface elevation of the reservoir is 160 meters and all pipes are ductile iron with the Williams Hazen roughness coefficient of 130.

Pipe diameters are varying from 80 mm to 500 mm as shown in the Fig. 1. The basic hypothetical water distribution system will be called as H1.

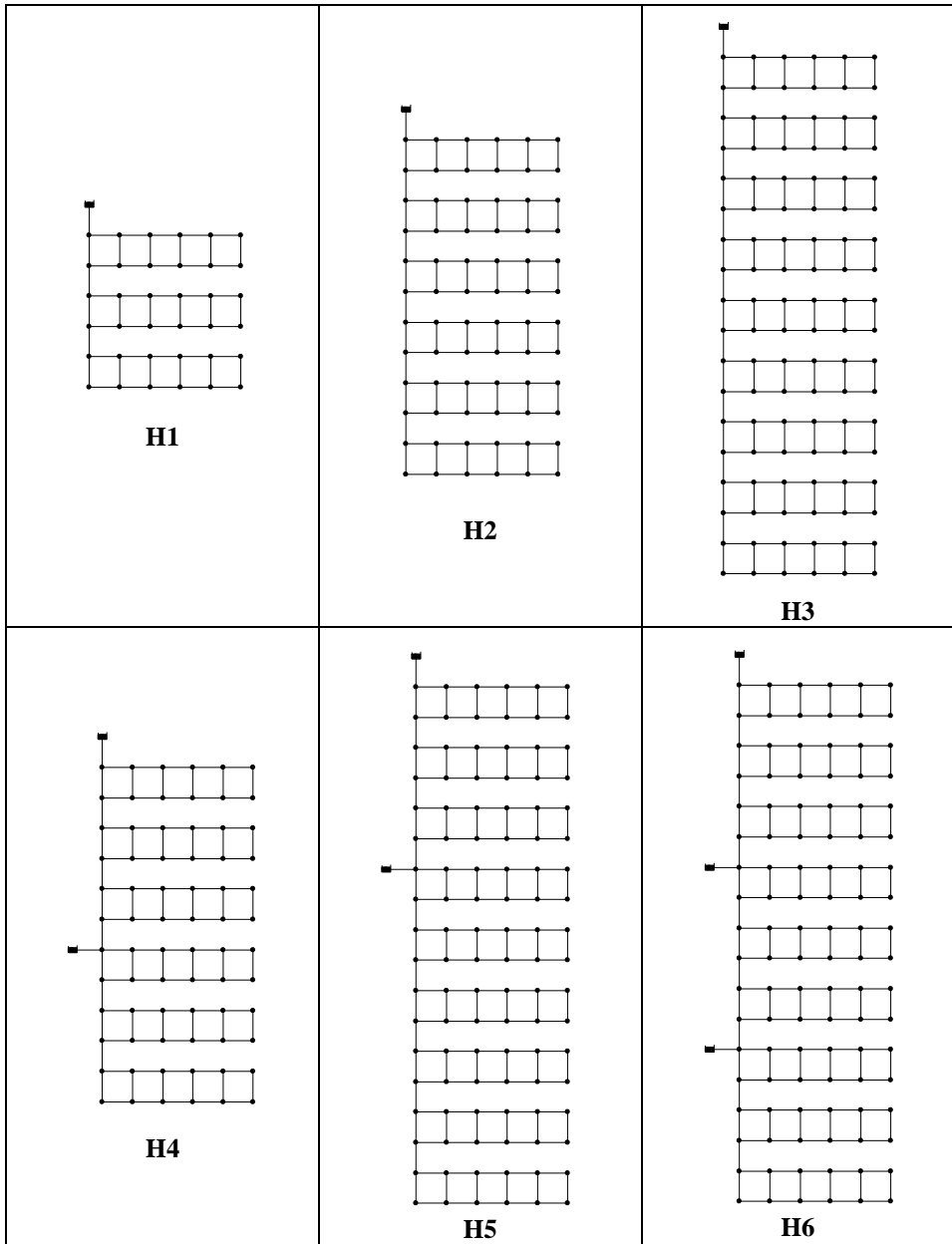


Fig. 1. Schematic drawings of the hypothetical water distribution systems (H1 – H6)

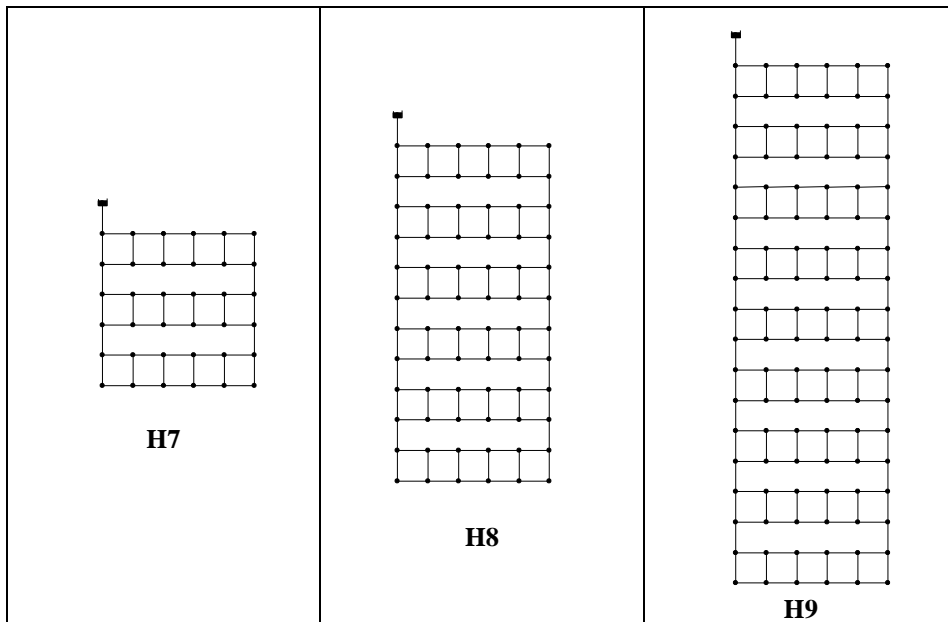


Fig. 1 (Cont.). Schematic drawings of the hypothetical water distribution systems (H7 – H9)

Based on the system H1, 8 more hypothetical systems were derived. Schematic drawings of these systems are given in Fig. 1. Other hypothetical water distribution systems were formed as follows; H2 system was obtained by doubling the H1 distribution system. H3 system is the triple of the H1 distribution system. An extra reservoir added in the mid of the system H2 and then the system H4 formed. One and two reservoirs added to the system H3 and then the system H5 and H6 developed, respectively. Edge of the eaves of systems H1, H2 and H3 were connected with pipes then the systems H7, H8 and H9 were obtained. Pipe lengths (100 meters), pipe materials (ductile iron) and Williams-Hazen roughness coefficient values (130), elevations of the nodes (100 meters) and reservoirs (160 meters), node demands (2 liters per second) are same for all other derived hypothetical water distribution systems. Only the pipe diameters of the main distribution line were changed to ensure reasonable velocities in the pipes and pressures in the nodes when the system enlarged. An extra node and 1 meter long pipe added just at the exit of the reservoirs in all systems and these nodes have no water demand.

Seismic performances of the hypothetical WDSs are evaluated using Monte Carlo simulations in conjunction with GIRAFFE. Up to 2000 MC runs were performed for each system and for each repair rate. There are 36 different system and repair rate combinations. Repair rates were selected as 0.2, 0.5, 2.0 and 4.0 for all pipes and pipe damage probability for ductile iron pipes was partitioned as 20% breaks and 80% leaks. Minimum pressure to elimination of a node is accepted as -5 psi (-0.34 Atm.). Duration of the simulation is taken as 0 hours because water source of the system is a reservoir not a tank, the amount of water will always be the same

for the other simulation times. Reservoir connected pipes were not let damaged so their repair rates were taken as 0.

3. RESULTS AND CONCLUSIONS

Serviceabilities were calculated for each node and each simulation with the GIRAFFE. Serviceability of the system was calculated for each simulation by dividing the number of nodes whose request was met to the number of total nodes. Serviceability of the nodes was calculated by dividing the number of the simulations in which node demand was met to the total number of simulations. The means of the both serviceabilities should be the same and this is the general serviceability of the system [11]. Mean serviceability values after Monte Carlo simulations of all hypothetical systems with repair rates were given in the Fig. 2.

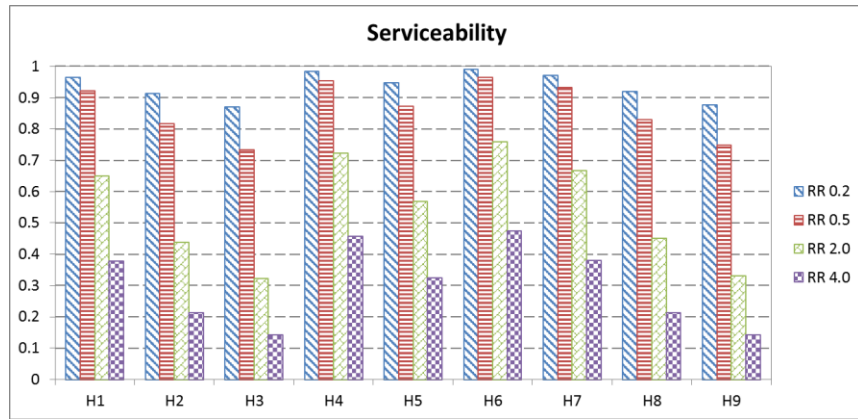


Fig. 2. Mean serviceabilities of all hypothetical systems for different repair rates

According to the Fig. 2 Serviceability decreases when repair rate (RR) increases for all hypothetical systems. When the system grows (H1-H2-H3) serviceability decreases for all RRs. Because the hypothetical system was enlarged along a main line and when this line breaks the other side was isolated from the system. Reservoirs addition (H2-H4 and H3-H5-H6) increases the serviceability for all repair rates. One of the reasons may be the system can meet the demand from the other reservoir when the main line coming from the first reservoir breaks. Connecting the edge of the eaves of system (H1-H7, H2-H8, H3-H9) increases the serviceability for all repair rates. This is because there is an alternative route for the transmission of water. Addition of a reservoir to the system increases the serviceability much more than a pipe addition. The simulation results show that to decrease the earthquake vulnerability of water distribution systems they should not be expanded along a line and alternative routes should be available in the system. Also the system should be fed from many reservoirs.

4. ACKNOWLEDGMENTS

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