COMPDYN 2013
4th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.)
Kos Island, Greece, 12–14 June 2013

RELIABILITY ASSESSMENT OF PIPE NETWORKS UNDER SEISMIC LOADS

Michalis Fragiadakis[1,2], **Symeon Christodoulou**[1,3]

[1]Department of Civil and Environmental Engineering, University of Cyprus
[2] School of Civil Engineering, National Technical University of Athens, Greece
e-mail: mfrag@mail.ntua.gr

[3] Nireas International Water Research Center, Nicosia, Cyprus
e-mail: schristo@ucy.ac.cy

Keywords: Water distribution networks (WDN), Lifelines, Graph theory, Survival analysis, Reliability assessment.

Abstract. *Piping systems are a key component of industrial structures. Most research on structures of industrial facilities is targeted to individual structures such as atmospheric tanks, pressure vessels, etc. Piping systems are considered of secondary importance and thus the research on their risk assessment is limited despite the significant consequences of their possible failure. We propose a methodology for assessing the reliability of pipe networks and is able to combine data from past nonseismic damage with the seismic vulnerability of network components. The fragility of the network components is assessed using the approach suggested in the guidelines of the American Lifeline Association (ALA), but the methodology presented is open to any fragility data. The network reliability is assessed using Graph Theory, while the system reliability is calculated using Monte Carlo simulation. Of particular importance is the degradation of the piping components due to repeated loading in the plastic range under strain-controlled conditions or due to failure of the supporing structure. The methodology proposed is demonstrated both on a simple, small-scale, network and also on a real-scale piping system. The proposed approach allows the estimation of the probability that the network fails and of capacity-upgrade actions pertaining to existing pipe networks.*

1 INTRODUCTION

Water distribution networks deliver the water from its sources to the customers of the network. Being able to assess the reliability of the network against different hazards, helps water distribution agencies to prioritize their interventions and ensure a minimum reliability level of the network. Therefore, water distribution agencies are required to develop and implement new methods for monitoring, repairing (or replacing) ageing WDN infrastructures, as well as modelling deteriorating WDN conditions and proactively devising strategies to keep the networks in operation. In essence, water distribution agencies are faced with the increasingly more complex task of intelligently and efficiently assessing (or modelling) the condition of a pipe network, while managing the network in ways that maximize its reliability and minimize its operational and management costs. The question that usually arises is whether an organization should repair or replace deteriorating water mains and, in either case, what should be the sequence of any such repairs as part of a long-term network rehabilitation strategy.

The seismic risk assessment of critical infrastructures has been the subject of extensive past research. For example, Nuti *et al.* [1] propose a methodology for the reliability assessment of electric power, water and road systems, neglecting the interdependence between the networks, while Poljnašek *et al.* [2] propose a method for gas and electricity transmission networks considering the increased vulnerability due to interdependency. Cimellaro [3] proposed a performance index for evaluating the functionality of a road network during extreme events such as earthquakes that can be utilized within the general PEOPLES framework for measuring disaster resilience indices for a community at various scales. Regarding water supply networks, Romero *et al.* [4] discuss the possible seismic hazards and present results that correspond to a severe event in California, while Esposito [5] worked on the seismic performance evaluation of gas distribution networks and produced fragility curves for these systems. Moreover, Wang *et al.* [6] propose a methodology for the seismic risk assessment and identification of critical links of water supply systems. The U.S. Federal Emergency Management Agency has also developed the nationally applicable standardized methodology and software program HAZUS-MH MR3 [7], which estimates potential losses from earthquakes, hurricane winds, and floods.

The reliability of a water pipe network can be calculated if the vulnerability (also termed fragility) of every element of the water network is known. Although water pipe networks consist of several elements (pipes, house connections, tanks, pumps, etc.), focus is given on the pipes, which are, not only the most important component in a piping network but they are also the most difficult component to inspect and replace. Many possible risk-of-failure parameters can be identified [4]. Our methodology takes into consideration the fragility that corresponds to pipe failures that occur frequently during the everyday operation of the water network and also more severe, but less often, failures due to earthquakes. The pipe vulnerability due to nonseismic causes is assessed using survival analysis techniques on available everyday measurements. Survival analysis considers a number of parameters, e.g. number of observed previous breaks (NOPB), pipe material, diameter or age that affect the pipe survival curves [8] in order to develop survival/hazard rates and time-to-failure curves for system components based on a multitude of risk-of-failure factors and data stratifications. To account for the vulnerability due to seismic hazard, we rely on the procedure described in the American Lifelines Alliance (ALA) [9] guidelines and we propose a rational approach for combining it with the results of survival analysis in order to consider the effect of previously observed breaks in the network.

Even though the procedure proposed herein is presented based on performance data from urban water networks of the island of Cyprus, it is general in scope and applicable to any locale with historical records of pipe-break incidents in its water distribution network. Being a South European island, Cyprus has suffered during the last years from low rainfalls and shortage in its water reserves. Under such conditions, a common practice followed by water distribution agencies has been to periodically interrupt the water flow in different areas of the city network for variable time intervals, e.g. 12 hours of water supply every 48 hours. This practice offers a more rational treatment of the water resources, but is also considered responsible for an increasing the failure rate of the network pipes. The worsening failure rate in the water pipe networks of all major cities of the island prompted the initiation of an extensive program of monitoring and keeping track of the every damage incident, in order to be able to assess the network conditions and assist its proper maintenance. The post-processing of the vast amount of available data is performed using survival analysis tools and producing pipe survival curves that allow considering the effect of different parameters (e.g. material, age, diameter) on the failure rate. In fact, although the island is located in a moderate seismicity environment, the seismic vulnerability of its water distribution networks increases to considerable levels due to the deterioration of the pipe properties.

2 SURVIVAL ANALYSIS

Survival analysis is a branch of statistics dealing with deterioration and failure over time and involves the modelling of the elapsed time between an initiating event and a terminal event [10]. In the case of piping networks such initiating events can be the installation of a pipe, a water-leak observation or the start of a pipe treatment. Cases of terminal events can be a relapse of a previous leak, a fix or a failure. The method is based on estimating the reliability of a system and its lifetime subject to multiple risk factors. The aim is to provide answers on the population fraction (pipes) that survives past an expected lifetime, on the effect of the various risk factors on the systems lifetime, and on the probability of survival and the expected mean time to failure [10, 11]. The data values used in the analysis are a mixture of both complete and censored observations. In the former case, a terminal event is thought to have occurred, while in the latter case a terminal event has not occurred. A terminal event is assumed to occur just once for every subject.

A pipe's survival function, S, for elapsed time, T, until the occurrence of a pipe failure is given by the expression:

$$S\left(t\right) = \int_{T}^{\infty} p\left(x\right) dx = 1 - P\left(t\right) \quad (1)$$

Thus, the survival function is the probability that the time to failure is longer than some specified time t. Moreover, $P(t)$ is the cumulative distribution function that denotes the probability that a pipe survives until time t and $p(t)$ is the corresponding probability density function. the rate of the survival function is denoted as $h(T)$ and provides the probability that a pipe at time T experiences the event in the next time instant. The cumulative hazard function $H(T)$ is the integral of $h(t)$ from 0 to T, and therefore:

$$S(t) = \exp\left[-\int_{0}^{T} h(x)dx\right] = \exp\left[-H(T)\right] \quad (2)$$

and

$$h\left(T\right) = p(T)\,/S\left(T\right) \quad (3)$$

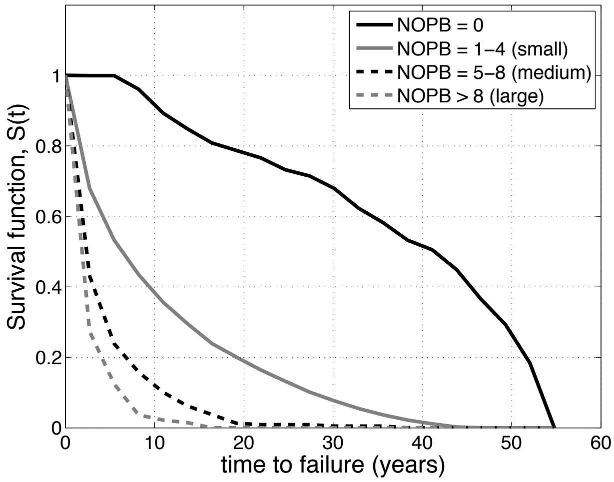


Figure 1: Survival curves for Asbestos Cement (AC) pipes as function of the number of previous breaks (NOPB).

The survival function S is usually the primary quantity of interest and is numerically calculated using kernels, such as the Epanechnikov kernel and the Kaplan-Meier estimator [12]. The Kaplan-Meier estimator is of particular importance because it is non-parametric and therefore relies on data rather than analytical equations and probability density functions in order to produce the survival curves. A plot of the Kaplan-Meier estimate of the survival function is a series of horizontal steps of declining magnitude which approaches the true survival function for the population in study and whose values between successive distinct sampled observations are assumed to be constant. Another important advantage of the Kaplan-Meier curve is that the method can take into account both left and right-censored data. When no truncation or censoring occurs, the Kaplan-Meier curve is equivalent to the empirical distribution function.

In terms of piping networks, the survival function has been shown to be dependent on several factors, the most important of which are the ‘number of observed previous breaks’ (NOPB), the age and the material of the pipes [13]. These risk factors have been studied extensively [13, 8] both when acting separately or together. The non-parametric survival analysis produces the effects of such risk-of-failure actions on the network, clustered by risk factor and its subgroups, and enables us a deeper insight into the behaviour of the piping network. For example, a survival analysis reported by Christodoulou and Ellinas [8] of an urban water distribution network under abnormal operating conditions, revealed almost identical survival curves for the network mains and its house connections, but when clustered by the ‘number of previous breaks’ (NOPB) the survival curves varied substantially.

A typical set of survival curves is shown in Figure 1. The curves have been derived from real data and refer to asbestos cement (AC) pipes. The data have been clustered according to the ‘number of observed previous breaks’ (NOPB) and four survival curves are derived. The four curves correspond to 0, 1-4, 5-8 and more than 8 previous breaks and are denoted as ‘zero’, ‘small’, ‘medium’ and ‘large’ NOPB clusters. According to Figure 1, even in the ‘NOPB = 0’ case, the pipe will have to be eventually replaced after approximately fifty-five (55) years, while a pipe that has already broken more than 8 times is not expected to survive more than eighteen (18) years. Moreover, a pipe that has broken at least once, is considerably more vulnerable compared to an intact pipe that has never been damaged.

3 SEISMIC VULNERABILITY ANALYSIS OF WATER PIPES

3.1 Pipe vulnerabilities according to the ALA guidelines

The seismic vulnerability (or fragility) of buried pipelines is discussed in the ALA (American Lifelines Association) document [9]. The ALA document 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. The vulnerability functions are defined as functions of 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. Parameters that also affect the vulnerability of a pipe are also the diameter, the age, the year of construction and possible discontinuities along the pipe. The pipe vulnerability functions of the ALA document [9], provide the repair rate (*RR*) per 1000 ft of pipe length and have the form:

$$\begin{aligned} RR_{PGV} &= K_1 \cdot 0.00187 \cdot PGV \\ RR_{PGD} &= K_2 \cdot 1.06 \cdot PGD^{0.319} \end{aligned} \tag{4}$$

The units for PGV and PGD are in/s and in, respectively. Tabulated values are provided for K_1 and K_2 depending on the material of the pipe. $K_1 = K_2 = 1$ refers to pipes made from cast iron (CI) or asbestos cement (AC). The pipe repair rates of Eq. 4 can be due to a complete fracture, a leak or a damage to an appurtenance of the pipe, or any other reason that requires the water agency to intervene. For typical water pipe networks, a rule-of-thumb is that for failure due to wave propagation 15-20% of failures are breaks and the rest are leaks, while for failures due to PGD 80-85% are breaks that result to the loss of pipeline hydraulic continuity [14].

Once the repair rate (*RR*) is known, i.e. the number of leaks/breaks per pipe length, the failure probability of the pipe can be easily calculated. The failure probability of a pipe is equal to one minus the probability of zero breaks along the pipe. Using the well-known exponential distribution CDF formula, the pipe failure probability $\bar{P}_{\mathrm{f}}$ is therefore calculated as [9]:

$$\bar{P}_{\mathrm{f}} = 1 - e^{-RR \cdot L} \tag{5}$$

where $RR = max(RR_{PGV}, RR_{PGD})$, with RR_{PGV} and RR_{PGD} calculated by use of Eq. 4. Note that Eq. 5 is a Poisson process and thus is “memoryless” disregarding any failures that may have occurred along the pipe in the past. Also note that the bar (‘-’) above P_{f} (e.g. Eq. 5) is used to distinguish the failure probability of a single pipe/edge from the failure probability in the network level, which in the remaining of the paper will be denoted as P_{f}.

3.2 Proposed strategy for pipe vulnerability assessment

As aforementioned, the study’s goal is to propose a seismic vulnerability assessment methodology for water pipe networks, exploiting available data of everyday network failures due to sources other than seismic. This methodology is useful in the case of networks under abnormal operating conditions, as in the case of intermittent water supply. Previous research has shown that survival analysis is a valuable tool for implementing methods for monitoring, repairing or replacing ageing infrastructures and proactively devising strategies to keep the network in operation. Compared to failures caused by earthquakes, failures from non-seismic causes are more frequent and well distributed in time, while failures due to seismic effects occur intermittently and only when a major earthquake strikes. Thus, it is convenient to compile separately the data from the two failure causes. This approach is also close to the current practice, since usually it is the water agencies that maintain records of the everyday failure causes, while the seismic effects on the lifelines are usually given a more high-level attention by the civil protection agencies. Moreover, the approaches followed for seismic and non-seismic effects have distinct differences and therefore it is not straightforward to post-process the data in a manner that allows to combine consistently pipe survival curves and vulnerability curves.

In our study we combine the vulnerability curves suggested in the ALA [9] guidelines with available survival curves that were compiled using network data available from the Water Boards. To this cause we adopt a simplified engineering approach that allows us to quickly combine data that are not similar. Having in our disposal the pipe survival curves (e.g. Figure 1) of $S(t)$ versus time we know the survival probability of a pipe, depending on the number of previous breaks (NOPB) and the pipe type (e.g. material, age, diameter). We thus penalize the pipe vulnerability function of Eq. 4 by the ratio of the survival curve of the damaged case (NOPB$\neq$0) over the undamaged pipe (NOPB=0). Therefore, after t days, we define the ratio:

$$k(t) = S_{UD}(t)/S_D(t) \geq 1 \tag{6}$$

where subscripts "UD" and "D" stand for "undamaged" and "damaged", respectively. The modified pipe failure probability that now includes memory of past nonseismic failures is obtained after modifying Eq. 5 as follows:

$$\bar{P}_{\mathrm{f}}(t) = 1 - e^{-k(t)\cdot RR\cdot L} \tag{7}$$

Therefore, Eq. 7 allows calculating the failure probability $\bar{P}_f$ of the pipe after t days given its NOPB metric, which is usually available from historical records.

4 RELIABILITY ASSESSMENT OF A WATER SYSTEM

Once the failure probability, $\bar{P}_{\mathrm{f}}$, of every pipe is known, the performance of the network and its failure probability P_{f} can be assessed. Depending on the problem at hand, different approaches can be preferred. Perhaps the most significant parameter that affects the selection of the strategy to follow is how the network performance is measured and thus how the failure probability of the network is defined. 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). Another, approach would consider the number of customers that are left without water. If such, rather simplified, network performance definitions are adopted, the performance of the network can be quickly evaluated using methods based on Graph Theory [15].

We consider as failure of the network its inability to provide water to a consumer/house connection. Therefore, we define the failure probability as the probability of the network being unable to provide water from an inflow source vertex i to an outflow (e.g. house connection) vertex j. If the failure probability to deliver water between i and j is $P_{\mathrm{f,ij}}$, the network reliability $R_{\mathrm{f,ij}}$ is defined as:

$$R_{ij} = 1 - P_{f,ij} \tag{8}$$

For water networks with more than one inflow sources, we consider as failure probability the smallest probability of all possible sources and the outflow vertex j examined. This definition refers to the probability that the outflow node j is left without water.

The Monte Carlo Simulation (MCS) method is often employed when the analytical solution is not attainable and the failure domain can not be expressed or approximated analytically. This is mainly the case in problems of complex nature with a large number of basic variables where other reliability methods are not applicable. When Monte Carlo simulation (MCS) is adopted on pipe networks, the calculation is based on reducing the network topology, i.e. removing pipe segments which are assumed as failed. Successful applications of MCS on networks can be found in [16] and [17]. For every simulation a state vector is produced. In this vector, two states can be considered for every pipe: *0-state*, which refers to a failed state with probability of $P_{\mathrm{f,ij}}(t)$ Eq. 7) and *1-state* that corresponds to non-failure with probability $1 - P_{\mathrm{f,ij}}(t)$. Once a state vector is obtained, the failed pipes are removed from the network. Using common graph algorithms we can determine whether a path between vertices *i* and *j* exists , thus allowing water flow delivery from node i to node i. In all our applications, a standard Dijkstra algorithm [15] gave quick and robust calculations. If at least one path exists the simulation is successful, otherwise it has failed. The network reliability $R_{\mathrm{f,ij}}$ can then be evaluated by dividing the number of successes with the total number of simulations performed. MCS can easily accommodate both pipe and node failures.

5 CASE STUDY

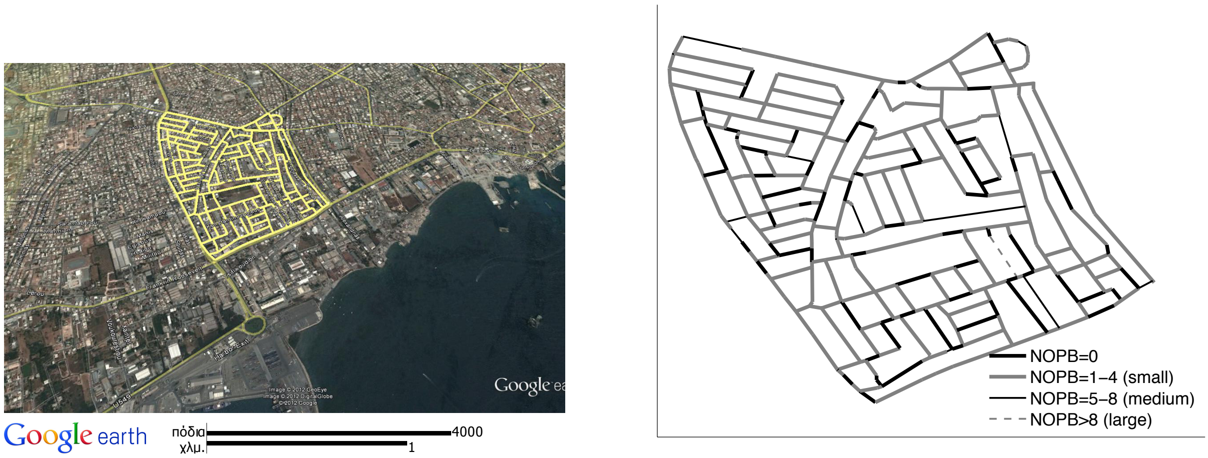
The case study considered, is a district metered area (DMA) of the water network of the city of Limassol, Cyprus (Figure 2). The city network is clustered into DMAs, which are areas with one inflow vertex. This practice allows the Water Board to isolate damage in the network within finite domains (DMAs) and then handle any problem that may occur within a DMA without affecting the rest of the city network. Fig. 2a shows the aerial view of the city together with the graph model used for simulating the network, which has been produced using available GIS data.

In total, the water network consists of 337 pipes/edges and 259 vertices/nodes. The total pipe length is 23,724 m, and according to the records of the Water Board, the number of consumers served by the DMA studied is 6,585 people. The pipe material is asbestos cement (AC) and is the same for every pipe. Since the elevation is practically constant throughout the network, we assume that the network is bi-directional. Figure 2b shows the topology of the network and the number of previous breaks of every network pipe/edge. The pipe survival curves were those of Figure 1, which were based on real data obtained from the Water Board of Limassol.

Based on the above observations, we consider two seismic scenaria. In the first scenario, damage is only due to wave propagation. Being consistent with the seismic hazard in the island of Cyprus which is mainly controlled by distant and moderate magnitude events, it is valid to assume uniform seismic intensity throughout the DMA. Here we measure seismic intensity with the aid of peak ground velocity (PGV). In the second scenario both PGV and PGD occur, but PGD is isolated in a small part of the network. For both scenaria, we produce fragility curves for every outflow node j.

Figure 3 shows the fragility curve of every vertex with respect to peak ground velocity (PGV) for four time instances measured from the installation of the network. As PGV increases we calculate the pipe failure probability $\bar{P}_{\mathrm{f,ij}}$ using Eq. 4 and the corresponding node probability $P_{\mathrm{f,ij}}$ using Eq. 5. Therefore, the gray lines correspond to the probability of water being able to reach the corresponding valve, while the black lines are the median (50% percentile) and the 16% and 85% percentile curves, which are shown to provide a measure of the overall condition of the network.

Figure 3a shows the fragility curves after 10 years of network operation. Since the network would be of ‘young age’, the mean fragilities lie below 0.1, even for considerably high PGV values, e.g. PGV$\geq$200 cm/s. Still, some house connections are vulnerable and their failure



(a) (b)

Figure 2: (a) Aerial view of the city of Limassol, Cyprus and the DMA considered, (b) topology of the graph network and number of previous breaks (NOPB) of every pipe.

probability may exceed 20%. Moreover, in Fig. 3a, there is one node whose failure probability is very high. This is due to the fact that this node is connected with the inflow source through pipes that are connected in series, thus if any of the connecting pipes fails the water will not be able to reach this node. In this case, the remedy will be to create conditions of redundancy by forming alternative water paths. Figures 3b,c,d have the well-known form of fragility curves, showing that the system vulnerability increased as the time passes and PGV increases. Note that since the construction of the pipes is made at a present time, the NOPB values are kept constant. Actually, NOPB will also vary as time passes, probably increasing the system vulnerability, but the prediction of survival analysis is based on the data available at the present time and therefore this effect is not considered in our analyses. Again in Fig. 3b,c there are stray lines away from the average, indicating that the vulnerability of some house connections may considerably differ from the average and thus the interpretation of the analysis should also be done on a node by node basis and not rely purely on global metrics on the DMA level. After forty years of operation (Fig. 3d), even a relatively moderate PGV ($\simeq$ 50 cm/s) will lead to high failure probabilities and therefore extensive damage on the network.

In the second scenario considered, we assume a permanent ground deformation (PGD) due to a random cause. The PGD affects a wide area of radius equal to 200m around a point shown in Fig. 4 with a red square. The deformation is assumed to be constant and equal to 12.6 cm (5 in). In Fig. 4 we also show with a thick red line the pipes that are affected by the imposed PGD. The fragility curves of every vertex for $t = 20$ years and $t = 30$ years are shown in Fig. 5. It is evident from the plot, that there are nodes whose vulnerability is considerably higher that the rest. More specifically, looking and PGV$= 0\ cm/s$ there are nodes whose probability $\bar{P}_{\mathrm{f,ij}}$ is larger than zero. The vulnerability of these nodes is governed by PGD and for visual purposes we show them with solid black lines and in the legend of Fig. 5 are denoted as “PGD-sensitive”. In a similar manner, the grey lines correspond to vertices whose vulnerability is “PGV-sensitive”. For the t=30 years case, the “PGD-sensitive” curves start from high probability values, and quickly approach 1, while for t=20 years a larger dispersion is observed. In any case, the “PGD-sensitive” curves are also affected by the increase of PGV (although with a smaller rate), since they operate within a network that combines PGV and

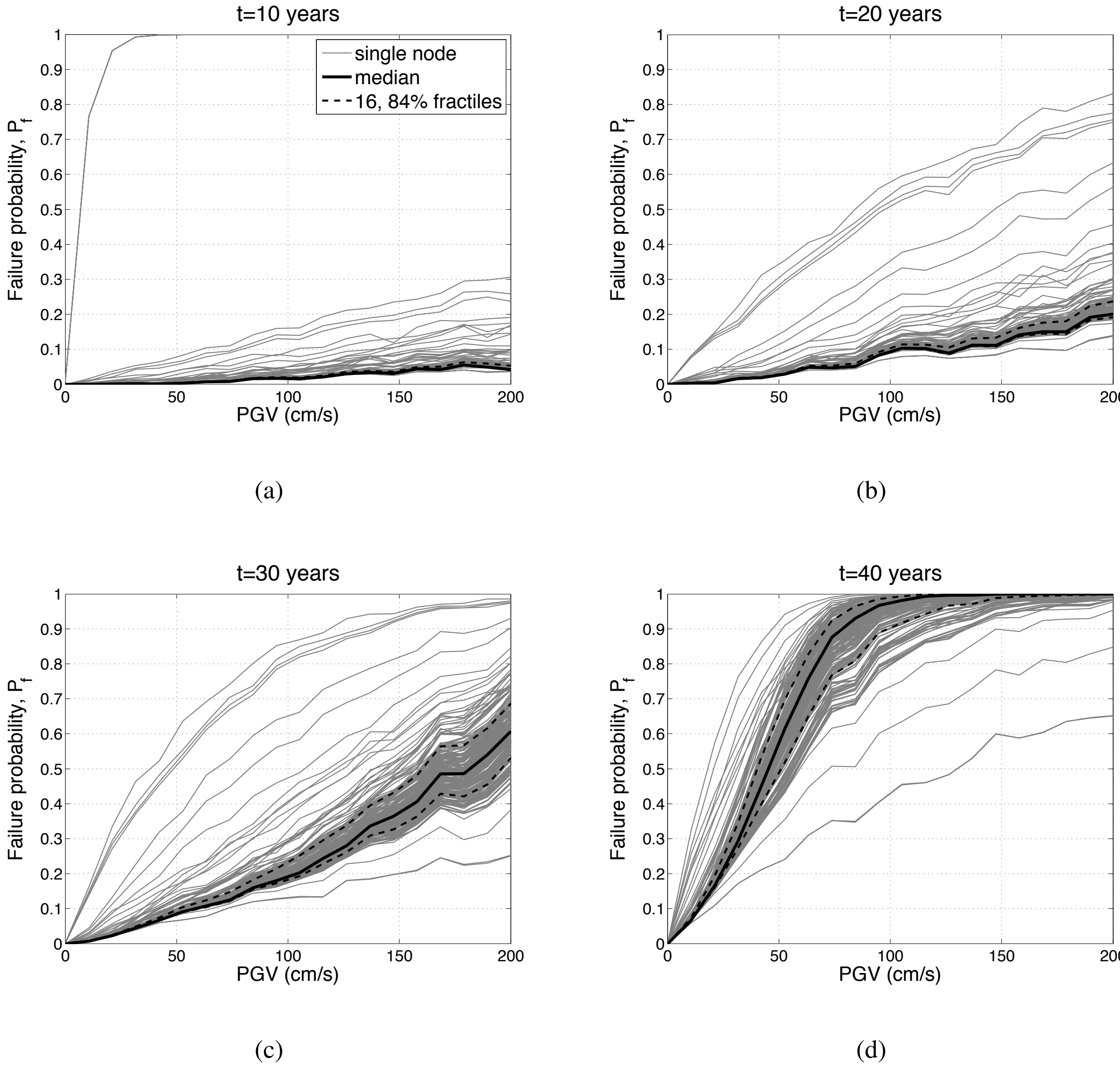


Figure 3: Fragility curves of every house connection versus the peak ground deformation (PGV), after: (a) t=10 years, (b) t=20 days, (c) t=30 days, and (d) t=40 years.

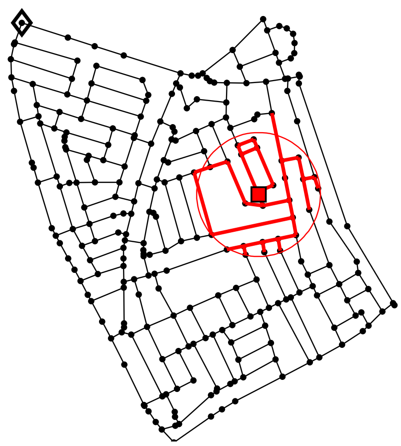
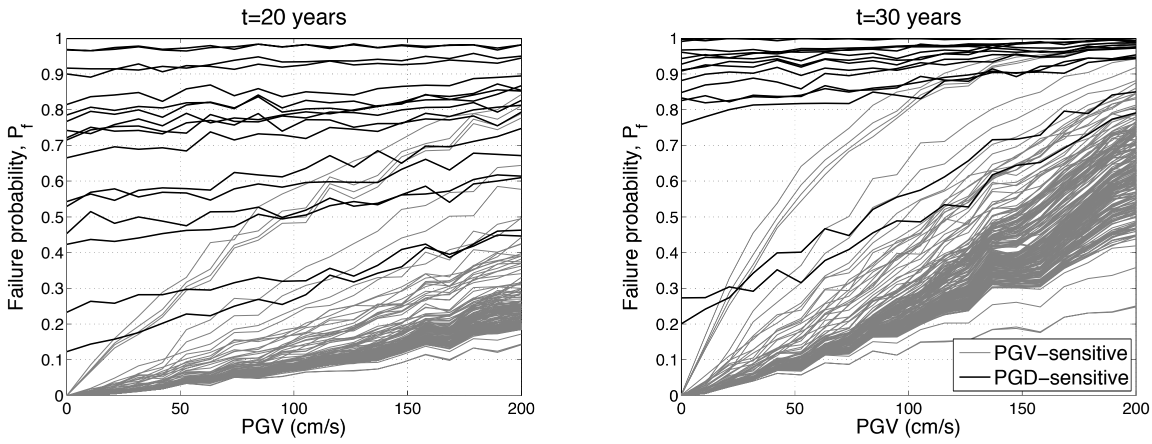


Figure 4: Water distribution network and the area where a PGD equal to 12.6 cm (5in) is imposed. The circle shows the affected area and the square is its center.

PGD-sensitive components. Moreover, when considering both PGV and PGD the practice of producing average curves (e.g. Fig. 3) is not useful, since the probabilities vary considerably and depend on the location of the node with respect to where the permanent ground formation occurred.



(a) (b)

Figure 5: Fragility curves versus peak ground velocity (PGV) when PGD is imposed, after: (a) t=20 years (b) t=40years.

6 CONCLUSIONS

A general-purpose methodology for the reliability assessment of water pipe distribution networks has been presented. The proposed methodology efficiently combines the general ALA guidelines with localized information on failures caused by seismic and non-seismic sources. The more frequent non-seismic failures are typically repaired immediately after the damage is reported to the water agency and result to increasing the future vulnerability of the damaged pipe. This sort of information is often available by water agencies and can be post-processed to provide the pipe survival curves.

7 ACKNOWLEDGEMENT

This research has been co-financed by the European Union (European Social Fund - ESF) and Greek national funds through the Operational Program “Education and Lifelong Learning” of the National Strategic Reference Framework (NSRF) Research Funding Program: **THALES**. Investing in knowledge society through the European Social Fund. The second author would like to acknowledge the NIREAS-IWRC research project, which is co-financed by the European Regional Development Fund and the Republic of Cyprus through the Cyprus Research Promotion Foundation (Grants No. NEA YPODOMI/STRAT/0308/09).

REFERENCES

[1] Nuti, C., Rasulo, A., Vanzi, I., Seismic safety of network structures and infrastructures, *Structure and Infrastructure Engineering*, **6**, 95-110, 2010.

[2] Poljanšek, K., Bono, F., Gutièrrez, E, Seismic risk assessment of interdependent critical infrastructure systems: The case of European gas and electricity networks, *Earthquake Engng Struct. Dyn.*, **41**, 61-79, 2012.

[3] Cimellaro, G.P., Renschler, C., Arendt, L., Bruneau, M., Reinhorn, A.M., Community resilience index for road network systems, *EURODYN 2011: 8th International Conference on Structural Dynamics*, Leuven, Belgium, 4-6 July, 2011.

[4] Romero, N., O'Rourke, T.D., Nozick, L.K., Davis, C.A.,Seismic hazards and water supply performance, *Journal of Earthquake Engineering*, **14**(7), 1022-1043, 2010.

[5] Esposito, S., Seismic Risk Analysis of Gas Distribution Networks. *PhD Thesis, University of Naples Fegerico II, Ph.D. Porgramme in Seismic Risk*, Naples, Italy, 2010.

[6] Wang, Y. Au, S.-K., Fu, Q., Seismic Risk Assessment and Mitigation of Water Supply Systems, *Earthquake Spectra*, **26**(1), 257-273, 2010.

[7] FEMA, HAZUS-MH technical manual: earthquake model. *Multi Hazard Loss Estimation Methodology. United States Department of Homeland Security, Federal Emergency Management Agency*, Washington, DC, 2003.

[8] Christodoulou, S.E., Water Network Assessment and Reliability Analysis by Use of Survival Analysis, *Water Resources Management*, **25**, 1229-1238, 2011.

[9] ALA, American Lifelines Alliance: Seismic Fragility Formulations for Water Systems-Guideline and Appendices, 2001.

[10] Hintze, J., *NCSS and PASS. Number Cruncher Statistical Systems*, Kaysville, Utah, 2001.

[11] Hosmer, D.W., Lemeshow, S., May, S. *Applied survival analysis: regression modeling of time to event data*, Wiley, Hoboken, 2008.

[12] Kaplan, E.L., Meier, P., Nonparametric estimation from incomplete observations. *J. Am. Stat. Assoc.*, **53**, 457-481, 1958.

[13] Christodoulou, S.E. and Deligianni, A., A Neurofuzzy Decision Framework for the Management of Water Distribution Networks, *Water Resources Management*, **24**(1), 139-156, 2010.

[14] Ballantyne, D., Earthquake Loss Estimation Modelling of the Seattle Water System, *Report N. 886005, supported by U.S. Geological Survey Project Number 14-08-0001-G1526*, Kennedy/Jenks Consultants, 1990.

[15] Gibbons, A., *Algorithmic Graph Theory*, Cambridge University Press, 1985.

[16] Javanbarg, M.B., Scawthorn, C., Kiyono, J. and Ono, Y., Minimal Path Sets Seismic Reliability Evaluation of Lifeline Networks with Link and Node Failures, *In Proc. Lifeline Earthquake Engineering in a Multihazard Environment*, ASCE Technical Council on Lifeline Earthquake Engineering, June-July, Oakland, CA, 2009.

[17] Ramirez-Marquez, J.E., Coit, D.W., A Monte-Carlo simulation approach for approximating multi-state two-terminal reliability, *Reliability Engineering and System Safety*, **87**, 235-264, 2005.