Ανάλυση αξιοπιστίας και εκτίμηση της αναταξιμότητας αστικών δικτύων ύδρευσης
Μιχάλης Φραγκιαδάκης

ΠΕΡΙΛΗΨΗ
Η εργασία παρουσιάζει την ανάλυση αξιοπιστίας (reliability analysis) και τον υπολογισμό της αναταξιμότητας (resilience) αστικών δικτύων ύδρευσης. Με τη βοήθεια των καμπυλών τρωτότητας των American Lifelines Alliance Guidelines (ALA) υπολογίζονται οι πιθανότητες αστοχίας των αγωγών, ενώ η επίλυση του δικτύου γίνεται με τη θεωρία γράφων. Παρουσιάζονται κατάλληλοι δείκτες ικανότητας του δικτύου για την τοπική και την καθολική εκτίμηση της λειτουργικότητας/αστοχίας του, ενώ η μεθοδολογία επεκτείνεται στον υπολογισμό της αναταξιμότητας αστικών δικτύων ύδρευσης. Η αναταξιμότητα αφορά στον υπολογισμό της ικανότητας του δικτύου να επανέλθει στην αρχική του κατάσταση λειτουργικότητας πριν από έναν καταστρεπτικό σεισμό. Παρουσιάζεται μία πιλοτική εφαρμογή στο δίκτυο ύδρευσης της Νέας Αρτάκης Ευβοίας, όπου η αξιοπιστία του δικτύου παρουσιάζεται με τη μορφή χαρτών πιθανότητας αστοχίας (heat maps) που βασίζονται στη συλλογή και στην απεικόνιση των πληροφοριών μέσω ενός γεωπληροφοριακού συστήματος GIS. Παρουσιάζεται επίσης μία παραμετρική διερεύνηση των παραμέτρων που επηρεάζουν την αναταξιμότητα του δικτύου.

1 INTRODUCTION
Lifeline systems, such as water distribution networks, are of critical importance to the uninterrupted provision of services and thus to the resilience of a city. Lifeline systems share the attributes of being distributed systems, rather than isolated facilities, providing products or services that are transferred through networks that often cross legal and jurisdictional boundaries. The term ‘resilience’ refers to a system’s capacity to quickly and effectively recover from a catastrophic event. Recent earthquakes have shown that following a strong earthquake, damage of the lifelines may cause a series of immediate, short-term and long-term problems, while the residential, commercial and industrial activities may be disrupted causing severe direct and indirect economic losses. Direct losses are related to the cost of repair, while indirect losses usually depend on the way the economy is affected by the disruption of the lifeline. It is presumed that the more developed a society is, the more severe indirect losses should be expected. A number of previous studies have assessed the vulnerability of water distribution networks, a literature review is found in references [1,2,3].

1 Επ. Καθηγητής, Εργαστήριο Αντισεισμικής Τεχνολογίας, Εθνικό Μετσόβιο Πολυτεχνείο, mfrag@mail.ntua.gr
2 SEISMIC VULNERABILITY

2.1 Vulnerability of Water Pipes

The seismic vulnerability (or fragility) of buried pipelines is discussed in the ALA document [4]. 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, whereas PGD is used to measure ground failure 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, provide the repair rate \( RR \) per 1000ft of pipe length and have the form:

\[
RR_{PGV} = K_1 \cdot a \cdot PGV
\]
\[
RR_{PGD} = K_2 \cdot b \cdot PGD
\]

(1)

when the units for PGV and PGD are in inch(es) per second and inch(es), the constants \( a, b \) and \( c \) are equal to 0.00187, 1.06 and 0.319, respectively. If SI units are preferred, PGV and PGD are expressed in meter(s) per second and meter(s), and the constants are equal to 0.001425, 4.281 and 0.319, 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 or asbestos cement. The pipe \( RR \)s of Equation (1) 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, whereas for failures due to PGD, 80–85% are breaks that result to the loss of pipeline hydraulic continuity [5].

Once the \( RR \) is known, that is, 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 \( P_f \) is therefore calculated as:

\[
P_f = 1 - e^{-RR \cdot L}
\]

(2)

where \( RR=\max(PP_{PGV}, PP_{PGD}) \), with \( PP_{PGV} \) and \( PP_{PGD} \) calculated as in Equation 1. Note that Equation 1 is a Poisson process and thus, is ‘memoryless’ disregarding any failures that may have occurred along the pipe in the past.

WATER NETWORK RELIABILITY

Once the failure probability, \( P_f \), of every pipe is known, the performance of the network and its failure probability 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. Alternatively, if the failure is defined with respect to hydraulic quantities, i.e., the hydraulic head in every house connection should not be less than a given minimum value, then hydraulic analysis of the network is required. Appropriate software is necessary in the latter case.

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 $j$. Inflow and outflow nodes are also called sources and sinks, respectively. If the failure probability to deliver water between $i$ and $j$ is $P_{f,ij}$, the network reliability $R_{f,ij}$ is defined as $R_{f,ij} = 1 - P_{f,ij}$.

The Monte Carlo simulation (MCS) method is often employed when the analytical solution is not attainable and the failure domain cannot 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. If $N_H$ is a large number, an unbiased estimator of the probability of failure is given by:

$$
\hat{P}_{f,ij} = \frac{1}{N_{MCS}} \sum_{j=1}^{N} I(x_j) \approx \frac{N_H}{N_{MCS}}
$$

where $I(x_j)$ is a boolean vector indicating successful or unsuccessful simulations. For the calculation of $P_{f,ij}$, a sufficient number of $N_{MCS}$ independent random samples is produced using a specific probability density function for each component of the array $x$. Therefore, $N_H$ is the number of simulations where failure occurred, whereas $N_{MCS}$ is the total number of simulations necessary to obtain an accurate estimation of the probability $P_{f,ij}$.

3 NETWORK RESILIENCE

The term resilience comes from the Latin word “resilio” which means “to leap back”. Resilience denotes the ability of a system to recover from events that disrupt its operation and usually cause damage [6]. Disaster resilience of infrastructure during and after natural or man-triggered disasters is vital for the recovery of the community. Resilience-based design refers to planning for hazardous conditions and prioritizing a series of actions in order to: (i) deal with emergencies immediately after an event, and (ii) gradually restore the services offered by the network [7]. A network with a high level of resilience is expected to recover quickly, whereas systems with low resilience would experience a slow recovery after a disaster. Resilience planning and designing requires prioritizing the services that should be operational after an earthquake, e.g. access to critical infrastructure such as hospitals should be a top priority, while a resilient system should
demonstrate reduced failure probabilities, reduced consequences from failures, and reduced time to recovery. The seminal work of Brunet al. [7] provides the conceptual basis of resilience. The study points out that resilience is a multi-dimensional problem that includes technical, organizational, social and economical facets. Latter studies (e.g. [8]) attempt to propose consistent frameworks that enable quantifying resilience and allow resilience-based design in engineering practice. Cimellaro et al. [9] study the resilience of the water distribution network of a town in Sicily.

The concept of resilience can be better understood with the aid of Figure 1. The plot shows the “functionality” of the network versus time. At \( t_0 \) a damaging event (e.g. an earthquake) occurs and suddenly the functionality of the network, i.e. its capacity to provide a service, is dramatically reduced. The time required for restoring the system’s “functionality” is the recovery time \( T_{RE} \). If the system is restored to a stable condition at time \( t_1 \), then \( T_{RE} = t_1 - t_0 \). The system’s resilience is measured as the area of the plot of Figure 1:

![Figure 1: Definition of resilience](image1.png)

\[
R_{es} = \frac{1}{T_{RE}} \int_{t_0}^{t_0+T_{RE}} Q(t) dt
\]

(4)

![Figure 2: Aerial of the water network of Nea Artaki in Evia, Greece.](image2.png)
where \( Q(t) \) is a parameter that measures the functionality that may represent different aspects of a lifeline's performance, such as serviceability, economic losses, number of deaths, etc. Note that we divide \( R_{ES} \) with \( T_{RE} \) so that \( R_{es} \) is dimensionless. The recovery time \( T_{RE} \) provides the downtime, or in other words, the overall time that the system is not in operation and therefore it can be seen as a random variable since it depends on many factors that are difficult to predict or determine. \( T_{RE} \) includes the time necessary to repair the system but in the general case it may include other factors such as an idle time period immediately after the event, evacuation times, or the time necessary to isolate the damaged area.

In order to better understand the underlying concepts, we focus on the resilience with respect to its capacity to provide water to its customers. In the case of water delivery, a simple loss function that considers the number of customers that will be left without water can be obtained with the aid of the serviceability ratio (SR):

\[
SR(t) = 1 - \frac{\sum_{j}^{N} \omega_{j}X_{j}}{\omega_{tot}}
\]

where \( \omega_{j} \) is the number of users of each household that suffer from insufficient pressure or are left without water at time \( t \), \( N \) is the number of households of the network and \( X_{j} \) is a binary parameter that denotes whether household \( j \) is accessible or not, i.e. water is able to move from the source/s to this household. \( \omega_{tot} \) is the total number of users of the WDN.

4 NUMERICAL EXAMPLE

The water distribution network of Nea Artaki, in Evia island (Greece) is used as a case study. Figure 2 shows an aerial view of the city and its water network. The topology of network is displayed as a new layer on top of the Google Earth map with the aid of the ArcMap software. The network has a tank and three main pipes that connect the different network sections with the customers. The main pipes appear as red. Since the possible failure of these main pipes will leave large parts of the network without water access we assume that they have zero probability of failure. The yellow pipes form the water distribution network; their failure probabilities are calculated with the aid of Eqs. (1) and (2). In total the network has 346 edges and 220 vertices and geographically spans an area of 9220 × 4150m. The total length of the pipes is 25453 m, while the population varies seasonally between 9500 and 13800 people. In our study, every edge of the network serves, on average, 31 customers, while the maximum number of customers is 50.

Figure 3 shows a heat map of the network failure probabilities. The map shows the probability that the network will fail to deliver water at a specific location. The simulations were performed using a graph theory-based code developed by Fragiadakis et al. [2,3]. More specifically, we performed \( N_{MCS} = 10000 \) Monte Carlo simulations assuming that this is a gravity network, i.e. the water flows only in one direction, i.e. from the vertex with the highest to the lowest altitude. Uniform seismic loading with PGV = 70 cm/sec was assumed as the basic seismic scenario, while no ground failures occurred (PGD = 0 m everywhere). It is evident that customers far away from
the vertices that the water enters in the network, are more likely to be left without water supply in the seismic scenario examined.

![Network diagram](image)

**Figure 3:** Network failure probability for a uniform PGV = 70 cm/s (unidirectional network).

Immediately after a damaging earthquake, the network will lose its functionality and repair actions are required in order to recover its capacity prior the earthquake. The serviceability of the network is measured with the SR ratio of Eq. (5). The serviceability ratio summarizes all kinds of services that a water network should be able to provide, i.e. water transfer quantity and quality. This calculation of the SR metric over the network recovery time is based on the rate of recovery operations.

Figure 4a shows the case of three different, but constant, recovery ratios, i.e. assuming that 5, 10 or 15 pipes are repaired over the whole network and during the recovery period assumed. Figure 4b shows how this is translated in terms of serviceability and recovery of the whole system. When 5 pipes per day are repaired, (solid blue lines) 60 days are required for the full network restoration, while if 15 pipes are fixed instead, the restoration will be completed within 20 days. The behaviour looks linear, but examining the case of 10 pipes per day linearity does not seem to hold, since less than 30 days are required instead. Furthermore, Figure 5 shows the case where the number of pipe repairs per days is linearly increased. This is a common scenario that in practice may occur for a variety of reasons related with the capacity of the community to react after a disaster and allocate increasingly more resources during the repair process. In Figure 5a, we
compare three different cases with the same, constant slope equal to 1/3, while Figure 5b shows how the overall system resilience is affected.

Figure 4: (a) Constant number of pipe repairs per day, (b) Network serviceability ratio (SR) for three different repair rates.

Figure 5: (a) the number of pipe repair per day increases linearly, (b) Network serviceability ratio (SR) for three different linearly increasing repair rates.

Figure 6 shows the system’s resilience as function of seismic intensity, measured with the aid of the PGV. The resilience is the area below the SR versus time curves of Figure 4b, when the constant pipe repair rates of Figure 4a were assumed. As PGV increases, the system becomes less resilient, while the reduction rate initially is small, then increases and it finally approaches zero asymptotically. Finally, Figure 7 shows the mean robustness and its variation as function of PGV. The network “robustness” measures the residual SR capacity of the network, immediately after the event. Figure 7a shows a trend similar to that of Figure 6, while according to Figure 7b, the
COV of the robustness is around 0.5; it initially receives small values and becomes larger and almost constant for larger PGV values.

Figure 6: Sensitivity of resilience to the PGV and the number of pipe repairs per day.

Figure 7: (a) Network “robustness” as function of PGV, and (b) Coefficient-of-Variation of “robustness” as function of PGV.

5 CONCLUSIONS

A general-purpose methodology for the reliability and resilience assessment of water pipe distribution networks has been presented. The proposed methodology builds on the framework of the ALA guidelines. Once the pipe failure probabilities are known, the reliability of the water network can be calculated using numerical (Monte Carlo) simulation methods. We propose a novel methodology for the vulnerability assessment of water networks and we later extend to the resilience-based assessment of these systems. It is shown that the sensitivity of network’s resilience depends on the number of pipes that can be repaired and how this number is increased or remains constant.
6 BIBLIOGRAPHY