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RELIABILITY ANALYSIS OF URBAN WATER SYSTEMS UNDER SEISMIC ACTION

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Abstract. *Water distribution networks are critical for the recovery of an urban area struck by a moderate to strong earthquake. In the paper a refined computational procedure is presented able to assess the post-seismic response of a water distribution system. The procedure permits to deal either a scenario analysis (when the earthquake that is going to hit the urban area is known in its essential features) or a full probabilistic analysis. In the latter case in input it is required to specify the basic parameters able to describe the seismotectonic framework around the area of interest. Other sources of uncertainty are due to network geometry and mechanical response to seismic action. The reliability computation is based on the Monte Carlo method: each simulation caries out the generation of an earthquake (location and magnitude), the propagation of seismic effect at network nodes, the simulation of possible leaks and breaks over the pipes and finally the flow analysis on the damaged network. The method is applied and discussed using a real case network.*

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1 INTRODUCTION

Moderate to severe earthquakes can cause extensive damages, especially when a seismic event occurs in the proximity of a highly developed area, like a city (Rasulo et al, 2015) [22]. The complex functioning of urban areas relies on several “lifelines” providing goods and services to satisfy the demands of people and enterprises.

Water distribution infrastructures are together with sewers, electric power, gas and liquid fuels, transportation and telecommunications networks pivotal in assuring modern standard of living that are essential for the very existence of complex communities such as urban agglomerates.

Damages to one of those infrastructures can have a devastating impact, harming the life of people on short term and economic and social stability of a region on medium term, impairing community functioning and social structures.

The disconnection in functioning of lifelines can seriously delay emergency, restoration and repair operations in post-event phase. In particular the shortage of clean water for drinking and hygienic uses after an earthquake can bring a serious danger to the life and health of the survivors, due to possible spread of waterborne diseases and infections.

A damaged water system can also aggravate the severity of indirect disasters like explosions and fires. Furthermore the direct and indirect costs for the restoration of a water distribution network is particularly high since the substitution of buried pipes implies excavation operations, usually along streets and buildings, with consequent interference with human activities (road closures, business and traffic interruptions, water service shut off …).

A summary of the effects that recent earthquakes have over water distribution system can be found in reconnaissance reports periodically issued by ASCE (TCLEE - Technical Council on Lifelines Earthquake Engineering) or EERI (e.g. Rasulo et al., 2004) [20].

The Northridge earthquake that hit in 1994 Southern California produced serious disruptions to the three major transmission systems, north of San Fernando, that provide drinkable water to the city of Los Angeles. The damage recovery required over 1400 repairs to the Los Angeles Department of Water and Power (LADWP) water distribution system, with about 100 repairs to critical mains and trunk lines. There were also significant damages to above ground reservoirs constructed according to old design codes. Approximately 500,000 people (14% of those served by LADWP) experienced major service interruptions. It took five days to restore water to 99% of customers and repairs continued for months, costing about $41 million (O’Rourke et al., 1998) [19].

The Christchurch earthquake (February 22, 2011) caused an extensive infrastructural damage, including both drinking-water and sewerage systems. Over 51 kilometers of water supply mains were severely damaged. None of the fresh water wells were designed for earthquakes so that 22 out of 175 had to be interrupted and all but 64 wells required some repairs. A reservoir was seriously cracked, losing all the water stored. The day after the earthquake it was estimated that there was no drinking water supply to 80% of the city, leaving more than 300'000 people without access to reticulated water. The reparation works, made difficult by aftershocks and the continuous discovering of further disruptions after the first attempts to put again the pipes in pressure, required 30 days to restore a regular supply.

Despite its importance, seismic reliability of water distribution systems has gained researchers’ interest only recently (Hwang et al, 1998; Rasulo et al, 2008; Nuti et al, 2009; Nuti et al, 2010; Fragiadakis & Christodoulou, 2014) [12, 15, 16, 6].

2 OUTLINE OF THE PROCEDURE

A water supply system (or network) is a system of engineered hydraulic components that provide drinking water to a community. A water supply system can vary from a very simple to an extremely complex scheme, but all the networks typically include:

- a source of raw water (generally stored in reservoirs, water tanks or water towers after purification);
- a pipe network for distribution of water to the consumers (which may be private houses or industrial, commercial or institution establishments) and other usage points (such as fire hydrants);
- additional water pressurizing components (pumping stations, usually located in proximity of a reservoir) when the orographic configuration of the usage points does not permit distribution simply by gravity.

The only feasible way to compute seismic networks performance is via repeated simulations of its functioning after an earthquake. This is done by Monte-Carlo method: (i) sampling the seismic action (force) (ii) sampling the componential fragilities (resistance) (iii) comparing force vs. resistance and determine the state of each structural component (iv) rewrite the flow equations for the network in the damaged state (v) solve the flow equations (vi) determine the network capability to perform its task. Steps (i) to (vi) are repeated until stability of results is achieved (see Figure 1).

In the above outline, step (i) involves all the aspects related to seismic hazard analysis: the modeling of the source (i.e. mechanism at the epicenter that produces the shaking), the attenuation of the seismic waves (along the path between the source and the site) and the local ground amplification (through the ground layers around the site). The ground shaking is sampled at all the relevant points for the study of the water network at study. Main features of this step will be discussed in section 3.Steps (ii) and (iii) involve the modelling of the state of damage of the components of the system, given the seismic shaking at ground sampled at step (i). In this step not only the structural damage of the system components is considered, but also their serviceability, i.e. their potential capacity of functioning in a post-event situation. Those steps will be commented in section 4.

Step (iv) involves the modelling of the system in the damaged state, i.e. with some of the component with limited serviceability (possibly even out of order), as obtained from step (iii). Since the approach of the network study followed here is capacitive (rather than connective), it is explicitly admitted that the system components have not a simple safe/fail status, but the post event damage can reduce their full service capability. In the case of a water distribution system it will be analyzed the amount of water the pipes are able to carry from one node to another node of the network, using the flow equations governing the specific problem. This step will be discussed in section 5. As briefly explained both quantities related to hazard (step i) and fragility (step ii) are sampled in the Monte-Carlo process through the relevant variables indicated in Figure 1.

As already said the simulations are repeated until the output variables statistics are stable, i.e. when at least their mean value is estimated with accuracy. With reference to the generic output random variable X, this may be checked by computing the estimators of the mean and of the coefficient of variation of X:

$$\hat{\mu}_X = \frac{\sum_{i=1}^{N} X_i}{N}$$
$$\hat{\sigma}_X = \sqrt{\frac{1}{N-1} \cdot \left[\sum_{i=1}^{N} X_i^2 - N \cdot m^2 \right]}$$
$$\hat{\delta}_{\mu_X} = \frac{1}{\sqrt{N}} \cdot \frac{\hat{\sigma}_X}{\hat{\mu}_X} \qquad (1)$$

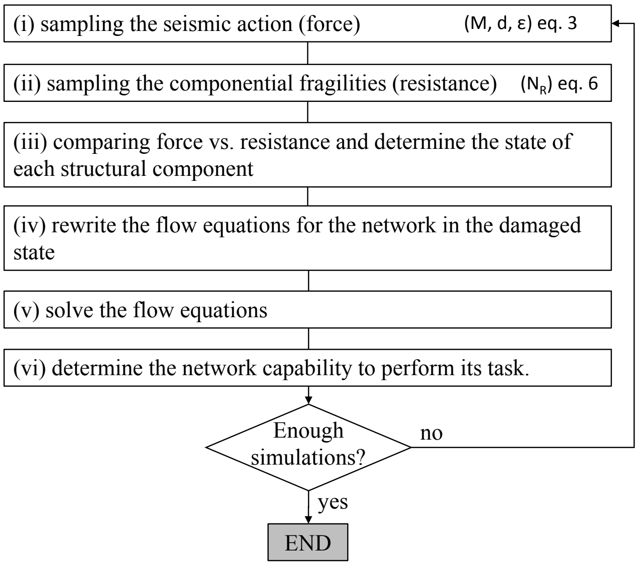

Figure 1. Flow Chart of numerical Monte-Carlo procedure with indication of relevant variables sampled.

In equation (1) the hat sign indicates estimators, N is the number of samples of X, X_i is the i-th outcome, μ_X is the mean value of X, σ_X the standard deviation of X, $\delta_{\hat{\mu}}$ the estimator of the coefficient of variation of μ_X.

3 MODEL OF SEISMIC ACTION

The Cornell model, with diffused seismicity, is usually assumed for earthquake generation. The main ingredient is the subdivision of the territory under scrutiny in a certain number of seismogenic area, within each of them the seismicity parameters are assumed constantly defined. A possible subdivision in zone of Mediterranean region is given in figure 2.

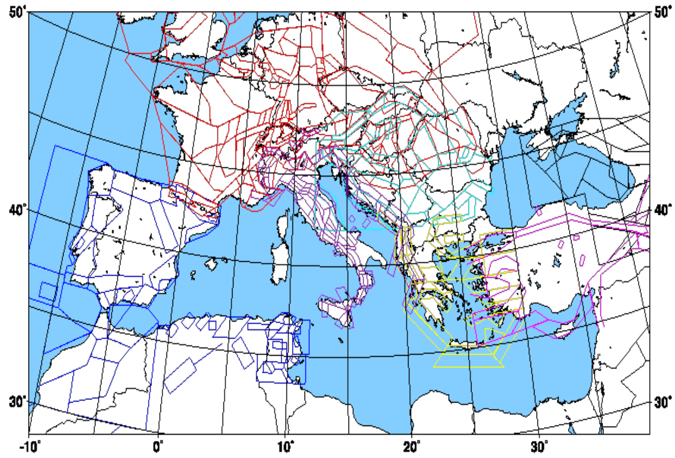

Figure 2. Seismic source zones for Mediterranean basin (GSHAP: Global Seismic Hazard Assessment Program)

In this model, the random variables are the position of the epicenter, the earthquake magnitude and the time between two events.

Since an earthquake event is assumed to occur uniformly over a single seismogenic area, the coordinates of the epicenter are assumed independent random variables, with constant distribution between the minimum and maximum values of the coordinates of the points of the seismogenic area (a further check is made to assure the so-generated points will fall inside the seismogenic areas, in the case of not-rectangular shapes).

The time random variable is modeled with the Poisson distribution whilst the earthquake magnitude random variable is modeled via the doubly truncated Gutenberg-Richter law (Gutenberg & Richter, 1954) [11]. Accordingly, within each seismogenic area, the probability distribution of earthquakes magnitude m is defined by:

$$\lambda(m) = \lambda(m_{\min}) \cdot \left[1 - F_M(m)\right]$$

$$F_M(m) = 1 - \frac{\exp(-\beta \cdot m) - \exp(-\beta \cdot m_{\max})}{\exp(-\beta \cdot m_{\min}) - \exp(-\beta \cdot m_{\max})} \qquad (2)$$

In the previous equation, β is the severity parameter, mmin and mmax are the lower and upper bound for the earthquake magnitude, λ(m) is the mean rate, according to the Poisson distribution, of events per year and F() is the cumulative distribution function. For each area, the parameters of the Gutenberg-Richter law are evaluated on the basis of the historical seismicity.

Earthquake shaking intensity at site may be expressed via different measures. Common choices can be either qualitative measures, like the Mercalli one, and those derived by it, as the Modified Mercalli scale, or quantitative measures, as, peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), the spec-tral ordinates at selected periods (both in terms of acceleration or displacement) or Arias intensity.

In the past research (Decanini et al, 2004; Nuti et al, 2007; Nuti et al, 2010) [4, 14, 16] a combination of the aforementioned measures was used for the seismic assessment of networks, on the basis of a judgmental choice of which one was the best in the case at study. The choice, in this study, to use the peak ground velocity, PGV as main parameter for the representation of the seismic action at site will be commented in the next section, since this topic is strictly related with damage representation.

A so – called attenuation law is required to compute the shaking intensity at site, given the earthquake magnitude and relative positions of seismic source and site. The simplest form for the attenuation law is circular, i.e. depends only on a measure of distance between the epicenter and the site, and reads:

$$\log_{10}(PGV) = C_1 + C_2 M_S + C_4 \log_{10}\sqrt{d^2 + h_0^2} + \dots$$
$$\dots + C_A S_A + C_S S_S + \sigma \cdot \varepsilon \qquad (3)$$

In the above equation, d is the distance from the epicenter to the site considered, PGV is the peak ground velocity, C1, C2, C4, CA, CS e h0 are coefficients to be determined as the outcome of experimental regressions, SA e SS are variables that accounts for soil conditions at site (SA = 0, SS = 0 for rock; SA = 1, SS = 0 per stiff soil; SA = 0, SS = 1 for soft soil), ε is standard normal random variable, and σ represent a measure of the residuals between observed data and predicted ones.

4 FRAGILITY OF COMPONENTS

In water distribution networks, the main source of damage comes from buried pipes (O'Rourke & Liu, 1999) [17]. Usually in a reliability analysis the use of refined computational techniques for the assessment or retrofit of structures or systems (Grande & Rasulo, 2013; Grande & Rasulo, 2015; Bursi et al; 2015, Uckan et al., 2015) [7, 8, 3, 28, 30] is not recommended. Analytical procedures are too complex to be used for the definition of damage so that simpler fragility functions are used instead.

On the topic of seismic vulnerability of water ducts, extensive studies have been conducted, and in literature it is possible to find dependable fragility curves, calibrated on observational data from past disruptive earthquakes (ALA, 2001) [1].

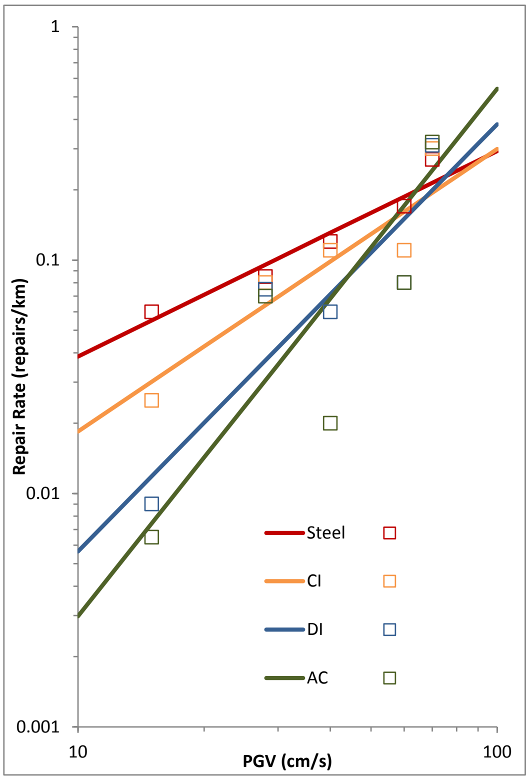

Figure 3. Seismic fragility curves for typical buried pipelines (lines) obtained through regression on observed damages (squares). Legend: Steel, CI (cast iron), DI (ductile iron), AC (asbestos cement).

The peak ground velocity, PGV, is by far the most used to relate structural damage of pipelines to a parameter of ground shaking.
Indeed reconnaissance reports on real pipes struck by an earthquake show that there is a good correlation between observed damage and PGV. This observation can be easily explained by the fact that PGV is directly related to transient ground strain induced by wave passage, ε_g (Newmark, 1967) [13]:

$$\varepsilon_g = \frac{PGV}{c} \tag{4}$$

where c is the velocity of propagation of the seismic waves through the ground, and that ground strain is the main cause of pipeline damage (due to excessive axial deformation, joint rupture, …).
Among many possibility offered by technical literature (Fig. 2), the damage model adopted in this study is given by the following equation:

$$\nu = 0.0001 \cdot PGV^{2.25} \tag{5}$$

where the damage rate along the pipe, ν (average number of breaks per unit length, 1/km), is a function of the peak ground velocity, PGV (cm/s).
Once the damage rate is known, the number of actual leaks/breaks, N_R, over the pipe with length L has been treated as a discrete random variable, distributed according to the Poisson law:

$$P(N_R) = \frac{(\nu \cdot L)^{N_R}}{N_R!} \exp(-\nu \cdot L) \tag{6}$$

5 FLOW EQUATIONS

The flow analysis on the damaged network has been set using the classical methods of analysis for water distribution networks (Gupta & Bhave, 2006) [10].

The problem can be condensed in matrix form, writing together the equations of continuity (in number of N, expressing the conservation of mass in each node) and the energy balance equations (in number of L, expressing the friction losses along the pipes) obtaining a system of N+L non-linear equations in N+L unknowns:

$$\begin{cases} \mathbf{A}_N^T \, \mathbf{q} - \mathbf{Q} = \mathbf{0} \\ \mathbf{R} \; abs(\mathbf{q}) \; \mathbf{q} + (\mathbf{A}_N \, \mathbf{h}_N + \mathbf{A}_S \, \mathbf{h}_S) = \mathbf{0} \end{cases} \tag{7}$$

N is the number of internal nodes (i.e. without tank), S is the number of nodes with a tank (representing a boundary condition for the hydraulic head) and L is the number of links (pipes), $\mathbf{Q}$ $[N \times 1]$ is the vector of discharged flows at nodes; $\mathbf{A}_N$ $[L \times N]$ and $\mathbf{A}_S$ $[L \times S]$ are the two sub-matrices (namely for internal nodes and tanks) composing the incidence matrix, $\mathbf{A}$ $[L \times (N+S)]$; $\mathbf{h}_N$ $[N \times 1]$ and $\mathbf{h}_S$ $[S \times 1]$ together are components of the vector $\mathbf{h}$ $[(N+S) \times 1]$ representing the N hydraulic heads (unknown) in the internal nodes and the S hydraulic heads (known) at the tanks; $\mathbf{q}$ is the vector $[L \times 1]$ of the flows (unknown) circulating in the pipes and finally $\mathbf{R}$ is a diagonal matrix $[L \times L]$ for the coefficients of the friction loss equation for

each link (accounting for pipes, pumps and minor loss), for the problem at hand specifically chosen, without loss of generality, of the Darcy-Weisbach type.
In seismic conditions, the flows discharged at nodes **Q** are represented not only by the usual flows distributed to the consumers, $Q_{consumers}$, but also by the water losses due to pipe damages induced by the earthquake, $Q_{earthquake}$.
Differently from the usual problem of analysis of water networks where it is assumed a-priori the ability of the system to satisfy the demand, Q_{demand}, and flow losses are evaluated as a fixed percentage of the circulating flow, in this case both these quantities cannot be assumed known, and must be evaluated as a function of the network response.
Indeed, the ability to serve the users has been expressed as a function of hydraulic head according the following expression (Gupta & Bhave, 1996) [9]:

$$Q_{consumers} = \begin{cases} Q_{demand} & \text{if} \quad h_{demand} < h \\ Q_{demand} \cdot \left(\dfrac{h}{h_{\text{ric}}} \right)^{1/n} & \text{if} \quad h_{\min} \le h \le h_{demand} \\ 0 & \text{if} \quad h < h_{\min} \end{cases} \qquad (8)$$

where h is the water head respect to the ground level, h_{demand} is the water head needed to assure to the consumers their demand, Q_{demand}, and $h_{\min}$ is the minimum water head to be assured in order to have a discharge greater than zero. In this case h_{demand} can be assumed to be equal to the average building height plus 3÷7 m (in order to account for the head losses due to domestic water system), whilst n is a model coefficient controlling the shape of the head dependent demand and to be assumed into the recommended range between 0.5 and 2.0. In this study, dealing with multi-storey buildings for which the effect of the demand, uniformly distributed along the building height, is predominant respect to the head losses in the domestic water system, the value has been set to 1, consistently with the suggestion by Gupta and Bhave (1996) [9].
Water losses due to pipe seismic damage can be treated using classic theory of the flow through an orifice/weir (Farley & Trow, 2003):

$$Q_{earthquake} = \mu\, A_{eq} \sqrt{2gh} \qquad (9)$$

where A_{eq} is the equivalent damage area to the pipe, estimated judgementally on the base of the outcome of eq (7), h is the water head, g is the acceleration of gravity and μ is the orifice/weir coefficient treated differently if the damage is a leak in the pipe or a complete pipe breakage. In the case of breakage the procedure suggested by Hwang & al. (1998) has been followed.
The problem, as formulated above, is substantially different from the conventional ones routinely solved in water distribution analysis, since its solution is no more conditioned by the discharges defined at nodes (*demand driven analysis*), but by the fact that they are a function of water heads (*head driven analysis*). Different analysis techniques have been recently adopted in literature to solve such a problem (Gupta & Bhave 1996; Tabesh, 1998) [9, 23], and can be roughly divided into recursive approaches, based on the transformation, at each iteration, of the general problem into a traditional one with known discharges, or in direct approaches where the non-linear system of equations is solved expressing the functional dependence of the discharges upon the unknowns.
In this study a direct solution strategy has been implemented, following the Gauss-Newton solution scheme.

6 CASE STUDY

Düzce is situated between Ankara and Istanbul, in one of the most tectonically active regions of Turkey. The local seismicity is dominated by the North Anatolian Fault, an active right-lateral strike-slip fault which runs for over 1'000 km westward across northern Turkey, from its junction with the East Anatolian Fault near the town of Karliova to the Marmara Sea, forming the boundary between the Eurasian and the Anatolian plates.
The North Anatolian Fault passes Düzce approximately 30 km to its south, near Lake Abant. The city was severely hit by the Kocaeli (Mw=7.6; August 17th, 1999) and Düzce (Mw=7.2; November 12nd, 1999) earthquakes.
The water supply system in Düzce is composed by an older network that dates back to 1940's and a newer one. The two networks are connected together by a series of bypasses. The pipes serving the old network (roughly 500 km in length) are mostly made in cast iron (CI), with some in asbestos cement (AC), the pipes serving the new network (roughly 280 km) consists of PVC pipes with diameters between 100 and 200 mm (Tromans, 2004; Tromans et al, 2004) [25, 26]. All the aforementioned pipes are seismically very vulnerable since are expected to fail with brittle collapses.
The total length of the pipes in the distribution system is about 780 km and the average depth of the pipes respect to the ground level is 1.50m.
Düzce water sources are mainly two: the River Ugur (which lies to the south of the town), whose waters require sanitation, and a well-field (north-east), which supplement the main water supply from the river. A 600 mm diameter AC pipe conveys raw water from the river to the water treatment plant. A 1000 mm diameter steel pipe then carries the treated water to the town. Twin CI pipes, each of diameter 125 mm, transport water from the well-field and reservoir to the distribution network.
Water table, due to proximity of the river to the city, is relatively shallow: the depth within the city ranges between 2 and 5 m. An extensive seismic micro-zonation study was conducted for the city, providing detailed site-specific amplification response. The data collected has permitted to define for each node in the water distribution network the site conditions, and therefore the parameters to be included in the attenuation model for the prediction of the ground shaking due to an earthquake.
In the case study a scenario rather than a complete Cornell analysis has been conducted. Therefore in the simulation the localization of the damaging earthquake has been constrained to represent the repeating in the future of the Düzce (Mw=7.2; November 12nd, 1999) event, rather than considering all the possible outcomes. The reasons of this choice were mainly to have a confrontation with the outcomes of the real case and also for a better understanding of the results. Indeed according to the Montecarlo approach, the final outcomes are obtained by the superimposition of different scenarios and results tend to be uniformly spread over the whole extension of the network.
Despite to the fact that the main parameters of the scenario event are known and therefore constrained in the reliability analysis presented here (i.e. magnitude and position, the latter approximatively 9 km south respect the city), the uncertainty of the ground motion due to attenuation law produces some variabilities that propagates over the results.
This study uses two indices to represent network performance: r, the ratio between the flow distributed to consumers in post-earthquake conditions, $Q_{\text{consumers}}$, and their demand Q_{demand} (representative of non seismic conditions), and s the ratio between water head computed in seismic, h_{seismic}, and non seismic, $h_{\text{non seismic}}$, conditions:

$$r = \frac{Q_{consumers}}{Q_{demand}}$$
$$s = \frac{h_{seismic}}{h_{non\,seismic}} \qquad (10)$$

For r and s it is possible to elaborate, for each node, and across Montecarlo simulations, the first and second statistical moment.

The results are presented in figures 4 through 7. In Figures 4 and 5 the geographic spread of the mean of the r and s indicators are presented. For the same case, Figures 6 and 7 present the scatter around the mean values (it shows mean values +/- one standard deviation), along the nodes of the network.

As expected, the position of the seismic source, together with local site conditions, played a key role over the definition of the reliability of water infrastructure. Indeed, as shown from figures 3 and 4, the area where the water network had the more serious problems were in the south-east quadrant, where are concentrated the soft soils, which corresponds a worst amplification of the seismic ground effects (Yargici, 2003) [29].

This justifies the importance of including a correct soil geotechnical model in risk response analysis.

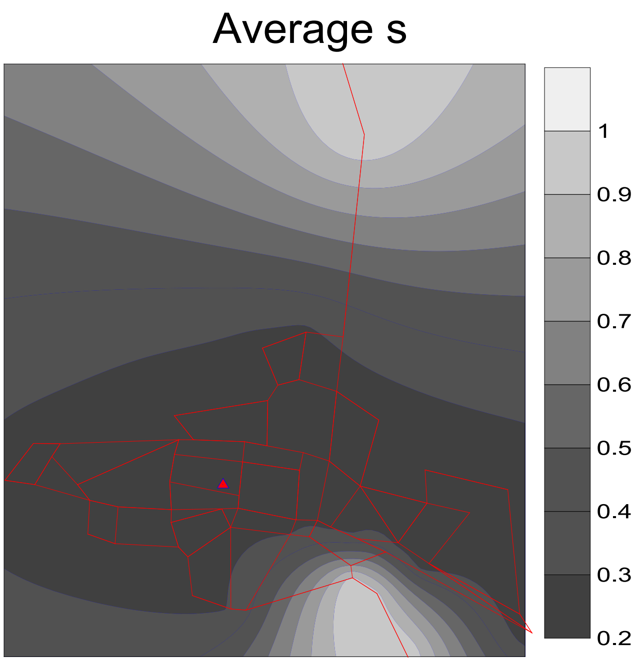

Figure 4. Average ratio of water head.

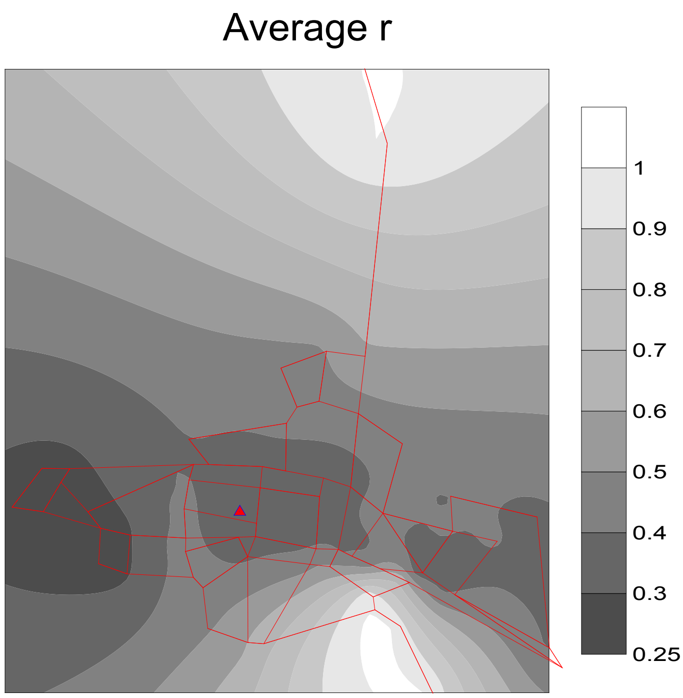

Figure 5. Average ratio of the water flow distributed.

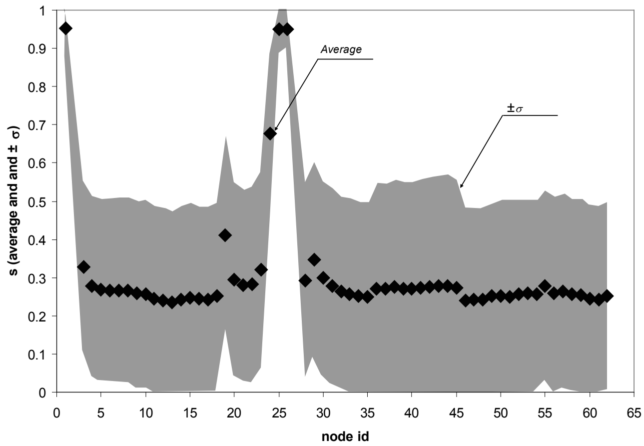

Figure 6. Average ratio and scatter (±σ) of water head along network nodes

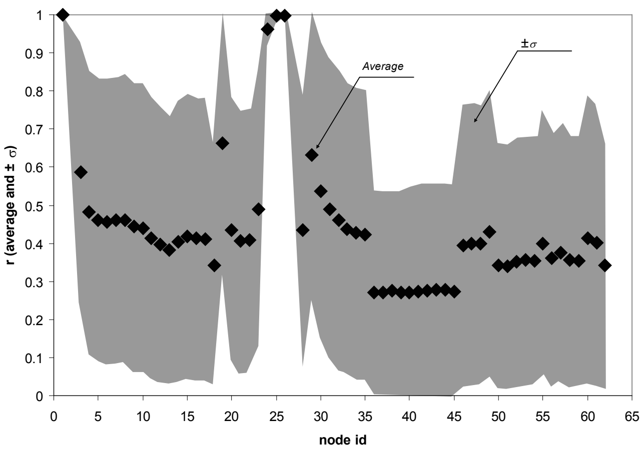

Figure 7. Average ratio and scatter (±σ) of water flow distributed along network nodes

7 CONCLUSIONS

The paper presents a procedure for the post-seismic reliability analysis of water distribution networks. The developed method is capable of integrating the features arising from structural or functional failures due to an earthquake. The post-earthquake damages to the buried pipelines due to the ground shaking are the main source of vulnerability and inefficiency for the whole water distribution system.

The method permits to identify the nodes where the network capacity decreases to the point that the system is unable to deliver the necessary flow rates (i.e. the capacity is lower than the demand).

The difficulty of the task has been overcome recurring to the Montecarlo reliability analysis technique. The power of the approach lies both in the ability to consider the main sources of uncertainty under which the analysis is conducted and to treat the networks as capacitive.

This has required to model the seismic action (accounting for possible seismogenetic sources, the probability of occurrence of earthquakes and the source to site attenuation process), to model the effects of the ground shaking on the network components (understanding possible interactions between mechanical and structural damage and functionality reduction) and finally to model the flow of the circulating water across the system.

Seismic hazard and componential fragilities have been combined through the functioning of the network: the ground shaking, consistent with the hazard at site, produces, in the pipes that form the water distribution network, some damages, according with componential fragilities, so that the whole system response under seismic action can be evaluate. System reliability has been analyzed considering the performance in delivering the water in single consumer points along the network.

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