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RELIABILITY ASSESSMENT OF WATER NETWORKS CONSIDERING SPATIALLY VARIABIABLE SEISMIC GROUND MOTION

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Water distribution networks are essential lifelines that must remain operational following a seismic event. Pre-earthquake assessment, management, and mitigation of the risk of lifelines is of paramount importance to their owners, i.e. authorities and water distribution agencies in designing, constructing and retrofitting their systems to reduce the damage potential in the light of a future seismic event. The assessment of lifeline capacity is of critical importance for the quick resilience of the city and therefore appropriate methodologies for calculating their reliability are always desirable.

In this work, we discuss a novel approach for assessing the probability of the water not being able to reach every house connection following a seismic event. The proposed methodology gives emphasis on the spatial variability of the seismic ground motion, which past investigations typically assume that is uniform throughout the network. Experience and measurements during past earthquakes has revealed that the seismic demand not only is not uniform, but it may vary significantly depending on the local topography and other parameters. We, therefore, attempt to provide a methodology for a system-wide analysis utilizing component analysis, network topology and methods for assessing the spatial variability of earthquake ground motion. We use graph theory to simulate the damaged network. Graph theory is a versatile mathematical tool that allows to extent the proposed approach to other lifelines (e.g. power, transport) and requires only basic knowledge of hydraulics.

The seismic capacity of water distribution networks is based on pipe fragility curves, i.e. relationships that provide the failure probability of a single pipe, given seismic intensity. The outcome capacity of the system is also conditional on the intensity. Relationships for estimating pipe fragility curves are given by US and Japanese guidelines (ALA 2005, JWWA 1997) and are based on data observed during past earthquakes. Herein we adopt the formula of ALA (American Lifelines Alliance), which is of the form:

$$RR = K \cdot a \cdot IM^{b} \tag{1}$$

IM stands either for peak ground velocity (PGV) or for permanent ground deformations (PGD). *K* is a parameter that considers the effect of different material and *a*, *b* are constants. Equation 1 calculates *RR*, i.e. the number of breaks (or repairs) per pipe length. With the aid of the Poisson formula, *RR* gives the failure probability of a single pipe. Recently Christodoulou and Fragiadakis (2014) extended the methodology of ALA including the effect of previous nonseismic damage that can be calculated from everyday measurements.

The capacity of the network, is measured either locally, i.e. as the probability of the network's inability to provide water to an outflow node (house connection). Alternatively, metrics that consider the global capacity of the network can be adopted (i.e. considering the number of customers that will be left without water). All network calculations are performed using Monte

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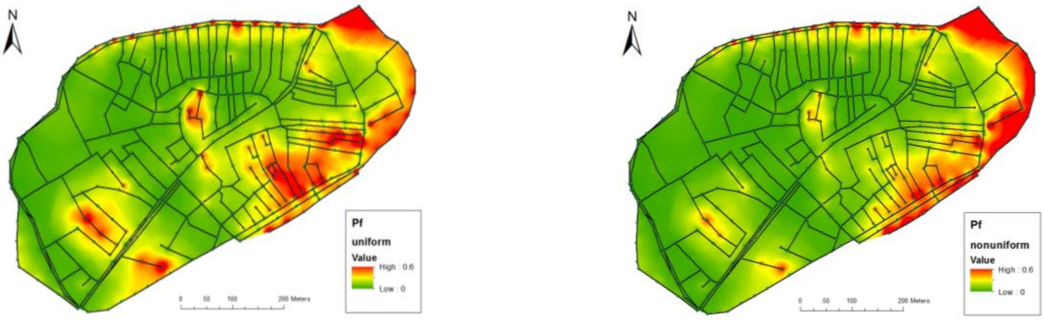
Carlo simulation, a method that is based on reducing the network topology, i.e. removing pipe segments which are assumed as failed. Combining the Monte Carlo method with common graph algorithms, we can quickly determine whether at least one path between two nodes (vertices) exists.

Previous studies that assessed the vulnerability of infrastructure systems, typically do not consider the spatial correlation of the peak ground velocities and permanent ground deformation. Most advanced approaches (e.g., Wu and Baker, 2014) utilize current rupture forecasts and ground motion prediction equations in conjunction with a ground motion spatial correlation model. Nevertheless, the generation of spatially correlated ground motion maps requires a wide range of seismic hazard data, which is not always available. Along these lines, a moderate complexity probabilistic model is utilized to predict the spatial variation of the desired ground parameters involving a series of one dimensional, nonlinear site response analyses of the multi-layered, damped soil profiles overlying an elastic bedrock. Liquefaction susceptibility is also considered through multi-yield-surface plasticity and control on the magnitude of cycle-by-cycle permanent shear strain accumulation in clean medium to dense sands (i.e., in specific soil layers of potentially liquefiable formations with the water network grid). Uncertainty is introduced in the bedrock ground motions used and the mechanical properties of the soil materials leading to the prediction of the spatial variation of the mean values of the ground parameters for nominal return periods of earthquake ground motion. In this study, free field ground motions are directly adopted from the previous analysis at characteristic locations of the grid. The reliability of the network under the above scenarios is then compared with the reference case of a uniform ground parameters, which consists the current state-of-practice.



(a) (b)

Figure 1: Distribution of network failure probabilities:
(*a*) considered uniform *PGV* and *PGD* values, (*b*) considering nonuniform *PGV* and *PGD* values, as obtained with the proposed approach.

A water distribution network inspired from Lefkas, a moderate-size Greek city, is used as our case study. The predictions of the general-purpose methodology for the area of interest are comparatively assessed. Twenty-one synthetic ground motion records, compatible with the site Eurocode 8 elastic design spectrum, were generated with aid of REXEL (Iervolino *et al*. 2010) software. The synthetic records were applied at the level of the underlying bedrock and the surface response was obtained by performing one-dimensional site response analysis. Such analysis allowed us to accurately and efficiently determine the response quantities (*IMs*) of interest all over the city grid. These *IM* values are used to calculate the pipe failure probabilities (Equation 1) which are given as input to our graph model to produce the network failure probabilities at the house connections. Figure 1 shows failure probabilities throughout the network. In order to pinpoint the significance of considering spatial variability, Figure 1(a) shows the failure probabilities when uniform *PGV* and *PGD* values are assumed, while the Figure 1(b) refers to the nonuniform case, when the pipe failure probabilities were obtained using *PGV* and *PGD* values calculated according to the proposed approach. The uniform values of the left plot are the mean of the *IM* values of the nonuniform case. The comparison reveals distinct differences in the results. The high failure probability regions (shown as red in Figure 1) refer to regions of soft soil formations. In those regions, the soil conditions abruptly change within the city grid, the assumption of uniformly distributed ground deformation is unconservative. On the other hand, the failure probabilities are overestimated for the rest of the city. In all, the outcome is a comprehensive methodology to measure the overall performance of lifelines that consists a valuable decision-making tool to water agencies and lifeline owners.

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