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Resilience Quantification of Large-Scale Water Distribution Networks: a Probabilistic Approach

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Abstract: The capacity of a community to react to and resist during an emergency situation is highly related to the proper functioning of its infrastructure systems. Improving the infrastructure response and recovery capacity through management and adaptation strategies can help increase community resilience. Infrastructural assets are considered outdated in almost all countries in the world. This poses a clear vulnerability to infrastructure systems when subjected to disaster events such as earthquakes. This paper proposes a statistical probabilistic approach to quantify the resilience of large-scale Water Distribution Networks (WDN). The resilience of the network is evaluated using two indices: (1) the number of users without water, and (2) the drop in the total water supply, assuming that the local failure of the system occurs when the water flow and the water pressure go below a certain threshold. A series of earthquake scenarios are applied to the studied water network whose damage is determined using fragility functions that integrate the WDN characteristics with the seismic intensity. As an illustration, the proposed approach is used to quantify the resilience of a WDN in a virtual community testbed with 900,000 inhabitants. Results obtained show interesting correlation between the earthquake occurrence time, the water demand pattern, and the pipes material. The presented approach is the first step towards a systemic planning of the maintenance activities and budget allocation of pipeline networks, where both vulnerability and criticality of pipes are combined to obtain a more comprehensive resilience index of the network.

Keywords: infrastructure, resilience, water distribution network, community resilience, restoration, fragility curves, Monte Carlo, testbed, Epanet.

1. Introduction

The resilience of a community is defined as the ability of its physical and non-physical infrastructure to return to their original functionality level within a reasonable time following a disaster (Ellingwood et al. 2016). Recently, much effort has been made to develop general procedures to assess the resilience of existing communities (Bruneau et al. 2003; Kammouh et al. 2019; Kammouh et al. 2018c), and more specific approaches for infrastructure resilience, such as the transportation infrastructure (Kammouh et al. 2018a; Nogal and Honfi 2019; Nogal et al. 2016; Nogal et al. 2017), water infrastructure (Pagano et al. 2019; Soldi et al. 2015), and building infrastructure (Marasco et al. 2018; Zamani Noori et al. 2017). The restoration time of communities and infrastructure is one of the main components of resilience; thus, some works focused solely on the assessment of the restoration time of infrastructure (De Iuliis et al. 2019; De Iuliis et al. 2020; Kammouh et al. 2018b). Nevertheless, more work is still needed to define intrinsic countermeasures for communities to improve their resilience response against events like earthquakes.

This paper focuses on the resilience assessment of Water Distribution Networks (WDN). There have been extensive attempts to propose resilience metrics and performance evaluation approaches for WDN. For example, Assad et al. (2019) proposed a new multi-attribute resilience metric based on the robustness and redundancy of the WDNs. Diao et al. (2016) introduced a global resilience analysis (GRA) approach that can be used as a comprehensive diagnostic framework to evaluate a range of interventions for improving

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system resilience in future studies. Farahmandfar et al. (2017) proposed an easy-to-use metric for quantifying resilience and an optimization framework for improving WDN resilience subjected to budgetary constraints. The proposed metric and the optimization framework can be helpful in rehabilitation planning and capital improvement works by water utilities. Laucelli and Giustolisi (2015) presented a methodology to analyse the vulnerability of water distribution networks (WDNs) to earthquakes by means of risk assessment. The methodology allows analysing and ranking the worst scenarios, being a valuable decision support for improving WDN preparedness to earthquakes.

Currently, a standard procedure to evaluate the resilience of water networks is missing in the literature. Most works propose resilience metrics for water network. These metrics are not able to capture all aspects of resilience, such as the dynamic behaviour of infrastructure functionality. Therefore, there is a need for computational models that allow testing different aspects of resilience. Such models can assist with various engineering applications and stand as decision support tools.

In this paper, a water distribution model for a virtual city is created. A significant effort was made to create the virtual city ranging from data collection, data analysis, and network modelling. The water network is used to evaluate the effect of a seismic event on the network pipes. Multiple earthquake scenarios are applied with different occurrence time to consider the time-dependent pattern of the water demand. The uncertainty of the behaviour of the pipes is also considered by using fragility curves for the water pipes. Finally, the impact of the pipes material on the total resilience is examined by comparing the results for three pipe material types. For each scenario, two resilience indices are evaluated. The first is based on the number of people suffering from the outage of water supply and the second considers the drop in the total water available. Results show a relationship between the resilience index, the water demand pattern, and the earthquake occurrence time. That is, earthquakes occurring at a low-demand hour yield higher resilience that earthquake occurring at a high-demand hour. In addition, the pipes material appears to be a key factor towards increasing or reducing resilience. The virtual city created in this work can be used in future work as a test bed for multiple applications, such as design, restoration, decision support, interdependency with other infrastructure, etc.

The rest of the paper is organised as follows. Section 2 presents the formulation of the resilience indexes used in this work. Section 3 describes the virtual city test-bed and the water distribution network modelling. Section 4 discusses the vulnerability of the water pipes and the fragility curves used. Section 5 presents the earthquake scenarios and discusses the results of the analysis. Finally, conclusions are drawn in Section 6.

2. Resilience metrics

High serviceability of a water distribution network implies the capability of supplying large amounts of water with acceptable water pressure. Generally, the supplied water depends on the customer's request and on the water pressure in the pipes. The damage induced by an earthquake causes a reduction of the pressure, and this consequently 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:

$$F_1\left(t\right) = 1 - \frac{\sum_{i}^{N} n_e^i(t)}{n_{tot}} \tag{1}$$

where $n^i_e\ (t)$ is the number of people connected to node i suffering from insufficient pressure at a given time (pressure < 40m), n_{tot} is the total number of inhabitants, which is assumed to be constant over time, N is the total number of nodes; the second performance function $F_2(t)$ is related to the water shortage at a given time:

$$F_2\left(t\right) = \frac{\sum_{i}^{N} Q_{supply,i}(t)}{\sum_{i}^{N} Q_{demand,i}(t)} \tag{2}$$

where $Q_{supply,i}$ is the available water flow (water supply) at node i, $Q_{demand,i}$ is the water demand at node i. The last two variables are time-dependent. For each serviceability function, a resilience index is computed as the area below the function for the defined control time (Cimellaro et al. 2016), following Equation (6); thus, two resilience indexes can be computed, R_1, linked to the serviceability function F_1, and R_2, linked to F_2. The resilience indexes can be computed as follows:

$$R = \int_{t_1}^{t_2} \frac{F(t)}{T_R} dt \qquad (3)$$

where t_1 is the time at which an earthquake occurs, t_2 is the time at which the functionality of the water network is recovered, thus, the recovery time is equal to $t_2 - t_1$ (Fig. 1). Without loss of generality, in this paper both the recovery time are assumed equal to 24 hours.

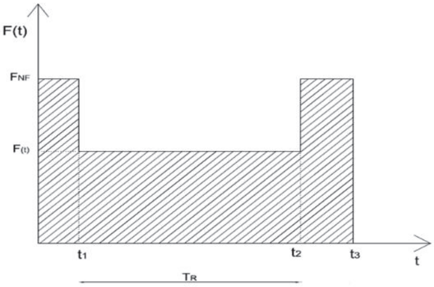

Fig. 1. Functionality of Water Distribution Network, adapted from (Cimellaro et al. 2016)

3. Model Description, Assumption, and Calibration

Virtual city applications allow performing resilience analyses as the information and data on the infrastructure are readily available. Currently, IDEAL CITY (Fig. 2) is a virtual city with almost 900,000 inhabitants. The area is about 120 km^2, divided into 10 districts, inspired by the real subdivision of the city of Turin, Italy. The inhabitants are 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 (ESRI 2011).

Fig. 2. IDEAL CITY: 3D view using "ArcGIS" software.

The water network analysed in this study is based on the urban water network of the city of Turin. Elevations of the grounds are from Google Maps®. Several assumptions are made to build the water network model. The geometry of the water network is assumed to overlap with the transportation network of the city. The water network model (Fig. 3) is built using the Epanet-Matlab toolkit, which allows controlling Epanet 2.0 using MATLAB® (Eliades).

The EPANET model comprises 19,654 ductile iron pipes (1,285,007 m of total length) with a Darcy-Weisbach roughness coefficient equal to 0.26 mm, 14,996 nodes, 9 valves, 38 pumps, 19 reservoirs, and 26 tanks. Nodes are situated 1.2 m below the ground surface. Ground elevations range between 207.76 m and 340.68 m above sea level. Water sources are aquifer (82%) and rivers/surface water (18%) with an average total daily demand of 353.38 Ml/day.

The water demand at each node (junction) depends on the number of people who are served by that node. In this work, 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 households, which also depends on the district as the population density is not the same across all districts. This is done as follows:

$$\rho_j (people / m^3) = \frac{P_j}{V_j} \qquad (4)$$

where ρ_j is the household population density in district j, given in terms of number of people per unit volume of household, P_j is the number of people in district j, and V_j is the total volume of households located in district j.

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

$$Q_{demand,j,w} = \rho_j \cdot \delta \cdot V_w \qquad (5)$$

where $Q_{demand,j,w}$ is the water demand in a mesh element w in district j, δ is the city water supply per inhabitant, obtained from the municipality of the city of Turin (315 l/capita/day), V_w is the volume of the households within mesh element w.

The total water demand per mesh element, $Q_{demand,j,w}$, is equally distributed among the adjoining nodes (Fig. 4 (a)). Hence, the water demand at each node, $Q_{demand,i}$, is the sum of the demand contribution from the adjoining mesh elements (Fig. 4 (b)):

$$Q_{demand,i} = \sum_{w=1}^{n_{w,i}} \frac{Q_{demand,j,w}}{n_{i,w}} \qquad (6)$$

where $n_{w,i}$ is the number of mesh elements adjoining node *i*, $n_{i,w}$ is the number of the nodes adjoining mesh *w*.

For the analysis of the water distribution network (WDN), the formulation is applied in a discrete-time domain assuming time steps of 1 hour.

Fig. 3. The analysed water distribution network.

Fig. 4. (a) Water demand $Q_{demand,j,w}$ within a mesh element w in district *j*, (b) Water demand at node *i*.

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 pressure. The pipes diameters and the positions of the valves, pumps, reservoirs, and tanks have been determined with the following constraints in mind:

$$0.5m/s \leq \text{Velocity} \leq 2m/s \qquad (7)$$

$$40m \leq \text{Pressure} \leq 80m \qquad (8)$$

Fig. 5 shows the calibrated WDN at the peak hour of water demand. 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.

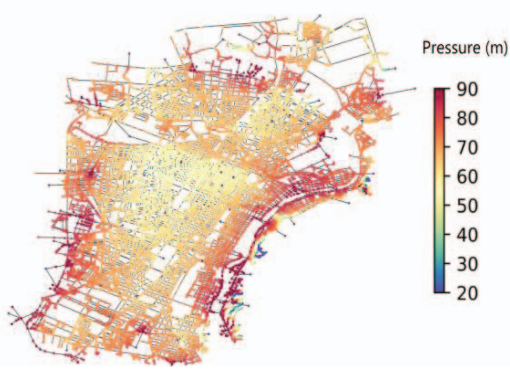

Fig. 5. Water pressure in meters at the first time step of the analysis from the calibrated WDN

4. Vulnerability of the water pipes

The reliability of a water network is strictly connected to the concept of vulnerability of its elements. Herein, the focus is given to the pipe, the most important component in a pipe network, because it is the most challenging part to inspect and replace, and also its extensive distribution and exposure make it especially vulnerable. The seismic vulnerability of the buried pipelines introduced in the American Lifelines Alliance (ALA 2001) (Eidinger 2001) 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 certain level of seismic intensity.

$$RR = 0.00187 \cdot K1 \cdot PGV \qquad (9)$$

where *K1* 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 $P_{f,k}$ of a pipeline *k* is evaluated through the Poisson exponential probability distribution, as follows:

$$P_{f,k} = 1 - e^{-RR \cdot L} \tag{10}$$

where L is the length of pipe, $e^{-RR \cdot L}$ is the probability of zero breaks along the pipe. In this paper, three different values of $K1$ are considered in order to investigate the influence of the pipe material on the failure probability $P_{f,k}$: $K1 \in \{0.5; 0.8; 1\}$. 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. Fig. 6 shows the fragility curves generated for the pipes. In the context of this work, only major damage is assumed to cause water leakage.

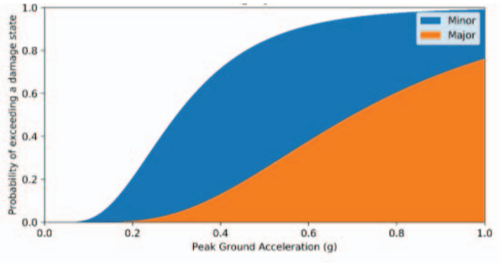

Fig. 6. Fragility function of the water pipes.

Pipe damage is modelled with EPANET2.0® as follows: each damaged pipe is divided into two equal parts. Then, two reservoirs are added at their endpoints in order to simulate the water leakage through the crack (Fig. 7). The reservoirs have a total head equal to the elevation of the middle point of the pipe (assuming that the pipe breaks in the middle). A check valve is inserted so that water only flows towards the reservoirs.

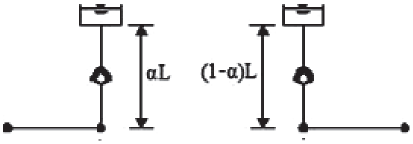

Fig. 7. Pipe break simulation in EPANET 2.0.

A demand-driven analysis (DDA) is carried out in a standard manner using the software EPANET. The problem with DDA is that it fixes the demands at the nodes. However, in the case of pipe damage, the pressure at some nodes drops, and this affects the water supply. Thus, a pressure-driven analysis PDA is needed to account for the dependence of water supply on pressure. To do so, a standard DDA is first performed. Then, nodes with pressure below the value required to satisfy the demand are converted into Emitter nodes. An Emitter is a node whose demand is proportional to a fractional power of the pressure, according to the following equation:

$$Q_{\text{supply},i} = C_i (H_i - z_i)^{\alpha} = C_i \times p_i^{\alpha} \tag{11}$$

where C_i is its corresponding emitter coefficient; H_i is the actual total head of node i, z_i is its elevation, p_i is the actual pressure of the node, and α is the emitter exponent (0.5 if no other information is available). The emitter coefficient is evaluated as follows:

$$C_i = \frac{Q_{demand,i}}{(H_{r,i} - z_i)^{\alpha}} = \frac{Q_{demand,i}}{p_{r,i}^{\alpha}} \tag{12}$$

where $H_{r,i}$ and $p_{r,i}$ are the total head and the pressure required to satisfy $Q_{demand,i}$, respectively. In this work, 20 m of water column is considered as the minimum value to satisfy the demand at any node. The model is run again with the emitters inserted. The PDA procedure is applied during the breakage. Three cases can occur:

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

5. Event scenarios and results

Resilience is a dynamic quantity characterized by a lack of certainty. Uncertainties are crucial both for risk management and resilience analysis (Bozorgnia and Bertero 2004). To study the uncertainty, a Monte Carlo approach is applied to generate a large number of simulations using a Matlab code provided by (Fragiadakis et al. 2012). The code requires pipes diameters, pipes lengths, start and end nodes, and pipes failure probabilities. The earthquake *El centro* that hit the Imperial Valley in south-eastern Southern California near the international border of the

United States and Mexico with a magnitude of 6.9 is considered in the analysis. Fig. 8 shows the earthquake epicentre and the Peak Ground Acceleration distribution considering the attenuation.

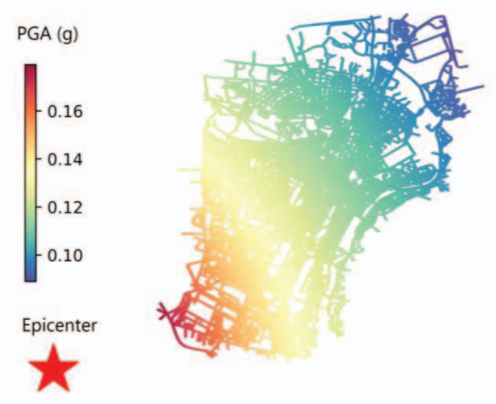

Fig. 8. Earthquake epicentre and Peak Ground Acceleration (PGA).

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 pipes connecting the districts. The number of scenarios is set to 5,000, which yielded an almost normal distribution of the results (Fig. 9). Fig. 10 shows the results of a single simulation in terms of water pressure.

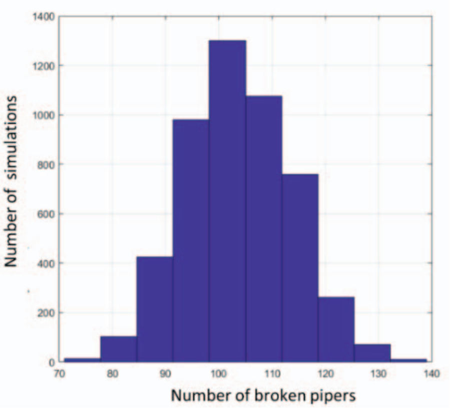

Fig. 9. Histogram of the simulation results. (5,000 simulations, K1= 0.5).

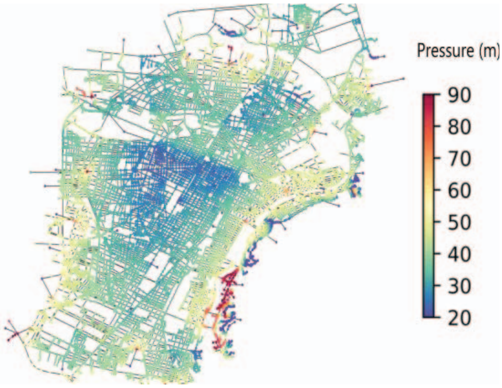

Fig. 10. Water pressure map of one simulation at time step *t=1* following the event with K1=0.5.

The serviceability functions $F_1(t)$ and $F_2(t)$ are evaluated for the 5,000 simulated scenarios and for three values of $K1$. The simulations considered a random occurrence time of the earthquake. For each simulation, the two resilience indexes are computed using Eq. (3). The results of the resilience indexes at each time step are presented in Fig. 11 in terms of mean value and standard deviation. As can be seen in the figure, pipes with ductile material (low $K1$) show a more resilient behaviour than pipes with fragile material (high low $K1$). The highest resilience indexes correspond to $K1$=0.5.

It is clear that the resilience value follows the water demand pattern: it is lower when damage occurs during high water demand periods. Moreover, from Fig. 11, the resilience index R_2 (referring to the variation of water supply) is more sensitive than the index R_1 (referring to people suffering from water outage).

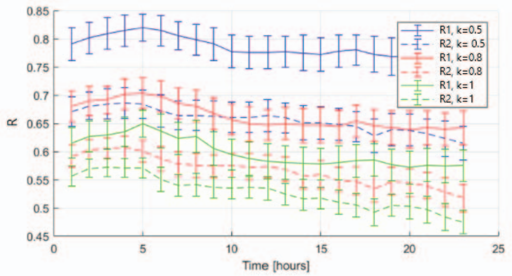

Fig. 11. Resilience indexes R_1 and R_2 for three pipe material values K1.

6. Concluding remarks

Two resilience indexes to measure the performance of a water distribution network after an 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 is applied to a virtual city. Two serviceability functions are identified: $F_1(t)$ is related to the number of users suffering water outage and $F_2(t)$ is related to the reduction in the total water supply. The resilience indexes are evaluated as the area under the performance curves. The resilience indexes seem to follow the daily water demand pattern and are affected by the earthquake occurrence time.

The introduced methodology can serve as a decision-making tool for water distribution systems in communities. 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. In addition, damage incurred to critical elements would result in a larger resilience loss than non-critical elements. The criticality of the pipes also helps in defining the best restoration strategy that guarantees a rapid recovery while keeping the incurred cost at a minimum. Therefore, future work will aim at combining both vulnerability and criticality of pipelines to obtain a more comprehensive resilience index of the network.

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