Resilience assessment of large scale water distribution networks: a simulation approach

Eleventh U.S. National Conference on Earthquake Engineering
Integrating Science, Engineering & Policy
June 25-29, 2018
Los Angeles, California

RESILIENCE ASSESSMENT OF LARGE SCALE WATER DISTRIBUTION NETWORKS: A SIMULATION APPROACH

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ABSTRACT

The capacity of a community to react and resist to an emergency situation is strictly related to the proper functioning of its own infrastructure systems. This paper proposes a simulation oriented approach to evaluate the resilience of large scale water distribution networks. The case study used in this research is the water network of a large scale virtual city. The water network is modeled using the software EPANET 2.0 with the help of an integrated Matlab toolbox. The network consists of 16000 junctions and 19000 water pipes buried under the road network of the city. A series of earthquake scenarios is applied to the water network and the damage induced by the earthquakes has been determined using fragility function. The failure of the system occurs when the water flow and the water pressure go below a certain threshold. The resilience of the network is then evaluated using two indices: (1) the number of users without water, (2) the drop in the total water supply.

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Taurino V, Kammouh O, Cardoni A, Cimellaro GP and Mahin S. Resilience Assessment of Large Scale Water Distribution Networks: a Simulation Approach. *Proceedings of the 11th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Los Angeles, CA. 2018.

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Introduction

The resilience of a community is defined by the ability of its physical and non-physical infrastructure) to return to an ordinary level within a reasonable time following a disaster [1]. Cimellaro, Reinhorn et al (2010), define the resilience index *R* as a measure of a system's capability to sustain a level of functionality over a period of time called the Control Time (T_{LC}), which usually corresponds to the system life cycle [2]. Recently, much effort has been done to develop new procedures to assess the resilience of existing communities [2-8]. Some work focused mostly on the assessment of the restoration time of infrastructure [9, 10]. Nevertheless, more work is still needed to define intrinsic countermeasures for communities to improve their resilience response against events like earthquakes.

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In this context, virtual cities can be a good tool to assess the reliability of infrastructures and their interdependency; therefore, the use of a virtual city, namely IDEAL CITY, is adopted in this paper. IDEAL CITY is an under-development virtual city which consists of 890,000 inhabitants. The objective of this virtual city is to integrate all critical infrastructures of a virtual community within the same model. Then, a seismic event will be applied to study several complex aspects, such as the interdependency among the infrastructures. Currently, the numerical models of the water network distribution, sewer plant, electric plant, road lines, and buildings have already been built and integrated in the virtual city.

In this paper, IDEAL CITY is used to evaluate the effect of a seismic event on the water distribution network. Multiple earthquake scenarios have been applied considering the time at which the earthquake happens (striking time). For each scenario, two resilience indices have been evaluated. The first one is based on the number of people suffering the outage of water supply and the second considers the drop in the total water available.

Resilience of Water Network Distribution

Currently, a standard procedure to evaluate the resilience of water networks is missing in the literature. A high serviceability of a water distribution network implies a high water supply with acceptable water pressure. Generally, the water supply depends on the customer request and on the water pressure in the pipes. The damage induced by an earthquake causes a reduction of the pressure and consequently this causes a reduction in the water supply.

In this paper, a 24-hour demand pattern is defined according to the customer request in the virtual city. Two serviceability functions $F_1(t)$ and $F_2(t)$are presented. The first is related to the number of people without water while the second measures the ratio between water supply and water demand. The mathematical equation of the first performance measure is:

$$F_1(t) = 1 - \frac{\sum_i n_e^i(t)}{n_{TOT}} \qquad \text{for } i = 1, \dots \text{N} \tag{1}$$

where $n^i_e\,(t)$ is the number of people connected to node i (i.e., who get their demand from the water supply provided by node i) suffering insufficient pressure; n_{tot} is the total number of people within the water distribution network; i is the generic node, N is the total number of nodes. The number of people without water at given node following a disaster event is assumed to be proportional to the water supply reduction at the same node:

$$n_e^i(t) = n_i \frac{w_{Lost}^i(t)}{w_i(t)} \tag{2}$$

where n_i is the total number of people connected to the node i; w^i_{Lost} is the volume of water lost at node i; w_i is the water demand at node i under normal operating conditions. The water loss and water demand at a given time step following a disaster event are computed as follows:

$$w_{Lost}^i(t) = \int_0^t \left[Q_{demand}(t) - Q_i(t) \right] dt \qquad \text{for } i = 1, \dots \text{N} \tag{3}$$

$$w_i(t) = \int_0^t Q_{demand}(t)\, dt \tag{4}$$

Q_{demand} is the water demand at node i, Q_i is the available water flow (water supply) at node i, t is a generic time step. The second performance function $F_2(t)$ is related to the water demand and is given by the following formula:

$$F_2(t) = \frac{\sum_i Q_i(t)}{Q_{Demand,TOT}} \tag{5}$$

where $Q_{demand,tot}$ is the total water demand in the city. The recovery time T_R is assumed to last 24 hours (Figure 1). The Control Time T_c is considered equal to T_R in attempt to get a normalized value of resilience. In this specific case, resilience index for each scenario is equal to the average value of the serviceability.

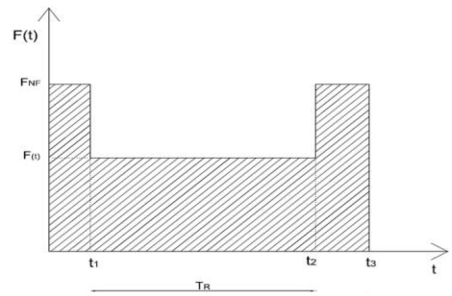

Figure 1. Functionality of Water Distribution Network (adapted from [2]).

For each serviceability function, a resilience index is computed as the area below the function for the defined control time [2]:

$$R = \int_{t_1}^{t_2} \frac{F(t)}{T_c} dt \tag{6}$$

IDEAL CITY: Virtual City for Resilience Analyses

Virtual city applications allow performing resilience analyses as information and data on the infrastructure are readily available. Currently, IDEAL CITY (Figure 2) is under development. It is a virtual city containing 890000 residents. The area is about 120 km^2 divided into 10 districts inspired by the real subdivision of the city of Turin. The inhabitants have been assigned to the districts in a way to create different population densities. Data and information about the city infrastructure are provided as separate layers in a GIS environment using "ArcGIS" software [11].

Figure 2. IDEAL CITY: 3D representation ArcGIS" software [11].

Model Description, Assumption and Calibration

The water network analyzed in this study is based on the urban water network of the city of Turin. Elevations of the grounds have been obtained from Google Maps[12].
Several assumptions had to be made to build the water network model. The geometry of the water network is assumed to overlap with the transportation network of the city as it was not possible to get the exact map of the water network due to security reasons. The water network model (Figure 3) has been built using the epanet-matlab toolkit, which allows controlling Epanet using MATLAB and Epanet 2.0 ([13], [14], [15]).

The EPANET model comprises 19654 ductile iron pipes (1,285,007 m of total length) with a Darcy-Weisbach roughness coefficient εequal to 0.26 mm, 14996 nodes, 9 valves, 38 pumps, 19 reservoirs, and 26 tanks. Nodes are situated 1.2 m below the ground surface. Ground elevations range between 207.76m and 340.68 m above sea level. Water sources are aquifer (82%) and other sources such as rivers and surface water (18%) with an average total daily demand of 353.38Ml/day.

The water demand at each node (junction) depends on the number of people who are served by that node. In fact, in the model, the nodes are connected to the households and not to the population. Therefore, it is first necessary to find the population density per each unit volume of household, which also depends on the district as the population density is not the same among all districts. This is done using the following formula:

$$\rho_j = \frac{P_{e_j}}{V_j}\left[\frac{people}{m^3}\right] \quad (7)$$

where P_j is the household population density in district j (number of people per a unit volume of a household located in district j), Pe_j is the number of people in district j, V_j is the total volume of the households located in district j.

Figure 3. Global view of the water network: 19604 pipes.

The water network is considered as a mesh in the model as the result of pipes intersection. Each mesh element (closed shaped) is assigned a demand based on the total volume of household located inside:

$$q_{j,w} = \rho_j \cdot \delta \cdot V_w \tag{8}$$

where $q_{j,w}$ is the water demand of the mesh element w in district j, δ is the city water supply per inhabitant (equal to 315 l/capita/days) [16], V_w is the volume of the households within mesh element w.

The total water demand per mesh element $q_{j,w}$ is distributed equally among the adjoining nodes (Figure 4a). In other words, the water demand for each node is the sum of the demand contribution of the adjoining mesh elements (Figure 4b):

$$q_i = \sum_{w=1}^{n_{w,i}} \frac{q_{w,j}}{n_{i,w}} \tag{9}$$

where q_i is the water demand at node i, $q_{w,j}$ if the water demand of the mesh element w which is located in district j, $n_{w,i}$ is the number of mesh elements adjoining node i, $n_{i,w}$ is the number of the nodes adjoining mesh w.

Figure 4 (a) Water demand *qj,w* for the mesh element *w*, (b) Water demand for the i-node.

The calibration of a WDN of such a size brings on several difficulties. It is a fundamental issue to ensure an accurate and realistic simulation for both the flow velocity and the pressure. The pipes diameters, the positions of the valves, pumps, reservoirs and tanks, have been determined with the following constraints in mind (Figure 5):

$$0,5\,\mathrm{m/s} \le \text{Velocity} \le 2\,\mathrm{m/s} \tag{10}$$

$$40\mathrm{m} \le \text{Pressure} \le 80\mathrm{m} \tag{11}$$

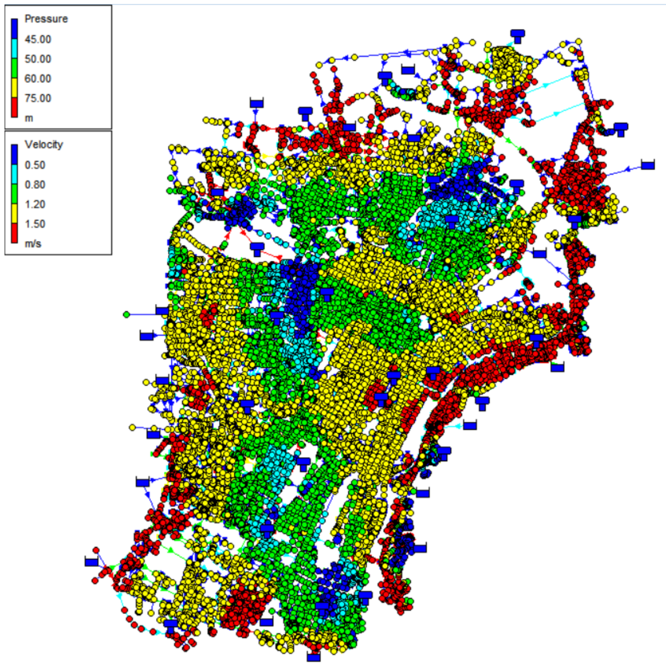

Figure 5. Calibrated WDN

The calibration procedure adopted in this paper is iterative. Future work will be oriented to apply a systematic parametric calibration for large scale water networks [17-19].

Seismic Hazard and Earthquake Damage of Pipes

The seismic hazard is evaluated through a probabilistic approach (PSHA, Probabilistic Seismic Hazard Analysis) according to the Italian code [20, 21]. The hazard is expressed as the occurrence probability of a seismic event of specific features within a certain period of time. The corresponding ground motion (peak ground acceleration PGA) is said to have a P probability of exceedance in T years, return period [21]. In this work, the return period assessed is 2475 years with a probability of exceedance of 2% in 50 years.

According the attenuation law by Sabetta and Pugliese [22], the *PGV* value is influenced by the soil local condition and it is a function of *M* and *R*:

$$Log\, PGV = a + bM + cLog\sqrt{R^2 + h^2} + e_1 S_1 + e_2 S_2 \pm \sigma \tag{12}$$

where a, b, e_1, e_2, are parameters determinate through multiple non-linear regression, h is a function of the depth, σ is the standard deviation of logarithm of PGV, S_1 and S_2 depends on geological soil conditions, M and R are respectively the magnitude and the epicenter distance of the scenario earthquake resulting from the seismic hazard evaluation.

In our case study the PVG value is 35.84cm/s and it is assumed as constant across the entire region of interest.

Vulnerability Analysis of Water Pipes

The reliability of a water pipe network is strictly connected with the concept of vulnerability of its elements. Herein, focus is given to the pipes, the most important component in a pipe network because it is the most challenging part to inspect and replace.

The seismic vulnerability of the buried pipelines discussed in the American Lifelines Alliance (ALA 2001) [23] is adopted in this work. Vulnerability functions are entirely empirical and are based on reported damage from historical earthquakes. Damage is expressed in terms of pipe repair rate *RR*, defined as the number of repairs per 1,000 m of pipe length exposed to a particular level of seismic demand.

$$RR = 0.00187 \cdot K_1 \cdot PGV \tag{13}$$

where $K_1$is a coefficient that depends on the pipe material, pipe diameter, joint type, and soil condition. Once the repair rate is known, the failure probability $P_{f,j}$ of a pipeline is evaluated through the Poisson exponential probability distribution, as follows:

$$P_{f,j} = 1 - e^{-RR \cdot L} \tag{14}$$

where L is the length of pipe and $e^{-RR \cdot L}$ is the probability of zero breaks along the pipe. In this paper three different K_1 are considered in order to investigate the influence of pipe material on the failure probability $P_{f,j}$: $K_1 = \{0.5;0.8;1\}$.

The seismic wave propagation induces strains to the pipes due to the soil-pipe interaction: strains could produce damage if the pipe strength is exceeded. When pipe damage occurs, the pipe is assumed to break in the middle.

A demand driven analysis DDA is carried out in standard procedure by the software EPANET. The DDA procedure fixes the demand at the nodes of the network. When a pipe damage occur, pressure drops at some nodes. The water supply is affected by the pressure drop, thus a pressure driven analysis PDA is carried out to take into account the dependence of water supply on pressure.

Pipe damage is modeled with EPANET2.0 as follows: the pipe is divided into two equal parts and two reservoirs are added at their endpoints in order to simulate the water leakage through the crack (Figure 6). The reservoirs have a total head equal to the elevation of the middle point of the pipe (as the pipe breaks in the middle). A check valve is inserted so that water only flow towards the reservoirs.

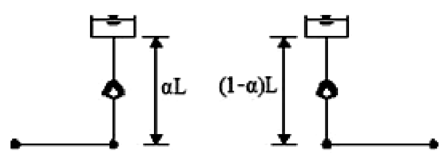

Figure 6: Pipe break simulation in EPANET 2.0 [24].

Under ideal operating conditions, the WDN pressures and velocities range between precise limits defined by the Italian prescriptions [25]. In the case of pipe damage, the pressure at some nodes drops. To take into account scenarios in which the demand is fully dependent on the pressure, a PDA is carried out: first, damaged pipes are introduced in the model and a standard DDA runs. Then, nodes with pressure below value required to satisfy the demand, are converted in Emitter nodes. An Emitter is a node whose demand is proportional to a fractional power of the pressure according the follow equation:

$$Q_i = C_i \left(H_i - z_i\right)^{\alpha} = C_i \cdot p_i^{\alpha} \tag{15}$$

where Q_i is the actual demand flow; C_i is the emitter coefficient; H_i is the actual total head of the i_{th} node; z_i is the elevation of the i_{th} node; p_i is the actual pressure of the node; and α is the emitter exponent (0.5 if no other information are available). Emitter coefficient is evaluated as:

$$C_i = \frac{Q_{demand}}{\left(H_{r,i} - z_i\right)^{\alpha}} = \frac{Q_{demand}}{p_{r,i}^{\alpha}} \tag{16}$$

where Q_{demand} is the demand flow; $H_{r,i}$ and $p_{r,i}$ are respectively the total head and the pressure required to satisfy Q_{demand}. Herein 20 m of water column is assessed the minimum value to satisfy the demand at the nodes. The software runs again with emitters inserted.

The PDA procedure is applied during the breakage. Three cases can occur:

- $Q_i \leq 0$, the actual demand flow at the node is equal to zero,
- $0 \leq Q_i \leq Q_{demand}$, the actual demand flow is equal to Q_i;
- $Q_i \geq Q_{demand}$, the actual demand flow is equal to Q_{demand}.

EPANET software doesn’t allow any upper bound for the equation above mentioned and, moreover, negative flow values have no physical meaning: the *PDA* can be corrected in order to reach a more accurate solution.

Definition of the event scenarios

Resilience is a dynamic quantity characterized by a lack of certainty. Uncertainties are crucial both for risk management and resilience analysis [26]. A Monte Carlo method has been used to generate a large number of simulations in order to study the uncertainty through a Matlab code provided by Fragiadakis [27]. The code requires: pipe diameters, pipe lengths, start and end nodes, and the pipe failure probability. In addition, an importance factor has been assigned to each pipeline: “2” is assigned to main pipelines, “1.5” to the pipes within the districts, and “1” to the connection pipes between the districts. The number of scenarios N_S considered is 5000 which yielded a stable distribution of the results (figure 7).

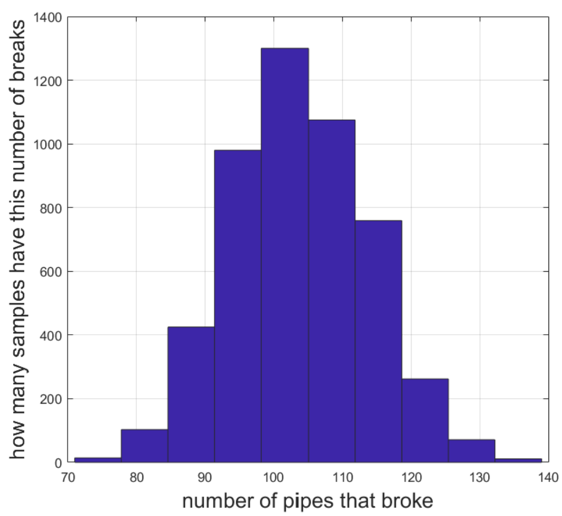

Figure 7 Distribution of scenarios events. The total number of scenarios is 5000. K1= 0,5.

Numerical results

Serviceability functions $F_1(t)$ and $F_2(t)$ are evaluated for the 5000 simulation scenarios and for three values of K_1. The simulations considered a random occurrence time of earthquake. For each of them, two resilience indices have been computed using equations (6). At each earthquake occurrence time, the mean value of the resilience indices has been computed with its standard deviation (Figure 8). Pipes with ductile material (low K_1) show a more resilient behavior than pipes with fragile material (high low K_1). The highest resilience indexes correspond to K_1=0.5.

It is clear that the resilience indicators are not very sensitive to the time at which the earthquake occurs. In addition, the value R follows the water demand pattern: it is lower when a damage occurs during a high water demand hour.

Moreover, the resilience index R_Q (referring to the variation of water supply) is more sensitive than the index R (referring to people suffering with water outage).

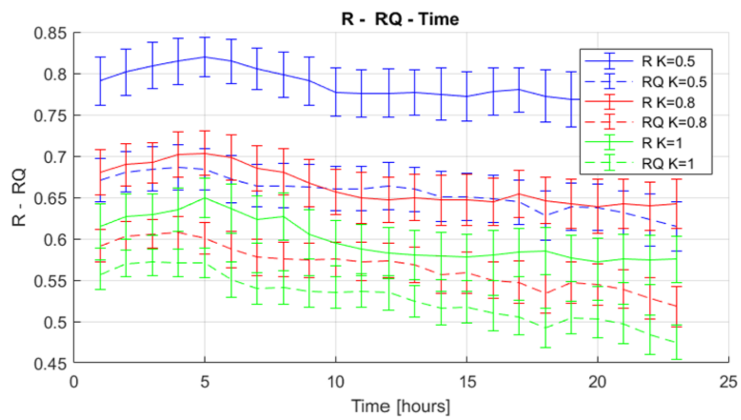

Figure 8. Resilience indices R and R_Q for three K_1 values (pipe material).

Concluding remarks

Two resilience indices to measure the performance of a water distribution network after a earthquake are proposed. The methodology presented here considers the pipes as the only element of the WDN that can be affected by an earthquake. The methodology has been applied to a virtual city, namely IDEAL CITY. Two serviceability function are identified. The first $F_1(t)$ is related to the number of users suffering water outage while the second $F_2(t)$ is related to the reduction in the total water supply. Finally, resilience indices are evaluated as the area under the performance curves. The resilience two indices show different values but they both followed the daily water demand trend.

The introduced methodology can serve as a decision making tool for water distribution systems in any community. Future work will aim at generalizing the methodology. Since water demand pattern, time control and recovery time affect the evaluation of resilience, future work will focus on a parametric study to understand the effect of each parameter on the resilience evaluation. The methodology will also be generalized to include the possibility of changing the seismic input and the geometry of the network.

Acknowledgements

The research leading to these results has received funding from the European Research Council under the Grant Agreement n° ERC_IDEAL RESCUE_637842 of the project IDEAL RESCUE—Integrated Design and Control of Sustainable Communities during Emergencies.

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