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SEISMIC RISK ASSESSMENT OF THE WATER SYSTEM OF THESSALONIKI

Maria ALEXOUDI [1], Anastasios ANASTASIADIS[2], Kyriazis PITILAKIS[3]

ABSTRACT

The paper describes a seismic risk assessment methodology for water network recovery after an earthquake. The methodology is useful to design preparedness actions and an efficient mitigation strategy. The proposed methodology considers seismic loading conditions for ground shaking and permanent ground deformation. The methodology comprises the vulnerability assessment, the serviceability analysis and direct losses estimates in terms of replacement cost. The methodology is applied in the Thessaloniki water system.

Keywords: Water system, fragility & restoration curves, vulnerability, site-effects, serviceability.

INTRODUCTION

Lifelines are vital for the community and the quality of living, the degree of the development and the growth of a society. Water system as part of the lifelines systems is absolute necessary in community for drinking and for sanitary purposes. Its large extent together with the complexity of water system components (e.g. pipes, tanks, water treatment plants, wells, pumping stations), the synergies between different systems and the spatial distribution of seismic ground motion make the estimation of their performance a major concern and a very challenging issue. The methodology illustrated herein presents a straight forward process for water networks to estimate the vulnerability, the seismic performance, the necessary restoration time to overcome the damages and to evaluate the direct economical loss based on the model of Greek construction practice and expertise.

METHODOLOGY

The seismic risk assessment methodology for water systems is illustrated briefly in the flow-chart of Figure 1. As every seismic risk assessment methodology, it depends on several assumptions and is influenced by the accuracy of seismic loading, the inventory, the selection of appropriate relationships for fragility and restoration, the interaction between lifelines and urban environment and synergies between different lifelines.

[1] Dr. Civil Engineering, Aristotle University of Thessaloniki, Greece, Email: alexoudi@civil.auth.gr
[2] Lecture, Department of Civil Engineering, University of Thessaloniki, Greece
[3] Professor, Department of Civil Engineering, University of Thessaloniki, Greece

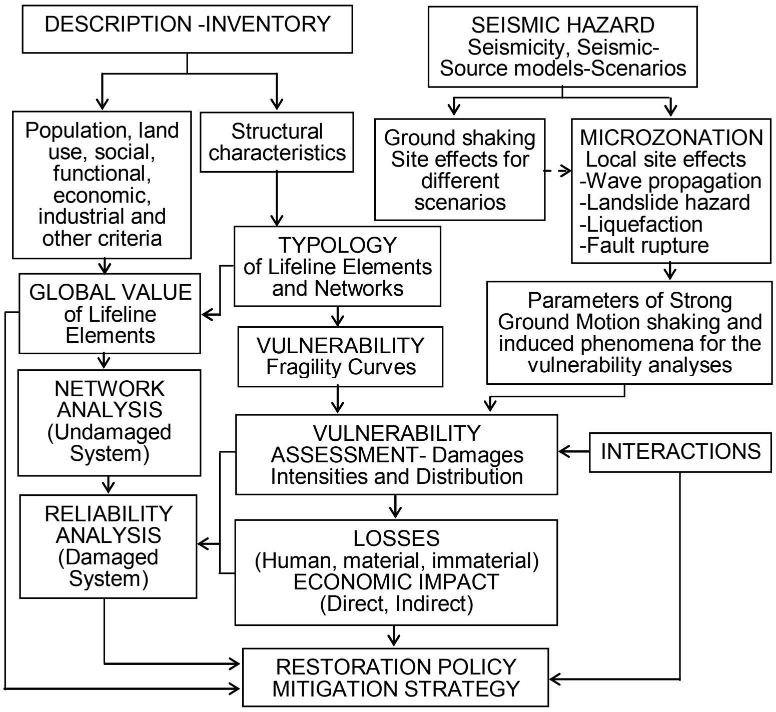

Figure. 1 Flow chart of the proposed methodology for lifelines (Pitilakis et al, 2006)

Inventory

The inventory of the network comprises of the distinctive features of the components (e.g. geometry, material, age, etc). It is a time and cost consuming process with large uncertainties due to lack or/and penury of data, the spatial distribution of the networks and sometimes the reluctance of manufacturers, owners and managers of the lifelines to share information.

Seismic Hazard/ Site-effects

Water system components are vulnerable to damages due to wave propagation and permanent ground deformation (PGD) or by a combination of both. The seismic input is often provided through and site effect estimates appropriate to the seismicity, the tectonics and the local site and soil conditions. .The spatial distribution of seismic ground motion must take into account local site-effects, geological conditions and the possible presence of basin and topography effects. Seismic loading is described in terms of peak ground acceleration (PGA), peak ground velocity (PGV) and sometimes simply with the seismic intensity (MMI, MSK). For pipelines, the seismic loading caused by ground shaking and wave propagation is described in terms of peak ground velocity (PGV), because it is directly proportional and better correlated to the strains observed in the ground. For other kind of water system facilities (water treatment plants; wells, pumping plants and storage tanks), PGA values are used.

Vulnerability/ Damage state

The seismic risk assessment of water systems comprises an assessment specifically for every component of the system. Vulnerability is calculated using appropriate relationships, basically empirical, that correlate the seismic load with the Repair Rate (RR/km). Fragility curves describe the probability of reaching or exceeding each damage state given the level of ground motion or ground failure producing permanent ground deformation.

In the present paper we used the fragility functions proposed by O'Rourke & Ayala (1993) and Honegger & Eguchi (1992), as it is suggested in HAZUS 2004. O'Rourke & Ayala (1993) relationship is based on data collected from actual pipeline damages observed in four USA and two Mexican earthquakes. The relation was validated with recorded damages in Lefkas (Greece) and Duzce (Turkey) water network after Lefkas (2002) and Duzce earthquake (1999) (Alexoudi M, 2005). Honegger & Eguchi (1992) relationship was also validated in Lefkas earthquake for the case of permanent ground deformations.

The Repair Rate according to O'Rourke & Ayala (1993) for wave propagation is given as:

$$\text{Repair Rate [Repairs/Km]} \cong K1*0.0001*(PGV)^{2.25} \qquad (1)$$

PGV (cm/sec) and K1: coefficient depending on the type of pipeline (brittle, ductile)

The Repair Rate according to Honegger & Eguchi (1992) for permanent deformation is:

$$\text{Repair Rate [Repairs/Km]} \cong K*(7.821*PGD^{0.56}) \qquad (2)$$

PGD (cm) and K1: coefficient depending on the type of pipeline (brittle, ductile)

For ductile pipelines (steel, ductile iron and PVC), K1=0.3, while for brittle pipeline (asbestos cement, concrete and cast iron pipes) K1=1.0. Welded steel pipes with arc-welded joints are classified as ductile, while welded steel pipes with gas-welded joints and pre-1935 steel pipes are classified as brittle.

Two damage states for pipelines were considered, leaks and breaks. In case of wave propagation, is assumed that 80% of damages are leaks and the rest 20% are breaks while for the case of permanent deformation 20% of damages are leaks and the rest are breaks.

In Greece most of the tanks are above ground R/C tanks and we have been selected the fragility relationship and the definition of damage states as proposed in HAZUS. In cases where the components of a system are made by an assemblage of subcomponents (i.e. pumping plants), fragility curves for these components are estimated applying a probabilistic combination of subcomponent damage functions using Boolean expressions to describe the connection of subcomponents to the main component. It should be mentioned that the Boolean logic is implicitly presented within the definition of a particular damage state. In the case of a water system components (expect pipelines), five damage states are defined: none (ds_1), slight/minor (ds_2), moderate (ds_3), extensive (ds_4) and complete (ds_5) damage. According to Boolean logic and HAZUS 2004, a pumping station is composed by 4 subcomponents: electric power supply, pumping, building and electrical/ mechanical equipment. Based on Boolean logic a "slight/ minor" damage for pumping station was defined by malfunction of plant for a short time (less than three days) due to loss of electric power and backup power if any, or slight damage to building. Therefore, the fault tree for slight/minor damage has two primary OR branches: electric power and building and two secondary AND branches under electric power: commercial power and backup power. The Boolean approach involves evaluation of the probability of each component reaching or exceeding different damage states, as defined by the damage level of its subcomponents. These evaluations produce component probabilities at various levels of ground motion. In general, the Boolean combinations do not produce a lognormal distribution, so a lognormal curve that best fits this probability distribution is determined numerically. In Greece, most of water pumping stations don't have electric power generators and although there is a type of anchorage in the electrical/ mechanical equipment the construction detailing do not follow an official prescription. Due to these distinctive characteristics we re-draw the fragility curves for pumping stations. For the building component we used the fragility curves proposed by Kappos et al (2006). Moreover, it is assumed that the prevailing damage state is the one with the possibility of exceeding the damage state of 50%. Table 1 illustrates the damage states elaborated for pumping plants in Greece.

Table 1: Damage Algorithms for Pumping Plants

Peak Ground Acceleration			
Classification	Damage State	Median (g)	Σ
Pumping Plants with anchored subcomponents and R/C 1.1.X.X building	slight/minor	0.10	0.55
	moderate	0.15	0.55
	extensive	0.30	0.70
	complete	0.40	0.75
Pumping Plants with anchored subcomponents and R/C 1.1.X.Y building	slight/minor	0.15	0.30
	moderate	0.30	0.35
	extensive	1.10	0.55
	complete	2.10	0.70

(R/C 1.1.X.X building: Low- height building, 1- 3 floors, with low level seismic codes; R/C 1.1.X.Y building: Low- height building, 1- 3 floors, with advanced seismic codes).

Economical losses

Direct damage is expressed in terms of the component's damage ratio which is the repair cost to replacement cost; functionality loss may also be included in terms of associated economic loss. Table 2 illustrates the way that the cost of water system components may be calculated according to different cost evaluations (Greek experience, HAZUS 2004 and TCLEE, 1991). The replacement cost evaluation is given as the percentage (%) of the construction cost according to the suggestion of ATC 25 (Table 3). The total economic (replacement) cost is estimated as following:

Economical Loss= 10%*Prob.Ds>ds1/PGA+30%*Prob.Ds>ds2/PGA+ 60%*Prob.Ds>ds3/PGA+ 100%*Prob. Ds>ds4/PGA)*Construction Cost (3)

Table 3 Damage States for Water System Components

Damage State description	% Construction Cost
Slight/Minor	1- 10%
Moderate	10-30%
Extensive	30- 60%
Complete	60-100%

Table 2 Construction cost of water system elements

Water system components	Greek experience*	HAZUS 2004	TCLEE (1991)
Pipes	1500- 2700	800	700- 2500
Tanks (R/C)	750.000-1.300.000	1.200.000	930.400
Drills	320.000	320.000	305.000
Pumping stations: Small ($<40.000m^3$/day) Medium/ Large ($>40.000m^3$/day)	 100.000-235.000 920.000	 120.000 420.000	 140.000-155.000 305.000
Water Treatment plant Small ($<2*10^5m^3$/day) Medium ($2*10^5$-$8*10^8$ m^3/day) Large ($>8*10^8$ m^3/day)	100.000.000 - -	24.000.000 80.000.000 288.000.000	7.020.700 17.000.000 -

*Data collected for Thessaloniki (2003- 2004)

HAZUS gives lower construction cost and furthermore replacement cost for pipes comparing to Greek practice and TCLEE (1991). This maybe true because the replacement cost isn't based only on the structural characteristics (e.g. material and diameter) but mainly to other factors like the accompanying works that depend on the accurate knowledge of water system, and the population density. The cost of R/C tanks and drill works are in good agreement while the cost of small pumping station in Greece is equivalent to HAZUS 2004 and TCLEE (1991). The replacement cost is different for large pumping plants (PP) and for water treatment plants (WTP). In Greece (especially in Thessaloniki were the data were gathered), both PPs and WTPs are equipped with SCADA systems and various automation equipment which are increasing the cost.

Restoration

The restoration is expressed in terms of the number of days needed to repair meaning the leaks and breaks in case of pipe damages or % of re-gain functionality of the damaged components according to the obtained damage state.

In Greece, it is anticipated that for small pipes (D<500mm) a 4 -person crew can repair a leak in 5 hours and a break in 10 hours. For large pipes (D>500mm) a 4 -person crew can repair a leak in 7 hours and a break in 12 hours. Appropriate restoration times for pumping plants can be estimated according to ATC-13 with small adjustment to specific city conditions. The regained functionality of R/C storage tanks and of pumping stations in Table 4 is based on Greek construction practice. For an example if a specific water component e.g water R/C storage tank faces a complete damage after an earthquake, in the 1^{st} day, the re-gained functionality is 2% while more than 90 days it would be needed for the totally repair.

Table 4 Proposed restoration times as % of re-gained functionality for Potable Water System components in Greece

Restoration (%)						
Classification	Damage State	1 day	3 days	7 days	30 days	90 days
Pumping Plants	slight/minor	100	100	100	100	100
	moderate	22	50	93	100	100
	extensive	10	15	25	95	100
	complete	3	4	6	40	100
Water R/C Storage Tanks	slight/minor	50	100	100	100	100
	moderate	30	60	95	100	100
	extensive	5	7	8	15	30
	complete	2	3	4	10	20

Performance analysis

Lifeline networks global performance is usually described in terms of serviceability, system reliability, connectivity indices, density of damage (%) etc. For a water network, the appropriate indicator is the serviceability level. It can be expressed by a certain demand in a specific node or by the reduced flow. A detailed serviceability analysis involves a relatively large number of hydraulic analyses of water system in various damage states. Such analysis was performed by Okumura and Shinozuka (1991) using Monte-Carlo simulation technique for Memphis Water delivery system. A rough estimation of water system functionality (i.e. the percentage of customers served immediately after the event) can be based to serviceability index for the entire system, through the identification of RR/km. Figure 1 illustrates the results of different analysis in USA indicating a rather important scatter (NIBS, 1999). The 100% in the same diagram means full serviceability

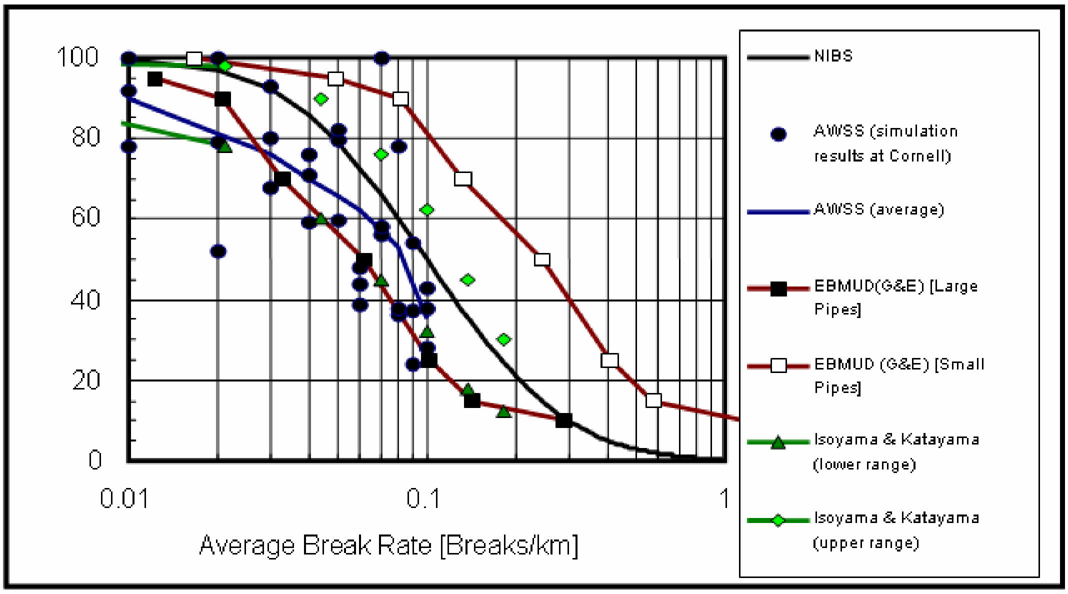

Figure 2. Damage index versus average break rate for post-earthquake system performance evaluation (NIBS,1999)

APPLICATION IN THESSALONIKI (GREECE)

Thessaloniki is the second largest city in Greece. With more than 420.000 connections the water system is serving about 1.000.000 people. The normal daily need for water consumption is 250.000 m^3. The length of the transmission system is 300km and the total length of the distribution system is about 1.300km. From them, 71km are the pressure pipes. The pressure in the internal network varies between 2-5 bar. The network comprises also 3 water treatment plants, 43 tanks and 39 pumping stations. The inventory of the water reservoirs includes information of their capacity (m^3), the shape (rectangular, circular), the height (m), the material (R/C), the roof system (R/C) and the existence of anchorage. For the pumping stations the inventory includes the available number of pumps and the flow served. Finally for the water pipes the inventory comprises all relevant construction characteristics (material, diameter and construction year).

The metropolitan area of Thessaloniki is affected mainly from the Axios Vardar and the Servomacedonian seismogenic zone (Papazachos B. et al, 1979). A description of the tectonics of the region can be found in Pavlides S. et al, 1990. A detailed description of the different geophysical and geotechnical surveys as well as the derived geotechnical zones specifically to perform ground response analysis is provided by Pitilakis et al (1992), Pitilakis K & Anastasiadis A, (1998) and Anastasiadis A., et al (2001).

Seismic hazard

The application presented herein concerns a probabilistic seismic scenario of 1000 years mean return period corresponding to a Mw=6.8 earthquake as developed in the research project SRMLIFE. The detailed ground response analysis is performed using five input motions in the bedrock properly scaled. Typical results in terms of peak ground acceleration and velocity values as well as in terms of permanent ground deformation due to liquefaction are given in Figures 3.

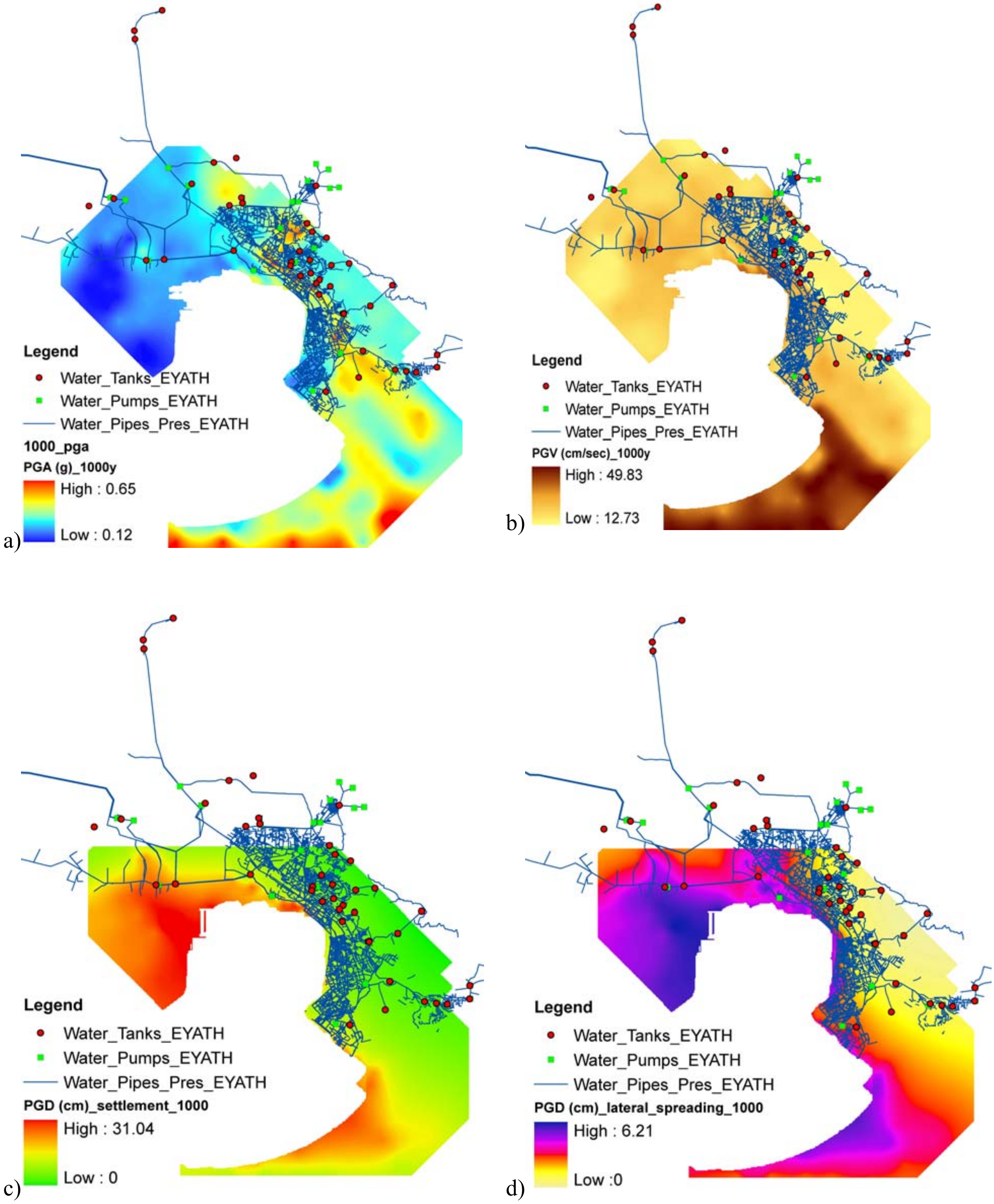

Figure 3. Spatial distribution of (a) PGA (g), (b) PGV (cm/sec), (c) PGD (m)- settlements, and (d) PGD (m)-lateral spreading in Thessaloniki for the 1000 years seismic scenario

Damages:

Figures 4 present the overall repartition of damages in tanks and pumping stations in the study area while Table 5 gives the probability of damages in each damage state for the water pumping stations. The final classification for any component is made with the damage state having a probability equal or higher to 50%. Figure 5 illustrates the spatial damage distribution of damages for the water pipes (no damage: green, leak: orange, break: red), the water tanks and pumping stations (slight/minor: green, moderate: yellow, extensive: orange, complete: red).

For the seismic scenario of 1000 years mean return period, it is anticipated that the water systems of Thessaloniki will undergo 379 pipe failures, 277 breaks and 102 leaks. Most damages are expected in areas of PGA>0.30g and PGV> 25 cm/sec (central part and the north –east part of Thessaloniki) accordingly.

Serviceability

Considering the total length of the water system (1085.02km) and the number of breaks, the average Break Ratio for the 1000 years scenario is calculated equal to $RR_{average}/km$ = 277/ 1351.20= 0.205. A rough estimation of water system serviceability using Figure 2 is 20% according to NIBS approach and 43% based on EBMUD (G&E).

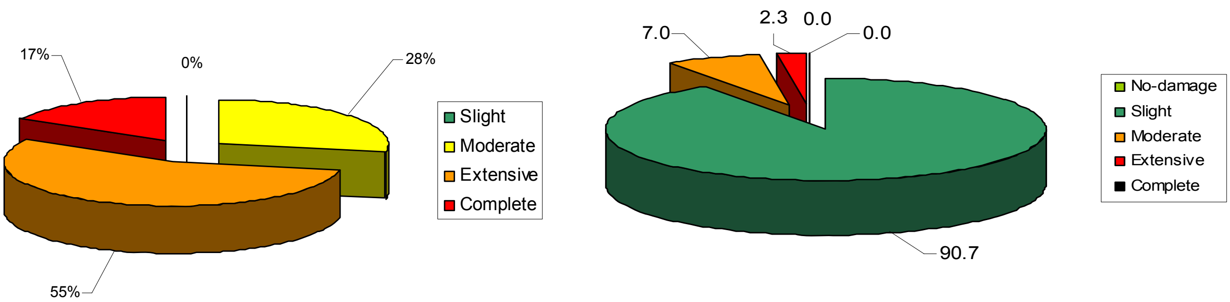

Figure 4. Distribution of damage in pumping station (left) and tanks (right) of Thessaloniki (Seismic scenario: 1000 years mean return period)

Economic loss

Considering the cost for pipeline replacement estimated for the metropolitan area of Thessaloniki and the expected number of repairs, the total cost of the reconstruction of city's water system for the extreme scenario of 1000years mean return period ranges for the pipes between 550.000- 1.050.00000 euro (2004 prices), for pumping stations between 2.050.000- 4.800.000 euros, while for tanks the cost ranges between 9.000.000- 15.600.000 euros. Summing these values the total repair cost is estimated between 11.600.000 and 21.450.000 euros.

Restoration time

Considering the real available man power and the organization scheme of the Water Supply Company of Thessaloniki and more precisely that it could mobilize at least 50 people for the repairing works on a 24h/day basis, it is estimated that it needs twenty days for the total recovery of water pipe network. In 12 days, all breaks should be repaired while 8 extra days are needed to repair the leaks.

Table 5 Probability of damages for water pumping stations in Thessaloniki for the 1000 years seismic scenario

LOCATIONDE	PGA1000	PF_SLI1000	PF_MO1000	PF_EXT1000	PF_COM1000	FIND1000
NEO RISIO	0.30	0.98	0.90	0.50	0.35	Extensive
AGIAS KIRIAKIS	0.42	1.00	0.97	0.68	0.53	Complete
VLATADON	0.30	0.98	0.90	0.50	0.35	Extensive
KAFKASOU	0.30	0.98	0.90	0.50	0.35	Extensive
TOUMPA	0.33	0.99	0.92	0.55	0.40	Extensive
OUTSARSO	0.34	0.99	0.93	0.57	0.41	Extensive
KASSANDROU	0.37	0.99	0.95	0.62	0.46	Extensive
KALLITHEA	0.35	0.99	0.94	0.59	0.43	Extensive
METEORA	0.28	0.97	0.87	0.46	0.32	Moderate
A2 PILEA	0.36	0.99	0.94	0.60	0.44	Extensive
AD8 (POLICHNI)	0.43	1.00	0.97	0.70	0.54	Complete
EVAGGELISTRIA	0.32	0.98	0.92	0.54	0.38	Extensive
SIKIES	0.28	0.97	0.87	0.46	0.32	Moderate
SFAGEIA	0.26	0.96	0.84	0.42	0.28	Moderate
SFAGEIA	0.25	0.95	0.82	0.40	0.27	Moderate
EPTAPIRGIO	0.28	0.97	0.87	0.46	0.32	Moderate
DENDROPOTAMOS	0.26	0.96	0.84	0.42	0.28	Moderate
BOOSTER EVOSMOS	0.45	1.00	0.98	0.72	0.56	Complete
BOOSTER NEAPOLI	0.30	0.98	0.90	0.50	0.35	Extensive

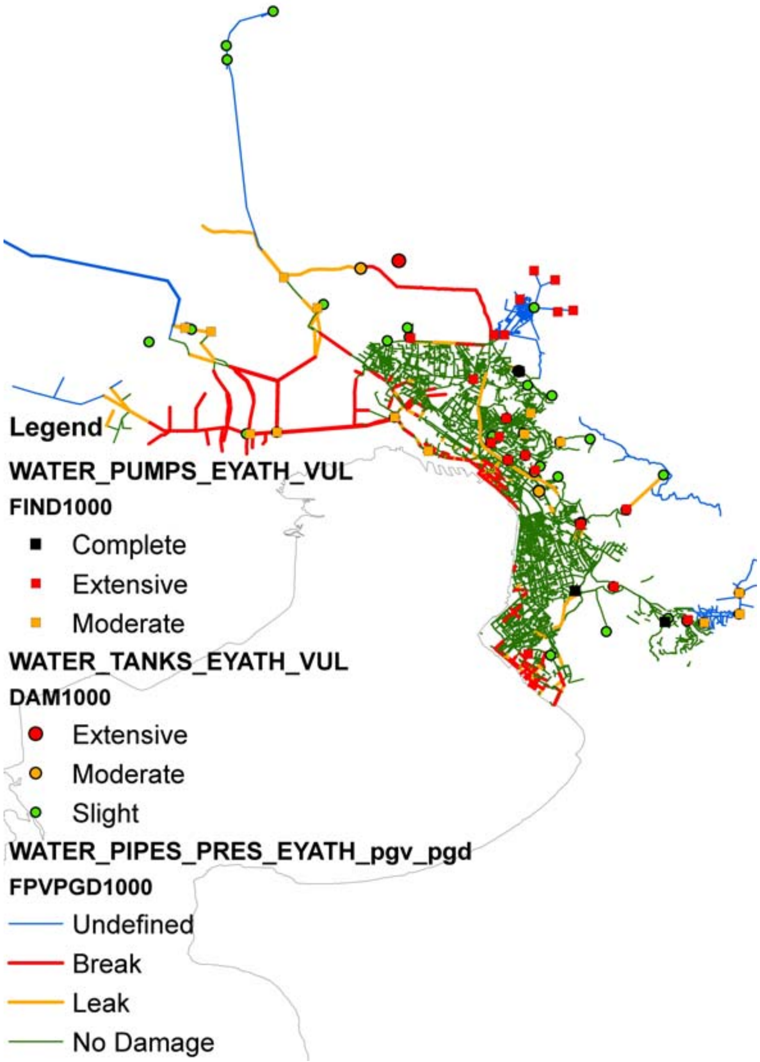

Figure 5. Estimated damages of water system elements due to wave propagation (Seismic scenario: 1000 years mean return)

CONCLUSIONS

The scope of the paper is to illustrate the basic features of the methodology for the seismic risk assessment of water networks and water supply systems considering besides the pipes the pumping station and the reservoirs. The application in the water system of Thessaloniki for an extreme seismic scenario of 1000 years mean return period provided not only the damages severity and the spatial distribution but also the serviceability levels, the direct economic cost of repair and the time needed for the full recovery (restoration). As important factor affecting the reliability of the proposed methodology is the good knowledge of the geotechnical conditions and the performance of specific site effect analysis to estimate the spatial variability of ground motion parameters. The methodology can be applied to develop a coherent mitigation strategy and preparedness policies.

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