Seismic Reliability Assessment of Lifeline Systems

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ABSTRACT

A methodology is proposed for the seismic assessment of the reliability of urban water distribution networks (UWDN). The method is based on general seismic assessment standards, as per the American Lifelines Alliance (ALA) guidelines, and on localized historical records of critical risk-of-failure metrics. The proposed methodology is applicable to UWDN under either normal or abnormal operating conditions, and the assessment of reliability considers not only the vulnerabilities of the network components against seismic loading but also the topology of an UWDN and data of past non-seismic performance. This past performance, obtained using records of pipe burst incidents, is utilized with network-specific ‘survival curves’ in fine-tuning the generalized fragility curves suggested by the ALA. The resulting vulnerability analysis is used in devising ‘repair-or-replace’ strategies for the studied lifelines.

INTRODUCTION

Lifeline systems, such as water distribution networks, are of critical importance to the uninterrupted provision of services and thus to the resiliency of a city. Thus, being able to assess the reliability of the network against different hazards helps water distribution agencies prioritize their interventions and ensure a minimum reliability level of the network.

A number of previous studies have assessed the vulnerability of infrastructure systems, but seldom has the non-seismic performance of such systems and the system-component interactions been considered in evaluating the seismic vulnerability of such systems. The process proposed in this paper combines data on historical non-seismic performance of urban water distribution networks (UWDN) and their components by use of survival analysis, simulation and a graph-based shortest-path algorithm. The intent is firstly to propose a methodology for assessing the vulnerability of a UWDN using available everyday measurements and secondly to extent the methodology of the American Lifelines Alliance guidelines (ALA 2001) with localized knowledge on the performance and vulnerability of such networks. The ALA guidelines present procedures and fragility relationships that can be used to evaluate the probability of earthquake damage to water transmission systems and to make informed decisions on how to mitigate risks. However, the generic form of the pipe fragility curves obtained through the ALA method does not take into consideration a network’s past performance and its effects when calculating the pipe repair rates due to seismic loading. Furthermore, in examining the vulnerability of a network one cannot but consider the vulnerability of the network’s components as well as the topology of the network.

Presented herein is a methodology for the seismic risk assessment of water distribution (pipe) networks based on general seismic assessment standards, as per the ALA (2001) guidelines, and localized historical records of critical risk-of-failure metrics pertaining to the specific UWDN under assessment. The assessment of reliability incorporates data of past non-seismic damage, the vulnerabilities of the network components against seismic loading, and the topology of an UWDN. Historical data obtained using records of pipe burst incidents are processed to produce clustered 'survival curves', depicting the pipes' estimated survival rate over time. The survival curves are then used to localize the generalized fragility values of the network components (primarily pipes), as assessed using the approach suggested by the ALA guidelines. The network reliability is subsequently assessed using Graph Theory, while the system reliability is calculated using Monte Carlo simulation. The methodology proposed is demonstrated on a small (real-life) district metered area (DMA) network. The proposed approach allows the estimation of the probability that the network fails to provide the desired level of service and allows for the prioritization of retrofit interventions and of capacity-upgrade actions pertaining to existing water pipe networks.

STATE OF KNOWLEDGE

The studies and methods reported upon in literature with regards to non-seismic assessment of UWDN are primarily on deterioration modelling, pipe-break forecasting and network monitoring. Such studies have traditionally attempted the identification of statistical relationships between water-main break rates and influential risk factors. Most such studies show a relationship between failure rates and the time of failure, and some of them suggest a method to optimize the replacement time of pipes.

Several findings on risk assessment and prioritization of 'repair-or-replace' actions were reported by Christodoulou et al. (2009-2011) based on neurofuzzy systems, survival analysis and geospatial clustering of WDNs under both normal and abnormal operating conditions. Their findings reinforced, among other, the importance of risk factors such as pipe age, pipe diameter/length, pipe material and of the network operating conditions, and pointed out the importance of the number of previously observed breaks (NOPB) as a risk-of-failure factor. Evaluation of the probability of failure was also addressed in the work reported by Carrion (2010), who used a semi-parametric model based on the proportional hazards model (PHM) to estimate the effect of each factor over the failure risk of a pipe section. PHM was also the basis of the work by Park et al. (2010) who addressed the evaluation of the economically optimal replacement times of pipes.

In terms of introducing a network's topology to its risk level, recent work by Pinto et al. (2010) introduced several theoretical concepts of a proposed theory of vulnerability of water pipe networks (TVWPN), based on the structural vulnerability theory. The fundamental contribution of this theory is to help design water pipe networks more robust against damage to the pipelines, through an analysis of the form of the network. Related work has also been reported by Yannopoulos and Spiliotis (2013), who presented a methodology for evaluating water distribution system reliability based on the minimum cut-set approach, combining the mechanical reliability and the hydraulic reliability of a UWDN.

Finally, in terms of seismic risk assessment of lifeline systems, the U.S. Federal Emergency Management Agency (FEMA) has developed the nationally applicable standardized methodology and software program HAZUS-MH MR3 (2013), which estimates potential losses from earthquakes, hurricane winds, and floods.

VULNERABILITY ANALYSIS OF WATER DISTRIBUTION NETWORKS

In general, a network's reliability is a function of not only the reliability of the network's components but also of its topology (connectivity) and operation (hydraulic parameters). Past research has put forward several network-based approaches, such as vulnerability theory (Pinto et al. 2010), graph theory (Yannopoulos and Spiliotis 2013), ant colony optimization (Christodoulou and Ellinas 2010b), and Monte Carlo simulation (Fragiadakis et al. 2012). The performance of the network and its failure probability can be assessed based on its topology/connectivity and on the failure probability, P_f, of every pipe in it and subject to how the network performance is measured. In the simplest case, the network fails when it is not able to deliver water from its sources (inflow vertices) to every house connection (outflow vertices). If such, rather simplified, network performance definition is adopted, the performance of the network can be quickly evaluated using methods based on Graph Theory and Monte Carlo simulation (MCS). Alternatively, if failure is defined with respect to hydraulic quantities, then hydraulic analysis of the network is required.

The seismic vulnerability of buried pipelines is discussed in the ALA (2001) guideline, which provides vulnerability curves for water pipes, using observations from past disruptive earthquakes. The failure parameters that affect buried pipes are identified and vulnerability functions are proposed, which are related to the peak ground velocity (PGV) and the permanent ground deformation (PGD). PGV is related with strong ground shaking caused by seismic wave propagation, while PGD is used to measure factors that include landslides, liquefaction, ground settlement and fault crossing. Other parameters identified are the diameter, the age, the year of construction and discontinuities along the pipe. According to the ALA (2001) guidelines, the pipe vulnerability functions provide the repair rate (RR) per 1000 feet of pipe and have the form:

$$RR_{PGV} = K_1 \cdot 0.00187 \cdot PGV \quad (1)$$

$$RR_{PGD} = K_2 \cdot 1.06 \cdot PGD^{0.319}$$

The units for PGV and PGD are 'in/s' and 'in', respectively. Tabulated values are provided for K1 and K2 depending on the material of the pipe. K1=K2=1 refers to pipes made from cast iron or asbestos cement. The pipe repairs of Eq. (1) can be due to a complete fracture, a leak or damage to an appurtenance of the pipe, or any other reason that requires the water agency to intervene. Once the repair rate (RR) is known, i.e. the number of leaks/breaks per pipe length, the failure probability of a pipe, P_f, can be computed as (ALA 2001):

$$P_f = 1 - e^{-RR \cdot L} \quad (2)$$

where RR = max(RR_{PGV}, RR_{PGD}). Note that a Poisson process is a "memoryless" process and thus Eq. (2) is valid regardless of any previous failures having occurred along the pipe.

Despite this, though, their power in terms of providing guidance on the expected seismic effects and on the repair rates in a water distribution network, the ALA guidelines have a number of inherent limitations the most important of which are: (1) they do not consider a network's past non-seismic performance when estimating the seismic performance (risk factors such as pipe age and NOPB are not considered in the analysis); (2) they do not consider the network topology (they arrive at an estimate of the repair rate and not at a network reliability metric); (3) they are in essence generic in nature and non-localized.

The issue of the NOPB risk factor, its significance and its differentiation from the repair rate (RR) factor used in the ALA guideline is worthy of a closer look. The ALA guideline furnishes us with estimation for the repair rate (RR) (Eq (1)) based on the PGV and PGD values, and on the material of the pipes. This metric is in essence postulated statistically and it does not relate to any pipe condition prior to the seismic event. In contrast, the NOPB factor is a metric of the historical performance of a pipe (how many breaks the pipe experienced in the past, under non-seismic operation) and relates to us a pipe's operational condition. Furthermore, the NOPB is a risk factor which, by use of survival analysis, can account for incomplete data. The importance of the NOPB factor as a risk metric has been studied and reported upon extensively in the past (Christodoulou et al. 2009, Christodoulou and Deligianni 2010, Christodoulou 2011, Christodoulou and Ellinas 2010).

Proposed strategy for pipe seismic vulnerability assessment. In our study we combine the vulnerability curves suggested in the ALA (2001) guidelines with available and localised survival curves that were compiled using network data available from the network operators (Fig. 1). Having at our disposal the pipe survival curves (Fig. 2) we can deduce the survival probability of a pipe,

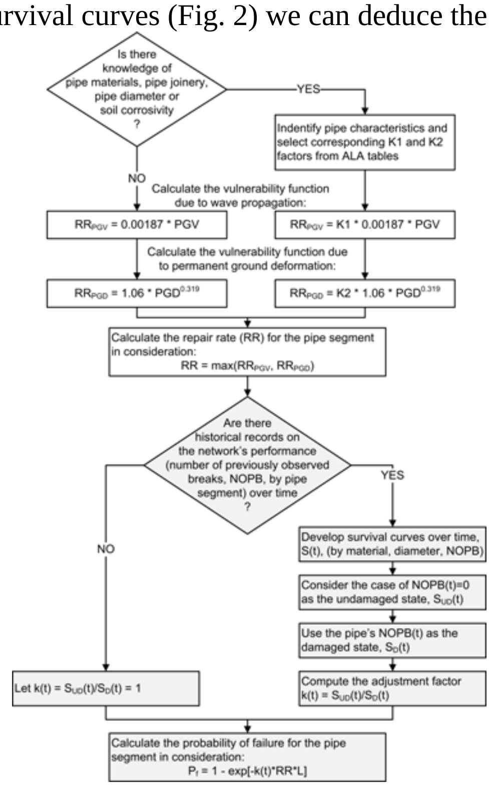

Figure 1. Proposed methodology (shaded shapes are proposed modifications to the ALA (2001) guideline).

depending on the number of previous breaks (NOPB) and the pipe type (e.g. material, age, diameter), which we then use to adjust the vulnerability curves proposed by the ALA.

In order to demonstrate the impacts of non-seismic performance on a network's reliability and how the ALA guideline could be improved, let us consider a real-life DMA, its non-seismic performance (NOPB) as shown in Fig. 3, the computed network reliability as per the ALA (2001) guideline and as per the proposed methodology.

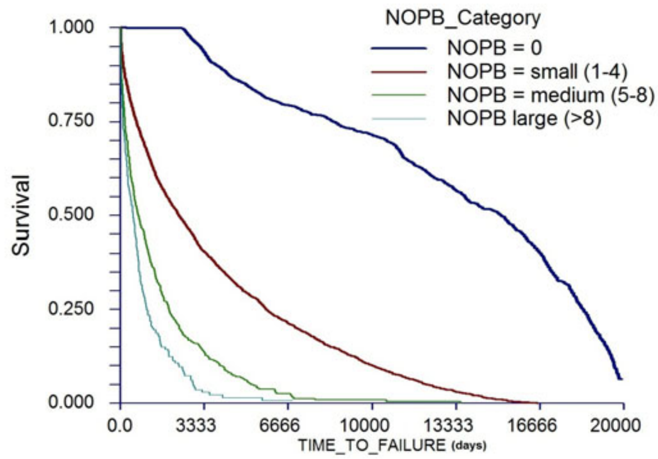

Figure 2. Survival curves for asbestos cement (AC) pipes, as a function of the number of previous breaks (NOPB).

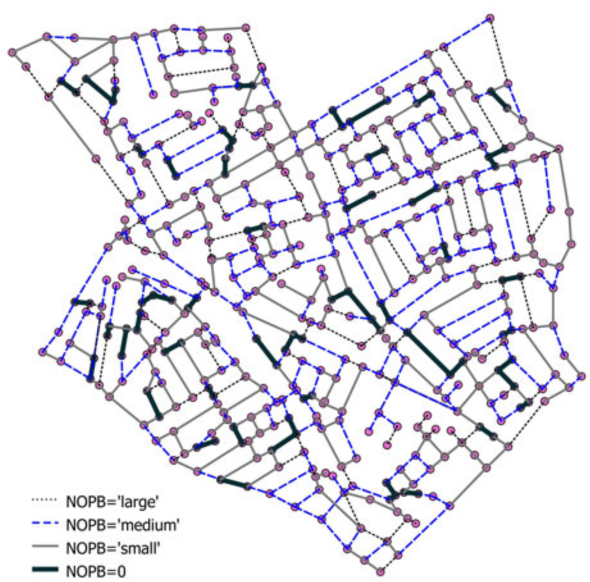

Figure 3. Topology of the DMA network considered, in a disturbed state (NOPB ≥ 0 for every pipe).

At first let us consider the deduced network reliability based on the ALA guideline. The material of each and every pipe is taken to be asbestos cement (K_1=K_2=1), the pipes' repair rate is obtained by use of Eq. (1) and the probability of failure is computed based on Eq. (2). The DMA is mapped as a graph and a Monte Carlo simulation, with an assumed seismic load of M_w=7.0, is performed to produce the failure probabilities (and thus the network reliability) at every network node. The result is then mapped as a spatial risk plot ('heat-map'), as shown in Fig. 4. The produced 'heat-map' helps us identify the areas in the network which are of high failure risk. In this case the areas of concern seem to be limited to three areas which, on closer inspection, are related to areas of open-ended pipe pathways. The horizontal allocation of risk (as per the ALA 2001 guideline) is actually shown to be highly sensitive to open-ended network topologies.

The situation changes drastically once the NOPB risk factor is included in the analysis (Fig. 5) by use of the algorithm proposed by Fragiadakis et al. (2012). The inclusion of a network's non-seismic performance, as expressed by the survival curves clustered by NOPB (Fig. 2) increases the pipes' risk of failure and thus alters the network reliability, while at the same time distributing unevenly their values over space. The increased network vulnerability is the direct outcome of the increased pipe vulnerabilities, as impacted by their performance prior to the seismic event and their decreasing reliability. The probability of failure is now highly sensitive to the condition of each network element, as manifested and influenced by their non-seismic performance over time (survival analysis), and introduced in the risk analysis by means of the proposed adjustments to the ALA 2001 guideline (Fig. 1).

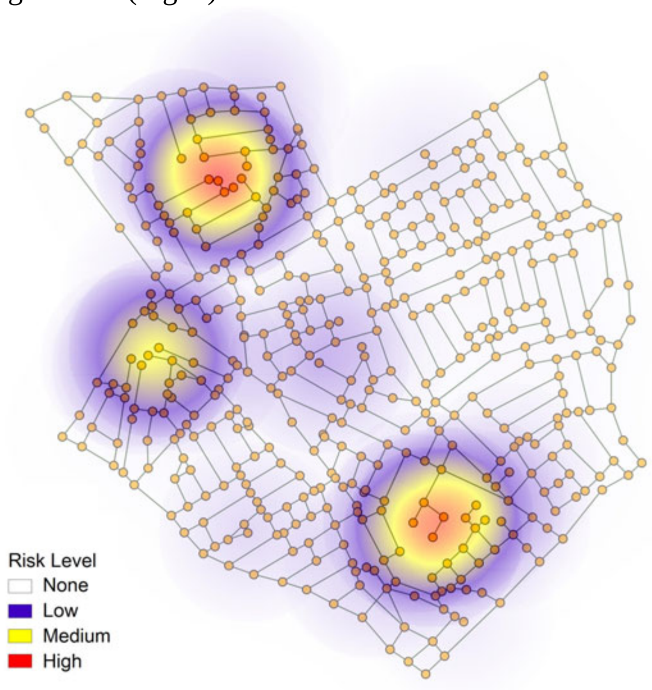

Figure 4. Spatial analysis (heat-map) of studied network's reliability based on the ALA guidelines. Seismic effects are considered (M_w = 7.0).

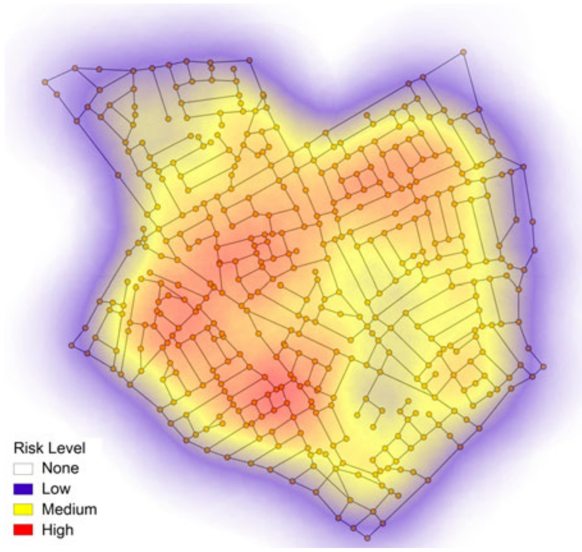

Figure 5. Spatial analysis (heat-map) of studied network's reliability based on survival curves and considering the effects of the NOPB risk factor. Seismic effects are considered (M_w = 7.0).

CONCLUSION

A methodology is proposed by which the ALA (2001) guideline on the seismic performance of UWDN can be enhanced so as to enable the inclusion of a network's non-seismic performance in the calculation of a UWDN's reliability. Available past network performance is processed through survival analysis techniques, clustered by a number of different risk factors, and then used to adapt the generalized pipe vulnerability considering data that refer to the specific network. The network reliability is subsequently assessed using Graph Theory tools and Monte Carlo simulation. The proposed approach, which is demonstrated on a real-scale DMA, allows for both the estimation of the probability that a network fails to provide the desired level of service and also the prioritization of retrofit interventions and of capacity-upgrade actions. A spatial analysis of the proposed method's derived network reliability is also included and compared to the network reliability based on the ALA guidelines, showcasing the effects of past non-seismic performance on a network's reliability.

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