



SEISMIC RISK ASSESSMENT AND MANAGEMENT OF LIFELINES, UTILITIES AND INFRASTRUCTURES

Kyriazis D. PITILAKIS¹, Kalliopi G. KAKDERI²

ABSTRACT

Vulnerability assessment and seismic risk management using advanced methodologies are of major importance for the reduction of seismic risk in urban areas. The development of an advanced and integrated methodological tool for the efficient seismic risk management of complex lifeline and utility systems is necessary for the establishment of efficient and effective mitigation schemes. To this end, a modular methodology has been recently developed in Greece in the framework of national and EU research projects for the vulnerability assessment and seismic risk management of lifelines, utilities and infrastructures. The general description of the methodology is provided, along with several representative example applications. Key factors of the methodology are the inventory, the typology, the fragility, the specific characteristics and the importance (global value) of the elements at risk, the development of seismic scenarios (seismic hazard) and the geotechnical characterization, with the detailed site response analysis. Based on estimated losses and assigned priorities, restoration policies and mitigation strategies could be defined. Furthermore, new developments and important aspects of the risk mitigation procedure are further analyzed and commented on, while the ongoing research efforts in Europe are shortly summarized. These new developments include mainly the systemic physical and socio-economic vulnerability and risk analysis, the incorporation of decision-making processes in the seismic rehabilitation studies and the use of real-time damage estimation for the reduction of potential impact on urban societies on the basis of timely and correct actions after a disastrous earthquake. Finally, specific guidelines are provided for the management and reduction of seismic risk of lifelines and infrastructures in urban environments.

Keywords: seismic risk, mitigation, vulnerability, seismic scenarios, lifelines, utilities, infrastructures

INTRODUCTION

Large destructive earthquakes occurred worldwide in highly urbanized areas in the last twenty years or so, (Loma Prieta, CA, 1989; Northridge, CA, 1994; Kobe, Japan 1995; Izmit, Turkey and Chi-Chi, Taiwan, 1999) have prompted researchers to undertake large-scale studies on the expected losses due to a major earthquake. Studies of this type serve the main purposes of designing mitigation strategies and of planning emergency and recovery measures.

Existing methodological frameworks have been developed mainly in the United States. HAZUS (NIBS, 2004) is a risk assessment methodology for analyzing potential losses from floods, hurricane and earthquakes and distributed by FEMA. HAZUS couples scientific and engineering knowledge with geographic information systems (GIS) technology to produce estimates of hazard-related damage before, or after, a disaster occurs. Recently the Impact of Earthquakes on the Central USA has been the object of

¹ Professor, Department of Civil Engineering, Aristotle University of Thessaloniki, Greece, email: kpitilak@civil.auth.gr

² Civil Engineer, MSc, Department of Civil Engineering, Aristotle University of Thessaloniki, Greece.

the “New Madrid Seismic Zone Catastrophic Earthquake Response Planning Project” funded by FEMA and carried out by the Mid-America Earthquake Center (MAEC, 2009). This project comprises a multi-phase investigation of possible earthquake scenarios, analytical earthquake impact assessments, and social impact estimates that will assist federal, state, and local governments to develop coordinated response plans for a catastrophic earthquake in Central USA. In Latin America there is a very interesting tool of similar possibilities (Central American Probabilistic Risk Assessment - CAPRA; Anderson, 2008). In Europe, among other efforts we state a software developed by the Earthquake Engineering Department of Bogazici University, Kandilli Observatory and Earthquake Research Institute (KOERI) (KOERILoss, Erdik and Aydinoglu, 2002; Erdik et al., 2003; Erdik and Fahjan, 2006), which applies a loss estimation methodology to perform analyses for estimating potential losses from earthquakes (building damage estimation analysis and estimation of the direct economic losses and casualties related to building damages). Another example is the LNECLOSS software package developed by the Laboratorio Nacional de Engenharia Civil (LNEC) in Lisbon, Portugal (Sousa et al., 2004). However, the direct application of these approaches to areas different than the ones they have been developed is not straightforward and requires serious re-adjustments. Moreover, a systemic treatment of the complex network of lifelines and infrastructures is still missing, while socio-economic issues are only addressed in a very simplified way.

A general modular methodology for the vulnerability assessment and seismic risk management of lifelines and infrastructures (potable water, waste-water, gas, electric power, telecommunication, fire-fighting, roadway, railway, airport, port and critical facilities) has been recently developed in Greece, in the framework of national and EU research projects (SRMLIFE, 2003-2007; RISK-UE, 2001-2004; LESSLOSS, 2004-2007). The general description of the methodology is provided below along with some representative example applications, while some important aspects of the risk mitigation procedure are further discussed, providing specific guidelines for the management and reduction of seismic risk of lifelines, utilities and infrastructures in urban environments.

METHODOLOGICAL FRAMEWORK

The general framework of the methodology is illustrated in Figure 1. The vulnerability of buildings and lifeline systems in the city are assessed for different seismic scenarios (Pitilakis et al., 2006a,b; Pitilakis et al., 2007a,b; Argyroudis et al., 2005). Loss estimates including direct and indirect losses, depend on the inventory and typology classification of the elements at risk, the vulnerability models and the existing interactions between lifeline components. Inventory is an essential step to identify, characterize and classify all types of lifeline elements, according to their specific typology and their distinctive geometric, structural and functional features. Geographical information systems (GIS) offer the perfect platform to implement any inventory inquires. Within this context, earthquake damage is directly related to structural properties of lifeline elements. Typology is a fundamental descriptor of a system, derived from the inventory of each element at risk. The level of seismic input motion is defined on the basis of site specific ground response analysis for several probabilities of exceedance. The hazard analysis is thus based on seismic scenarios, and a detailed ground response mapping (Anastasiadis et al., 2001; Pitilakis et al., 2007a). The vulnerability assessment deals mainly with the quantification of damage of each element at risk, using appropriate fragility functions. Given the spatial distribution of the characteristics of earthquake motion, loss scenarios for buildings, utility and transportation systems, critical facilities and strategic buildings are produced, using inventory data and adequate fragility relationships. Furthermore, a hierarchy model has been proposed to evaluate and quantify the relative importance of various elements at risk and systems as well as city regions and districts, taking into account different criteria, such as their functional relations and the urban activities and relations of lifelines with the surrounding urban or rural environment (see Global Value approach in RISK-UE, 2001-2004). The assessment of the “global value” (physical and non-physical) is performed, in order to classify the importance of each lifeline element in

different periods (normal, crisis and recovery) and prioritize in a more efficient way the pre-earthquake retrofitting actions and the post earthquake restoration efforts. Based on the hierarchy of importance of lifeline components, as well as available techniques, man-power, material and equipment, estimates of the restoration process are performed. An important step for the implementation of an “efficient mitigation strategy” includes a simplified or a more advanced reliability analysis of the damaged and the undamaged system, in order to estimate the level of the remaining serviceability of the system, which is closely connected with the functionality of the community. Thus, a rigorous disaster management process including mitigation, preparedness, response and recovery actions could be assigned.

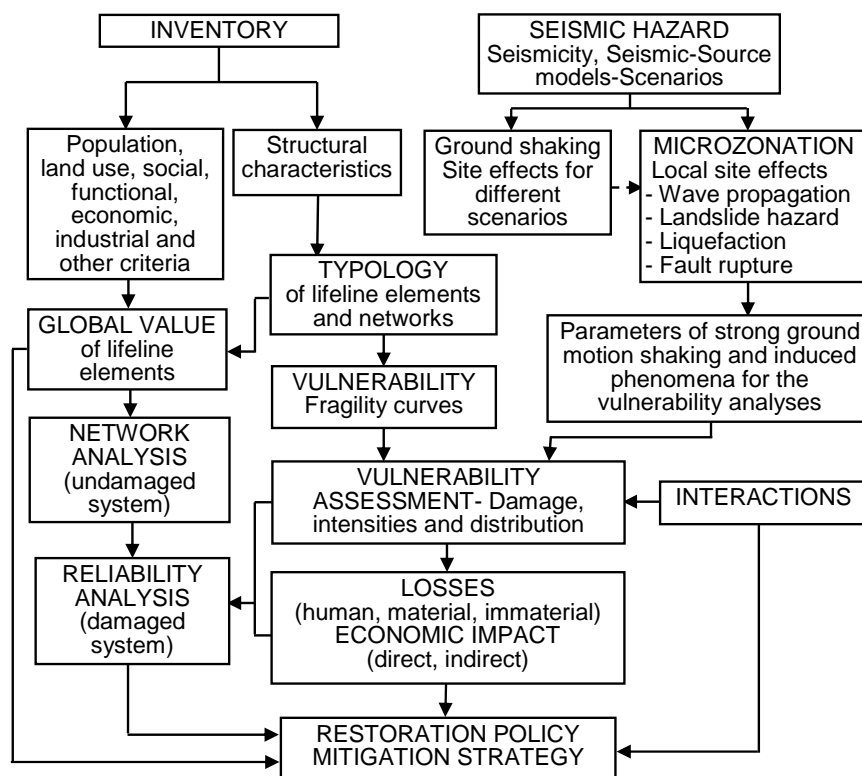


Figure 1. Seismic risk mitigation approach for lifelines and infrastructures.

SEISMIC SCENARIOS – SITE SPECIFIC GROUND RESPONSE ANALYSIS

Seismic hazard for the vulnerability analysis and risk assessment of lifelines, utilities and infrastructures, should be specified according to the precise needs for the particular lifeline components and networks, as well as the most adequate models used to describe vulnerability and fragility relationships. Moreover due to the spatial extent of lifeline systems, spatial variability of ground motion, considering local soil conditions, is of great importance (Pitilakis et al., 2005a). Site effects play a crucial role and with respect to the spatial variability and typology of various assets, their spatial variability may change completely the intensity and spatial variability of damages and losses. The simple use of seismic code soil classification schemes, and associated design acceleration values, is completely inadequate for a “high technology” vulnerability analysis and risk assessment.

Thus, specific geotechnical-surface geology information is required, and adequate studies should be performed to estimate the necessary ground shaking parameters, in terms of seismic scenarios with

different mean return periods. These studies are conventionally referred as “microzonation studies”. Moreover, advanced seismic risk analysis studies require maps with the spatial distribution of strong ground motion parameters (e.g. PGA, PGV, PGD) in the study area.

In the following, two examples are given of the detailed microzonation and ground response analyses that have been performed in the cities of Thessaloniki (Greece) and Düzce (Turkey) in the framework of national and European research projects (RISKUE, 2001-2004; SRMLIFE, 2003-2007; MERP, 2002-2005; SRM-DGC, 2006-2008), aiming to the definition of ground motion input parameters for the vulnerability assessment of lifelines and infrastructures in the two cities.

Thessaloniki microzonation study

In Thessaloniki, a detailed microzonation study has been conducted for three different mean return periods of $T_m=100, 475$ and 1000 years. The study is based on the results of a probabilistic seismic hazard analysis using recent data regarding the seismicity, the corresponding seismic zones and the seismic faults in the greater area (RISK-UE, 2001-2004; SRMLIFE, 2003-2007). A detailed model of the surface geology and geotechnical characteristics, for site effect studies, was generated for the city area. The initial geotechnical map is based on numerous data provided by geotechnical investigations, geophysical surveys, microtremors measurements, classical geotechnical and special soil dynamic tests (Pitilakis et al., 1992; Pitilakis and Anastasiadis, 1998; Raptakis et al., 1994a,b; Raptakis, 1995; Anastasiadis et al., 2001; Apostolidis et al., 2004). The dynamic properties of the main soil formations have been defined from an extended laboratory testing including resonant column and cyclic triaxial tests (Pitilakis et al., 1992; Pitilakis and Anastasiadis, 1998; Anastasiadis, 1994).

Site effects are based mainly on 1D linear equivalent response analyses, and few 2D analyses in selected cross sections, in order to take into account the influence of local geotechnical characteristics and dynamic properties of the main soil formations, on expected seismic ground motion. The analysis is conducted for five different scaled real accelerograms (for bed rock motions), appropriately selected according to the seismic hazard study, for the three scenarios (Papaioannou, 2004).

As an example, the characteristics of the calculated mean seismic ground motions at the free surface, in terms of peak acceleration (PGA) and velocity (PGV) are presented in Figure 2 for the earthquake scenario with 10% probability of exceedance in 50 years (mean return period of 475 years). It is mentioned here that PGA values are varying from 0.15g to 0.55g while, if the whole analysis was based on the Hellenic seismic code, the design PGA should be equal only to 0.16g. Similar maps have been generated for all seismic scenarios, and for several other ground motion parameters (i.e. ground strains, response spectra at different periods, etc).

Finally, in order to account for the liquefaction-induced phenomena, the evaluation of permanent ground horizontal and vertical displacements, (lateral spreading and settlements), has been performed for the three scenarios, using empirical and analytical procedures (Seed et al., 2003; Youd et al., 2001; EC8; Ishihara and Yoshimine, 1992; Elgamal et al., 2001). Figure 3 illustrates the spatial distribution of permanent ground settlements for the 475 years scenario.

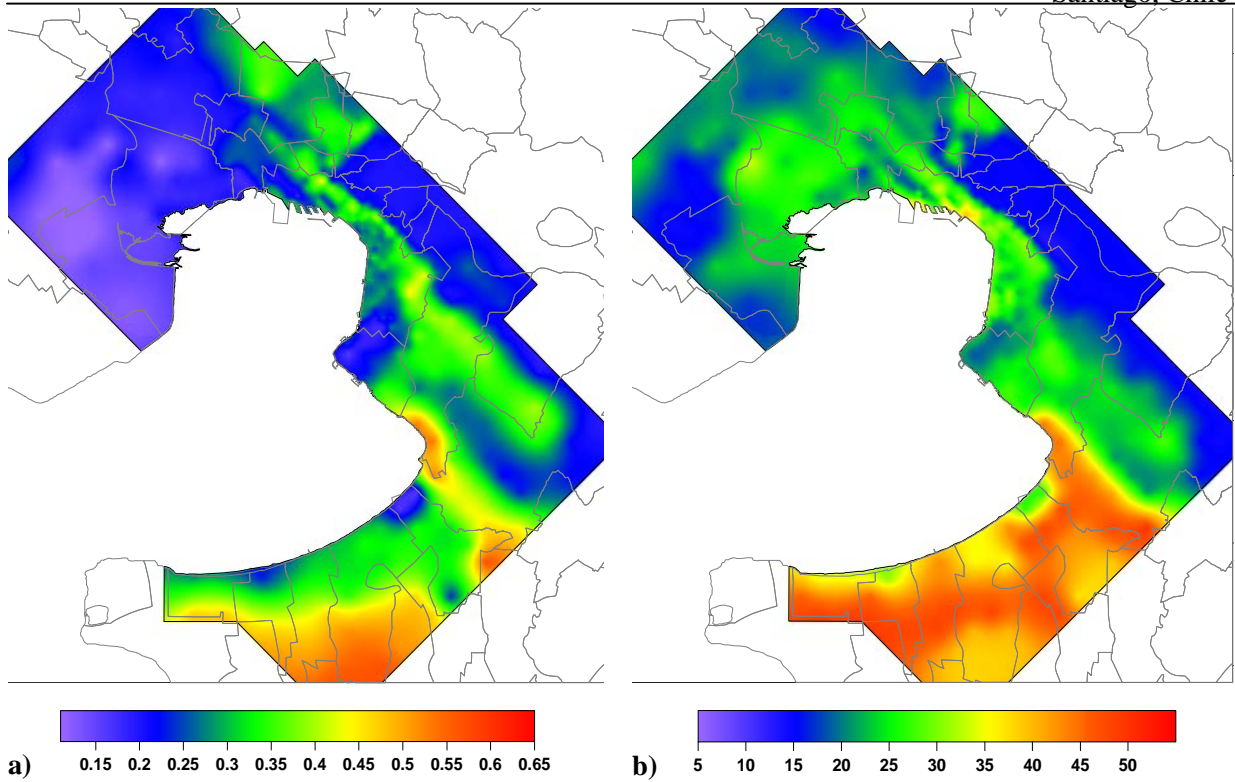


Figure 2. (a) Distribution of mean peak ground acceleration (PGA in g) and (b) mean peak ground velocity (PGV in cm/s) for the 475 years seismic scenario.

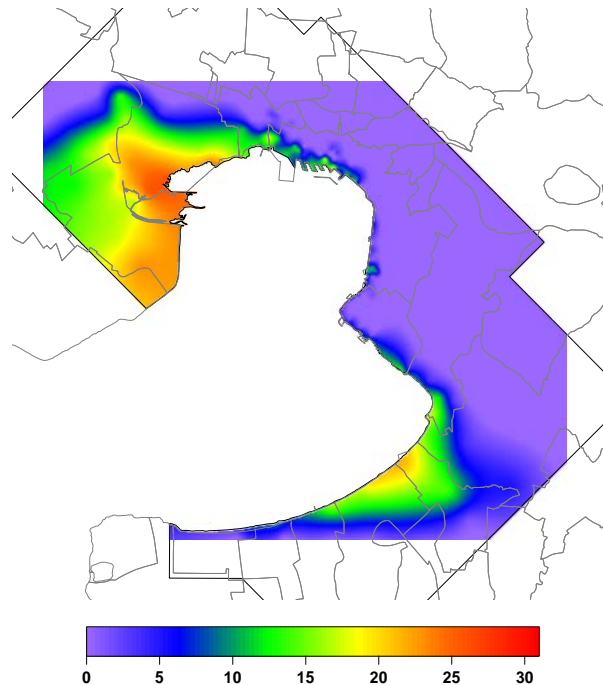


Figure 3. Distribution of the mean values of peak permanent ground settlements due to liquefaction - Δv (cm) for the 475 years seismic scenario.

Düzce microzonation study

The region of Düzce is one of the more active seismic areas worldwide, as is located very close to the North Anatolian Fault (NAF). Both Kocaeli (August 17, 1999, $M=7.8$) and Düzce (November 12, 1999, $M=7.2$) earthquakes occurred in a region dominated by the North Anatolian Fault. Site-specific ground response analysis has been performed for the city of Düzce, for different earthquake scenarios, based on one hand on the available geological, seismological and geotechnical data, and on the other hand on specific geotechnical and geophysical surveys performed for the purposes of this study (Manou et al., 2007, 2010; Pitilakis et al., 2010a). The study has been conducted in the framework of several research projects (MERP, 2002-2005; SRM-DGC, 2006-2008).

A simplified soil classification provided by EC8 was followed taking into consideration the geological zonation of the Düzce region, for the case of the Düzce 1999 earthquake event based to the deconvoluted acceleration time history of Düzce 12-11-1999 record. The estimation of the peak ground acceleration was based on the results of the seismic hazard study for the Düzce case. Then a series of 1D analysis was performed in several well-selected and representative sites along the city of Düzce, for several seismic scenarios proposed by the seismic hazard analysis (Alexoudi et al., 2008a) and for six input motions scaled to the estimated in each scenario, PGA for outcrop conditions. The dynamic properties of the soil configurations for the synthesis of the soil profiles were derived from the results of all available geotechnical data and geophysical surveys (HVSr technique and microtremor measurements), that are performed in Düzce. This correlation led to the synthesis of 2D geotechnical cross-sections; then, based on these detailed cross sections, we derived thirty representative 1D dynamic soil profiles for the 1D EQL site response analysis.

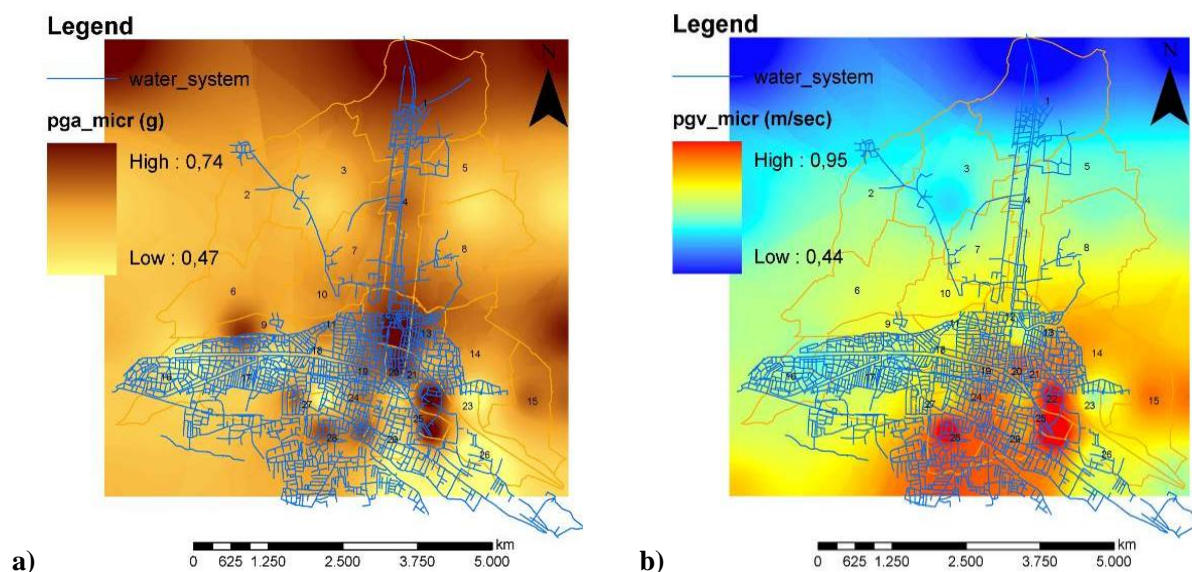


Figure 4. Spatial distribution of (a) average PGA (g) and (b) average PGV (cm/sec) values in Düzce.

The results derived from the 1D seismic response study were further analyzed in order to estimate average acceleration response spectra, peak ground acceleration and displacement values at the ground surface, peak ground velocity values at the pipelines' depth and peak spectral acceleration values for specific period values. Based on the geophysical, geotechnical and geological investigations, a correlation of the results in adjacent sites was carried out in order to accomplish the zonation of the city in uniform seismic response zones. The results are presented in terms of tables, diagrams and maps in GIS format that present the spatial distribution of the strong ground motion. Figure 4 illustrates the spatial distribution of the average Peak Ground Acceleration (PGA) and Velocity (PGV) values in Düzce.

VULNERABILITY ASSESSMENT AND LOSS SCENARIOS

A fundamental requirement for assessing the seismic performance of a system is the ability to quantify correctly the damages related to the level of seismic hazard intensity, and of course the typology of each component and system. In general, vulnerability functions are deterministic, statistical or probabilistic relationships relating the component's damage state, functionality, economic losses etc, with an appropriate measure of the intensity of the earthquake hazard. The characterization of the components is based on the specification for each component type generic fragility functions (see e.g. HAZUS, NIBS, 2004; RISK-UE, 2001-2004; LESSLOSS, 2004-2007). Besides the great inherent uncertainties, the key assumption in the vulnerability assessment of lifeline systems and infrastructures is that structures having similar structural characteristics, being in similar geotechnical conditions are expected to perform in the same way for a given seismic loading. The spatial variability of the ground motion, which is one of the major causes of lifeline damages, is due mainly on the differential site amplification characteristics inherent to the local site conditions. Basin edge and azimuth effects may be also considered through appropriate 2D or/and 3D modeling of ground motion, which may modify the final ground motion for the vulnerability assessment (Pitilakis et al., 2010b; Pitilakis et al., 2001; Paolucci and Pitilakis, 2007). Thus, the respective fragility functions should be defined on the basis of the typological characteristics of the elements at risk, taking also into consideration specific construction practices and distinctive features affecting their seismic behaviour.

Several representative examples are given below of the vulnerability assessment of lifelines and infrastructure systems in the cities of Thessaloniki and Düzce. Seismic loss scenarios have been estimated in the framework of national and European research projects (RISK-UE, 2001-2004; SRMLIFE, 2003-2007; LESSLOSS, 2004-2007; SRM-DGC, 2006-2008), based on the results of the microzonation studies performed for the two cities. To this end appropriate inventory has been performed and appropriate fragility curves have been selected.

Roadway system of Thessaloniki

The inventory for the roadway network in the metropolitan area of Thessaloniki includes about 600 km of road-lines and 80 bridges. The roadway system is rather insufficient, especially in the centre, where the densely built up area creates a complex network, with narrow streets and inadequate parking areas. Roads are classified in freeways, major and secondary arterials, primary and secondary collectives, based on their geometry and functional role in the network. The majority of bridges are in the ring road and the main exits of the city. Their classification is based on the number of spans (single or multiple), the design seismic code level (low or upgraded), the pier type (single or multiple columns) and the span continuity (continuous or simple support). The vulnerability analysis of the network includes the estimation of direct losses such as bridge and road damage due to ground shaking or ground failure, and indirect such as street blockades, due to debris of collapsed buildings.

The expected level of damages for bridges is assessed based on the fragility curves that are provided in HAZUS (NIBS, 2004), for the input earthquake hazard scenario and the estimated mean spectral acceleration at $T=1.0$ sec considering the site specific analysis of ground motion (Argyroudis, 2010). The estimated damage state for each bridge for the 475 years seismic scenario is presented in Figure 5 (Pitilakis et al., 2010c). The majority of bridges will respond in a satisfactory way, but there are still few bridges, which are expected to sustain serious damage for the specific seismic hazard scenario. This is due to the higher vulnerability of these bridges (single column, simple support bridges and inadequate seismic design), and the higher values of the expected surface spectral acceleration. The latter is attributed to the local soil conditions and the proximity of the seismic source (ex. southeast part). For instance, in the west

part of the city, deep soft alluvium deposits of sandy-silty clays to clayey sands-silts, with low strength and high compressibility, (category C and D in EC8), present stronger amplification at longer periods.

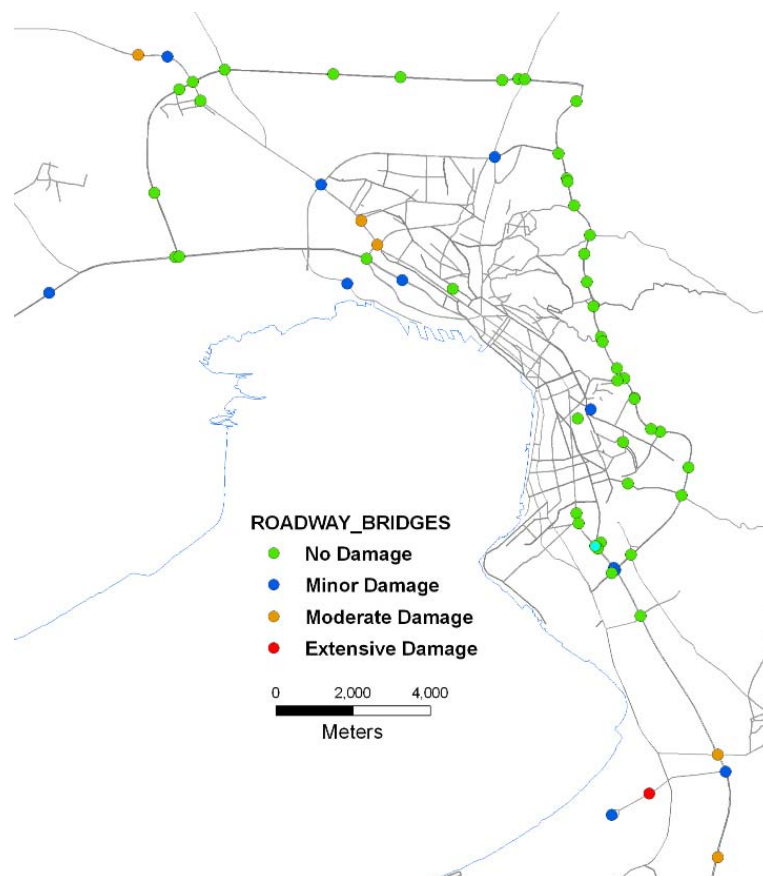


Figure 5. Distribution of expected damages to roadway bridges of Thessaloniki for the 475 years seismic scenario.

For the functionality of roads just after the earthquake a correlation between the building's height (i.e. number of storey) and the width of the induced debris is used, in order to estimate the impact of collapsed buildings (Anastassiadis and Argyroudis, 2007; Argyroudis, 2010). The spatial distribution of the collapsed or heavily damaged buildings is again depending on their typology and the site conditions. A Gaussian distribution describes the variation of the debris width, which is a function of the building collapse angle (φ) and the building volume reduction (k_v). This model is used in order to estimate the exceedance probability of certain road function levels (100% open, 50% open, 0% closed or one lane open). The collapse probability of buildings is estimated based on appropriate fragility models which have been developed for the building types commonly presented in Thessaloniki, as a function of the peak ground acceleration (Kappos et al., 2006; Penelis et al., 2002).

Past experience in Greece reveals that a percentage of collapses ranging between 10 and 20% can have such form and amount of debris, which can result to road closure. The probability of closure due to building collapse is calculated based on the combination of the aforementioned probabilities for each road segment (node to node). Figure 6 illustrates the probability of closure for the main roads in the central city due to building collapses for the scenario with a mean return period 1000 years. The reduction of the road width depends on the distance from the buildings, the width of the road and the induced debris width,

while the closure probabilities depends on the concentration of the most vulnerable building type, the length of the road segment and the discrete collapse probabilities related to the local site conditions.

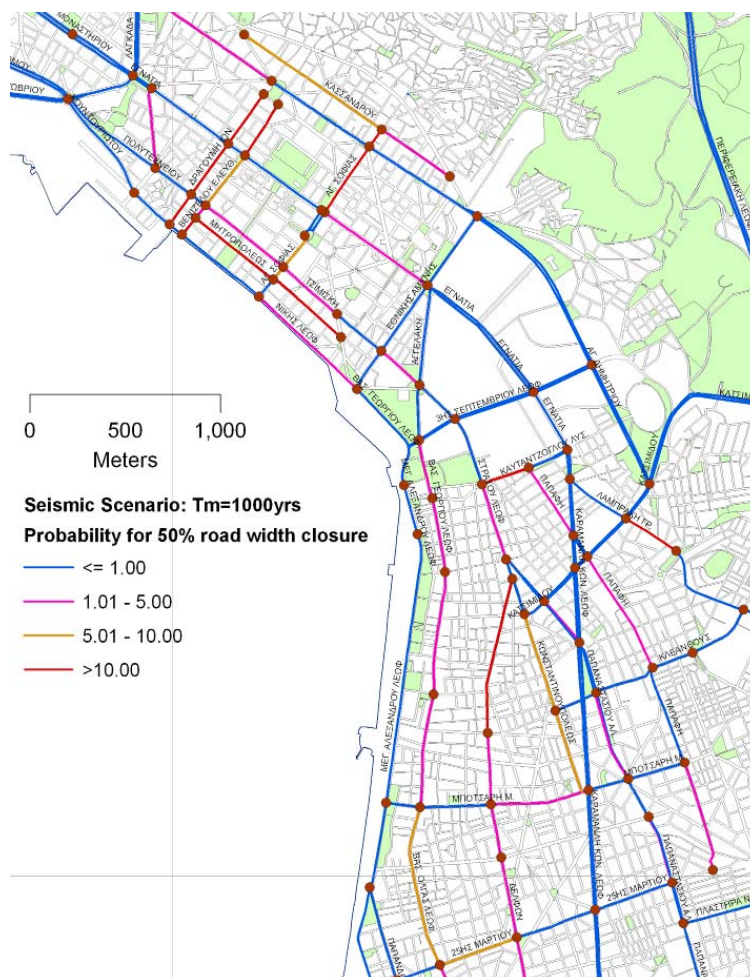


Figure 6. Sample map with probabilities for 50% road width closure of the main road network due to building collapses for the 1000 years seismic scenario.

Port system of Thessaloniki

The Port of Thessaloniki covers an area of 1,500,000 m² and trades approximately 15,000,000 tons of cargo annually, having a capacity of 200,000 containers and 6 piers with 6,500m length. In collaboration with the port authority (Thessaloniki Port Authority, THPA), various data was collected and implemented in GIS format for the construction, typological and functional characteristics of the considered elements at risk, including cargo and handling equipment, waterfront structures, electric power, potable and waste water, telecommunication, railway and roadway systems as well as buildings and critical facilities.

Loss estimations are performed for the port facilities, utility networks, transportation systems and buildings based on the results of the site specific (microzonation) study presented earlier and for the three seismic scenarios ($T_m = 100, 475$ and 1000 years). The soil conditions are quite poor dominated by soft – loose alluvial deposits at great depth. In each particular system, adequate fragility curves and/or vulnerability relationships were used, based on the specific features and typology of the considered elements at risk. The type, extent and spatial distribution of induced earthquake damage were specified and illustrated in GIS thematic maps (Kakderi and Ptilakis, 2011). In the following, an example of the

vulnerability assessment and estimated direct damages is provided for the building structures of Thessaloniki's port.

Buildings in a port system include administration and control buildings, traffic control buildings, passenger terminals, offices, security and maintenance buildings, sheds and warehouses and other critical facilities. Furthermore, buildings within lifelines systems and infrastructures are also considered (e.g. pumping stations, engine-houses, electric power substations, etc). Thessaloniki's port includes 88 elements of this type. Their typology was defined based on the construction material, structural type, height and seismic design code level.

The vulnerability analysis of R/C buildings is performed based on fragility curves (in terms of PGA) that have been developed using a hybrid technique combining analytical results and statistical data (Kappos et al., 2006). Moreover, fragility curves (in terms of both PGA and S_d) for masonry structures that were developed for all typologies common in Greece were used in the present application (Penelis et al., 2002). Vulnerability assessment for the three seismic scenarios has been performed, using a reduction factor of 0.7 for the conversion of peak to effective values of ground acceleration. The distribution of estimated damages for the port building for the 475 years scenario is illustrated in Figure 7. 27%, 64% and 9% are estimated to sustain minor, slight and complete damages respectively.

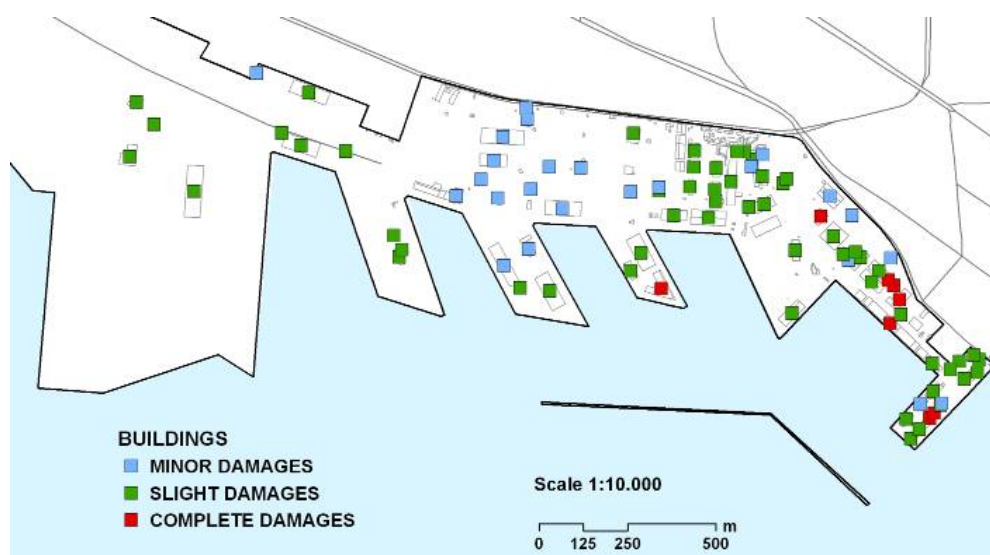


Figure 7. Distribution of damages to building structures of Thessaloniki's port ($T_m=475$ years).

Water system of Düzce

The water system in Düzce is about 500 km long and the great percentage dates back to 1940s (Taday and Sahin, 2001). The network consists mainly of cast iron (CI) and asbestos cement (AC) pipes, which could be classified as brittle pipes. A 600mm diameter AC pipe conveys raw water from the main source, the River Ugur, to the water treatment plant at the south of the town. A 100 cm diameter steel pipe then carries the treated water to the distribution network, joining the town in the Azmimilli District. Twin CI pipes, of diameter 125 mm, transport water from a well field and reservoir to supplement the main river water supply; these pipes join the town in the north east district. The digitized pipeline network, with a total length of 298km, is a mixed system, comprising both old and recently constructed parts.

The vulnerability assessment of the water supply network of Düzce (in terms of the expected Repair Rate per pipe km - RR/km) is performed combining the results from the microzonation study of Düzce, with a

mean return period of 475 years, and from two specific earthquakes using as input the deconvoluted time histories of Kocaeli and Düzce earthquakes recorded at the Meteorological Station in Düzce. Expected damages (leaks and/or breaks) caused by wave propagation are estimated using O' Rourke and Ayala (1993) fragility relation proposed by HAZUS (NIBS, 2004) according to the type of ground failure (for wave propagation: 20% of failures is assumed as breaks and 80% as leaks); the seismic loading is described in terms of peak ground velocity (PGV). Prior to their application, these empirical vulnerability functions have been validated with recorded damages in Düzce 1999 earthquake and in Lefkas- Greece 2003 earthquake (Alexoudi, 2005; Pitilakis et al., 2005b). Tromans' (2004) and Alexoudi (2005) database for water pipelines in Düzce was used for the validation. The percentage of the pipelines of the network that are expected to have some type of damage for the Kocaeli and Düzce earthquakes, and for the average values given by the microzonation study, is 7%, 9% and 13% respectively (Alexoudi et al., 2010).

Figure 8 illustrates the spatial distribution of the estimated water pipe damages per district in Düzce for the microzonation study. The majority of damages are expected at the southern and eastern part of the city, which is well compared with the recorded damage distribution during the sequence of Kocaeli and Düzce earthquakes (Manou et al., 2007).

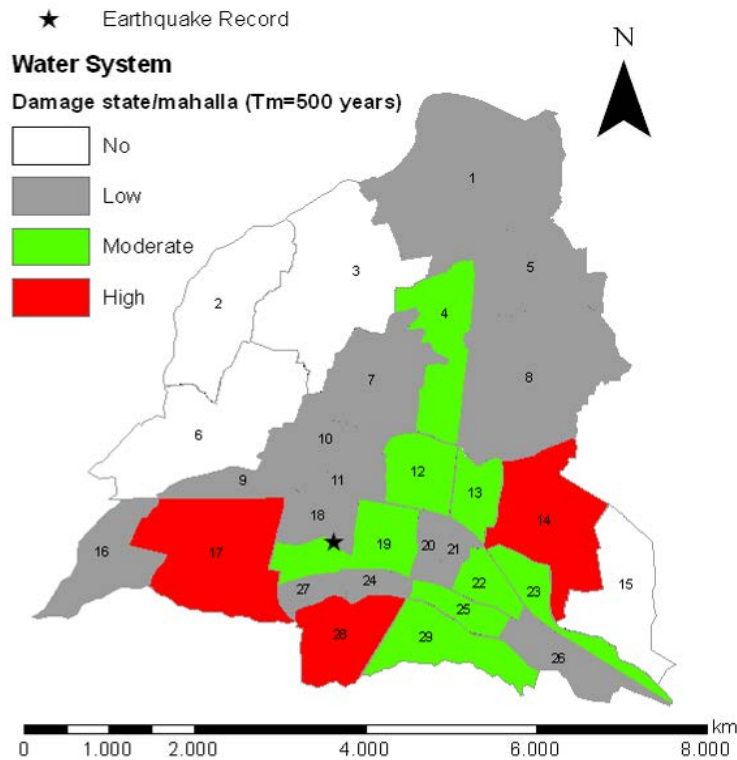


Figure 8. Estimated water pipe damages per district (mahalla) in Düzce for the microzonation study.

SYSTEMIC SEISMIC PHYSICAL AND SOCIO-ECONOMIC VULNERABILITY AND RISK ANALYSIS

The impact of the disaster caused by a natural hazard (like an earthquake event) on a system evolves with time elapsed from the event and in space. In the aftermath of the event, the damaged infrastructure operates in a state of emergency, and only progressively returns to the previous or a different state of normal functionality. Correspondingly, the spatial extent of interest to the study of the infrastructure response increases, involving adjacent regions in the economic recovery phase and multiple interactions between systems and with the built environment. A representative case of interactions among different lifeline systems during the restoration period is reported after the 1995 Kobe earthquake by Hada and Meguro (2000). They outlined the problems in the restoration activities of water and gas network in Kobe area due to traffic congestion, street blockades, damaged buildings and water flowed into gas pipelines; they also analyzed their effects based on real data. In the framework of a comprehensive risk analysis and management of interacting lifeline and infrastructure systems, their seismic performance should be considered in a rigorous and unified way. This could only be achieved through the assessment of the systems functionality, considering the complexity of structures and the interdependencies among systems and their components.

The relation/ interactions between the components can be distinguished into intra-relations between the components of each system, and inter-relations between the systems making up the infrastructure (Figure 9). The formulation of a system function allows for the evaluation of the state of the system as a function of the states of its components. The availability of such a function is a prerequisite for the evaluation of the system performance. It is noted here that the spatial characterization of the components (sub-systems) of an infrastructure has a direct relation with the approaches to be used for the definition of both their hazard and vulnerability.

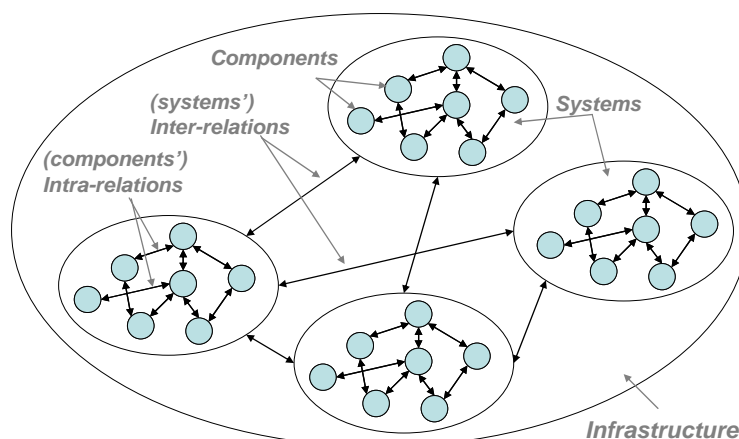


Figure 9. Graphical representation of an infrastructure comprising a number of systems with their interactions.

Several approaches are available in the literature to help describe the relations existing between a system's components. Some of these are: Graph theory; Fault-tree analysis (FTA); Event-tree analysis (ETA); Series system in parallel (SSP); Agent-based models and Complex Adaptive Systems (Amin, 2001; Little, 2002; Brown et al. 2004; Bernhardt and McNeil, 2004; Tolone et al., 2004).

The probabilistic evaluation of the performance of the system (PNET) can be carried out employing the methods of System Reliability Analysis. These include expansion methods, such as FORM/SORM or the response surface technique (Ditlevsen and Madsen, 1996), as well as the Monte Carlo simulation methods

(Rubinstein, 1981). Depending on the nature of uncertainty and the aptitude to determine them, the probabilistic approach may be replaced or enhanced by possibilistic approaches based on Fuzzy Logics, so-called Fuzzy Networks.

Despite the fact that non-simulation methods have recently seen interesting advances, e.g. in the form of Matrix System Reliability Analysis (Song and Der Kiureghian, 2003; Der Kiureghian and Song, 2008), the complexity of civil infrastructural systems, (especially the analysis of capacitive networks such as transportation, power transmission and water-supply networks), and the increasingly quantitative approach to the evaluation/ prediction of the behavior of other complex systems, of economic or social nature, the simulation approaches have recently undergone most significant progresses. These new developments, collectively denoted as “Modern simulation methods”, consist of smart techniques dealing with sensitivity analysis and stochastic optimization of computer simulation models (Rubinstein and Melamed, 1998) or Neural networks (NN).

Several researchers have tried to go beyond the simple summation of direct loss and include consideration of the interactions between system components in determining the deterioration of the system function due to an earthquake. As an example, one can mention the studies undertaken by Franchin et al. (2006), Nuti and Vanzi (1998), Basoz and Kiremidjian (1996), Werner et al. (1999), Shinozuka et al. (2003), Douglas et al. (2007), Karaca (2005), and Veneziano et al. (2002) for transportation networks, by Pachakis and Kiremidjian (2003, 2004) for harbor facilities and by Shinozuka et al. (1999), Liu et al. (2004), Ostrom (2003), Giannini et al. (1999), Vanzi (1996, 2000), Nuti et al. (2007) for electric supply networks. The studies for the seismic risk analysis of roadway networks in terms of road closures due to collapsed buildings and/or adjacent are limited (Goretti, 2005; Anastassiadis and Argyroudis, 2007; Argyroudis, 2010).

Furthermore, the probabilistic assessment of the seismic performance of any system must yield as outcome a quantity that is meaningful to the decision-makers and the stake-holders (JCSS, 2008). The definition of the most appropriate quantity for each system, denoted as “performance measure”, is itself a challenging task. For example, measures have been proposed to quantify the reduced performance of a damaged/ congested transportation network in the form of a “Driver’s Delay” (Shinozuka et al., 2003) or, to quantify the performance of a health-care facility, in the form of the “Hospital Treatment Capacity” (HTC) i.e. the number of patients that can be given surgical treatment per hour (Lupoi et al., 2008). For electric power transmission or water supply networks performance measures have been proposed in the form of the “Service Flow Reduction”, i.e. the amount of flow that can be delivered to users compared to the amount prior to the damage/ disturbance (Dueñas-Osorio et al., 2007).

Moving to a higher level, interactions between different critical infrastructures which may seriously affect the seismic risk management (response, recovery and mitigation) is an emerging research area where special interest has been recently given into. Several researchers have proposed different types of interdependency simulation models (Wong and Isenberg, 1995; Kameda, 2000; Giannini and Vanzi, 2000; Rinaldi et al., 2001; Peerenboom et al., 2001; Amin, 2001; Haines and Jiang, 2001; Little, 2002; Li and He, 2002; Tang et al., 2004; Yao et al., 2004; Brown et al., 2004; Bernhardt and McNeil, 2004; Santos and Haines, 2004). Only few methodologies have incorporated interdependencies in the seismic risk analysis of lifelines (Hoshiya and Ohno, 1985; Nojima and Kameda, 1991; Scawthorn, 1992; Eidinger, 1993; Shinozuka et al., 1993; Shinozuka and Tanaka, 1996; Menoni, 2001; Dueñas-Osorio, 2007; Tang and Wen, 2009) in a quite simplified way and lacking an integrated view of the response of complex infrastructure networks during the different periods in respect to the occurrence of an earthquake event.

Furthermore, very few studies can be found in the literature dealing with the highest level problem of multiple systems interaction in the case of seismic vulnerability and loss estimates (Dueñas-Osorio et al.

2007, Kim et al. 2007). They have still an exploratory character and are based on rather extreme simplifications, being limited to the analysis of at most two systems. Infrastructures' interdependencies are usually addressed through network analysis. Graph theory is adopted by several researchers. The Bayesian approach is often used for network analysis. The function states of the systems are also analyzed using flow analysis and connectivity analysis. One of the most comprehensive studies available, albeit including only a part of the vulnerable systems, is the one in Karaca (2005), which explores the consequences of a major earthquake in the Central-Eastern US by modelling the economic activity in the whole US and its disruption due to the event. Finally some recent studies have been focused on the proposal of a methodology to evaluate the associated losses of interacting lifeline elements for various strong motion intensities and the estimation of complex fragility curves of interdependent components (Kakderi et al., 2007, 2008; Alexoudi et al., 2008b,c).

In the most recent study developed in Aristotle University of Thessaloniki (AUTH) by Selva et al. (2010) a generic procedure is developed for the assessment of the serviceability of a system, if one or more interacting components of the system are damaged by an earthquake, assessing and merging the different levels of both "physical damage" and "non-functionality". Either a single system composed by many interacting components (e.g., one lifeline) or a system of systems (e.g., a set of lifelines and infrastructures) are addressed, where interaction among components and systems are accounted for. The various types of uncertainties (aleatory and epistemic) are treated with the use a Bayesian inference. The proposed methodology is quite general and it is applicable, eventually with several further improvements, assumptions and/or simplifications, to real systems with diverse degrees of complexity and knowledge of system and components details.

What is also of major importance is to transfer the interdependencies and consequences of losses in physical systems (buildings, utility and transportation network components, critical facilities) to their direct and indirect consequences on society and economy (city and regional scale), as measurable indicators and values of socio-economic losses upon which policy and decision-making can take place. The quantification of the socio-economic consequences of a major earthquake is currently carried out at different levels of complexity. The vast majority of available studies are limited only to a first estimation of direct economic losses. The simple summation of the monetary losses separately incurred by the various systems does not represent, however, the actual total loss suffered by a society hit by an earthquake. Loss can be subdivided into direct and indirect. The former correspond to direct damage to the physical components of the system, while the latter stem from loss of function resulting from the physical damage, associated for example with economic losses due to business interruption, loss of productivity due to increased travel times on damaged transportation networks, the interruption of harbour activities, etc. Even if indirect loss can likely be the dominant contributor to total loss, it is usually estimated in approximate ways, since an accurate estimation of the economic consequences of the loss of function of one system requires the evaluation of its impact on the other systems of the infrastructure.

Regarding merely social costs losses (i.e. fatalities, injuries, homeless, shelter needs, etc.), one of the most referenced social loss methodologies is the one proposed by Coburn and Spence (2002), which however has not been proved reliable for developed countries. Other available in the literature global social and economic consequence functions include the methods proposed by Spence (2007), ATC-13, Badal and Samardzhieva (2003), KOERILoss (Erdik et al., 2003) Bal et al. (2008 a, b), MAEViz (MAEC, 2009), Porter et al. (2008 a, b). The current state of the art in earthquake loss estimation software provides several parameters of direct socio-economic consequences which are needed to support effective decision making. These include parameters such as casualties, homeless, and business failures by industry, for example. However, poor linkages between damage estimates at a system's and system of systems level and the social and economic vulnerability conditions contribute to significant limits within existing earthquake loss estimation. Including social vulnerability allows for a greater level of information to be obtained from

the vulnerability modeling results for use in disaster response (e.g. homeless shelter needs and required supply). The definition and characterization of human, institutional and functional vulnerability (and resilience) of a city or region to earthquake damage of complex infrastructures should be accounted for in terms of recovering from the impacts of an earthquake.

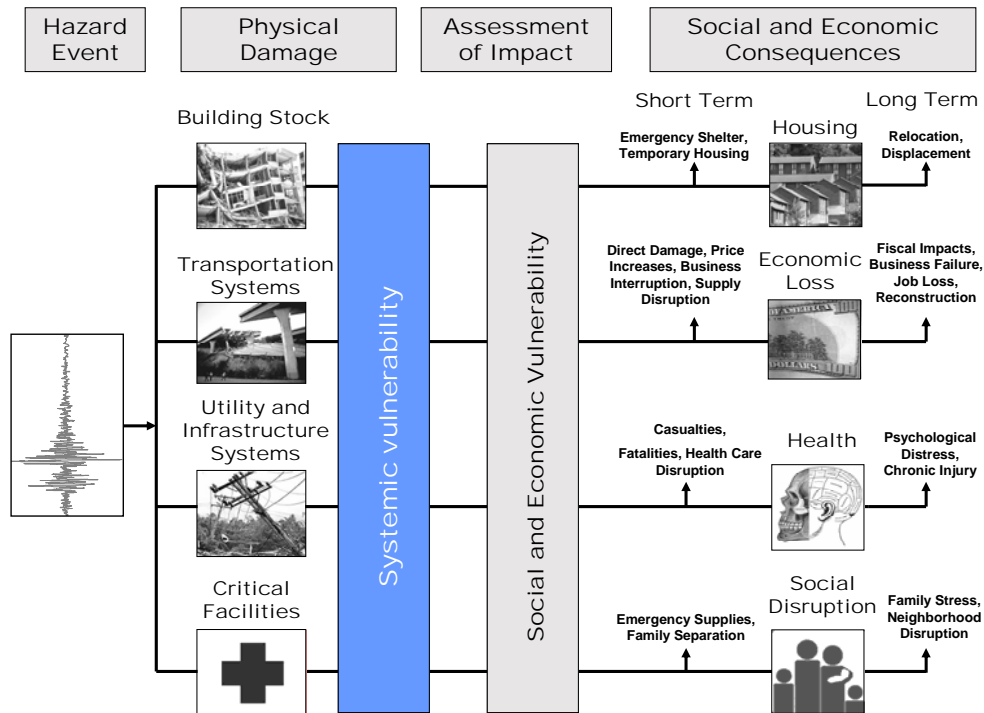


Figure 10. General graphical layout of the concept and goals of SYNER-G (2009-2011) (www.syner-g.eu)

Currently, there is an ongoing research effort to increase the understanding of the vulnerability of various societal elements at risk belonging to a system (city, region, lifeline network, etc) and to develop appropriate methods and tools to consider inter-element and intra-systems interdependencies, including socio-economic features under the European project SYNER-G (2009-2011) coordinated by the first of the authors of this paper (www.syner-g.eu). Figure 10 illustrates graphically the main concepts and goals of SYNER-G. Apart from the selection of the most advanced fragility functions and methods to assess the physical and societal-economic vulnerability of assets (buildings, utility systems and transportation infrastructures, society, economy), improving and further developing new ones where necessary, considering European distinctive features and the proposal of the most appropriate means of selecting seismic scenarios at system level, the ongoing research efforts are focused on the development of a unified methodology to assess vulnerability at a system level considering interdependencies between elements at risk (physical and non-physical), belonging to different systems and between different systems as a whole at city and regional scale. An appropriate open-source software and tool will be built to deal with systemic vulnerability in order to improve the seismic risk assessment and management, while the effectiveness of the methodology and the tools will be validated to specific and well selected case studies at city and regional scale.

MANAGEMENT AND MITIGATION OF SEISMIC RISK

Global value analysis

A conventional seismic risk analysis is limited to the evaluation of the direct impact (usually in economic terms and fatalities), of isolated components, based on the seismic hazard and the physical vulnerability of the elements. An advanced seismic risk study of lifelines, utilities and infrastructures should include the functional and social vulnerability, taking into account the functional relations between the different elements, urban activities (production, consumption, exchanges) and relations of the network with its surrounding urban or rural environment. In that way each system will be analyzed as an integrated part of the seismic risk scenario and as a part of the urban system, while the main issues of the lifeline system will be identified. This is performed through a “global value” analysis of the elements at risk; a methodology originally developed within the RISK-UE (2001-2004) project.

The aim of the global value analysis is to identify the main issues and relative importance of each lifeline network, through appropriate ranking of the value of the exposed elements, based on various factors that describe the role of each element in the urban system. In that way, the global value of each element at risk, depends not only on its direct specific value or content (physical and human), but also upon its indirect/immaterial value, that is represented by the usefulness and relative role in the whole urban system, at a specific time. Three periods are identified in respect to the occurrence of an earthquake event: normal, crisis and recovery. “Global value” evaluation in different periods could be a powerful tool for the prioritization of pre-earthquake actions and quantification of the overall importance of different complex and coupled lifeline systems (Pitilakis et al., 2006a). Several criteria for this are used, such as operational attributes, land use, population influenced, human losses, economic and social weight under normal, crisis and recovery circumstances, identity/ radiance, environmental impact and other. Appropriate qualitative or quantitative indicators can then be defined for each period, while relevant measuring units are used for their evaluation and the identification of “main”, “important” and “secondary” elements and system’s weak points.

Table 1. Indicators used for the global value analysis and classification of importance of waterfront structures of Thessaloniki’s port.

WATERFRONT STRUCTURES			PERIOD		
Components	Indicators	Description	Normal	Crisis	Recovery
Operation	1. Operational depth	Maximum draught of the ships able to harbor.	•	•	•
Operation	2. Alternative use (redundancy)	Alternative equipment to cover the activity.	-	•	•
Urban activities and interactions	3. Impact radius	Impact radius. Type of cargo/ movements served.	•	•	•

The methodology has been applied for the global value analysis of lifelines and infrastructures systems in Thessaloniki (Greece), in the framework of the national project SRM-LIFE (2003-2007) (Pitilakis et al., 2007b; Pitilakis et al., 2010c). An example of the indicators used for the classification of the importance of Thessaloniki’s port cargo handling equipment is provided in Table 1. Cargo handling operation during and after the crisis is crucial for the successful recovery reaction and resilience following a major earthquake event. Other elements at risk have different indicators depending on their relative importance in the crisis management process. Representative GIS maps illustrating the definition of main, important and secondary elements at risk can also be constructed. As a representative example, Figure 11 illustrates the classification of the importance of waterfront structures of Thessaloniki’s port during the crisis period.

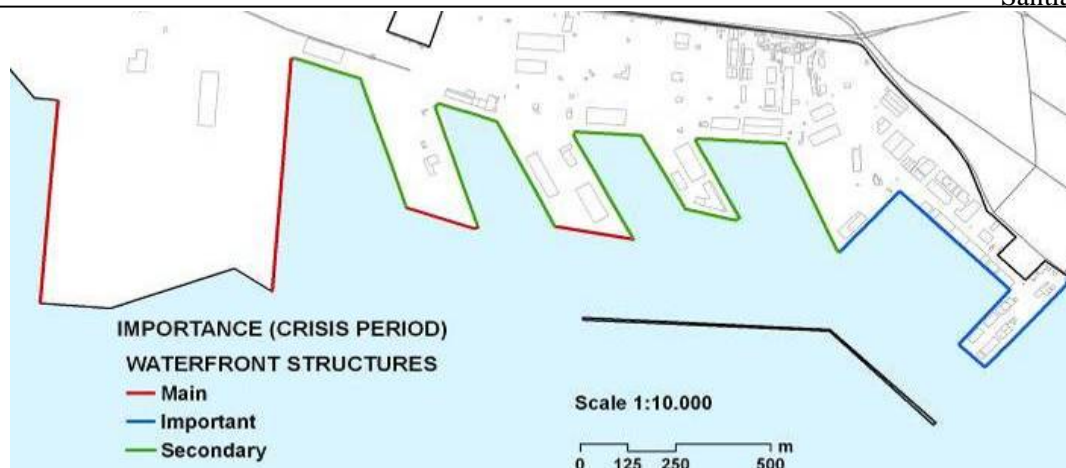


Figure 11. Classification of the importance of waterfront structures of Thessaloniki's port during the crisis period.

Restoration policies and mitigation strategies

The pre-earthquake mitigation plans must be based on appropriate prioritization criteria that combine engineering techniques, economic analysis tools and decision-making or political aspects. The identification of “main”, “important” and “secondary” element at risk in “normal” period provides a prioritization according to the importance of the activities, the social and economical values and the daily demand for serviceability.

A disaster management plan can enhance the pre-earthquake activities for retrofitting (or strengthening), important and critical components in the urban environment and prepare an efficient organization of public services and local authorities for “crisis” period. For the “recovery” period an efficient management plan must minimize the restoration time, the efforts and the cost. In order to achieve reliable estimates of the required time for recovery, lifeline owing and operating companies, local actors in collaboration should define restoration curves for every component in each lifeline system, with lifelines experts using basically qualitative evaluations.

A method was developed applying the “global value” approach which uses the classification of lifeline system components into main, important and secondary, according to their global value (SRM-LIFE, 2007-2007). Combining “global value” evaluation and vulnerability assessment, it is possible, using, if necessary, an “expert opinion” as well, to estimate priorities and to account for the economic and social losses, for a specific utility system and a given seismic scenario. Recovery activities could also follow these priorities aiming at efficient seismic risk management procedures.

This method was applied to the city of Thessaloniki (Pitilakis et al., 2007b; Pitilakis et al., 2010c). Table 2 provides an example of the pipelines retrofitting priorities. Restoration curves have also been defined in collaboration with the local authorities, based on available man power, and capabilities, local experience and expertise. Figure 12 illustrates the functionality level of water pipelines 7 days after the seismic event for the 475 years scenario, assuming that the restoration process starts immediately after the earthquake.

Table 2. Risk analysis matrix showing pipelines seismic retrofit priorities.

URBAN RISK/ SEISMIC HAZARD	PRIORITIES		
	Main	Important	Secondary
Break	1 st priority	1 st priority	2 nd priority

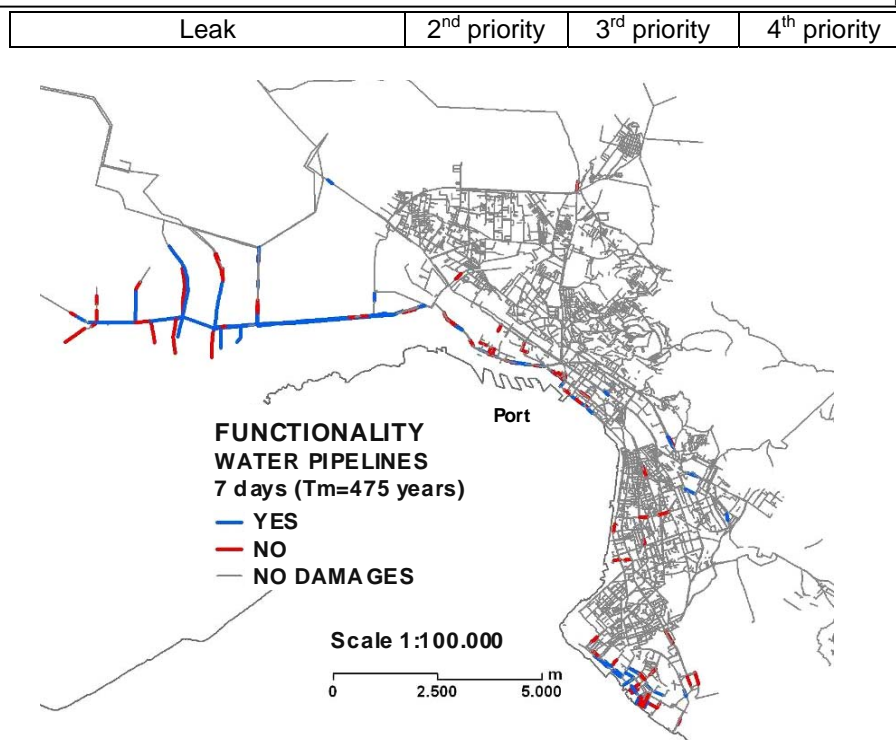


Figure 12. Functionality of pipelines of Thessaloniki's water system 7 days after the seismic event ($T_m=475$ years).

Retrofitting actions – Decision analysis

Seismic rehabilitation of structures is certainly the best way to reduce seismic losses. Multiple conflicting criteria and various uncertainties inherent in the seismic hazard and the systems' response, are systematically incorporated in any decision of intervention schemes to be applied for the reduction of earthquake risk (Park, 2004). Several factors like structural performance and/or direct structural cost, life losses and secondary economic losses, should be taken into consideration.

On the basis of a decision analysis for identification of the optimal target reliability level for rehabilitation of a given structure against seismic hazard as well as the best solution among several alternative rehabilitation schemes, different mitigation actions could be identified and implemented. The final decision on mitigation action(s) and level of intervention should be based on estimated results in relation to the reduction of potential losses, direct and indirect costs estimates for different mitigation actions and expected economic losses. Cost-benefit models have been proposed for the evaluation of the profitability of public or private investment in seismic retrofitting. Cost-benefit analysis (CBA) is a systematic procedure for evaluating decisions that have an impact on society. There are different ways to conduct a CBA, depending on the information one has and the nature of the problem at hand. In the case of seismic mitigation strategies, a comparison between the upfront investment costs of mitigation to the benefits of mitigation (e.g., reduction in loss, reduction in casualties, and reduction in lifeline system downtime) is completed. Studies performed mainly for buildings are for example the ones given in FEMA(1992), Chang and Shinozouka (1996) and Kanda and Shah (1997). These models permit comparison among alternatives by assigning monetary values to costs and benefits happening in the future and discounting them at the present time accounting for inflation and interest rate. In the case of Thessaloniki, the effects of three mitigation schemes that could be proposed for the reduction of potential losses of the building stock are investigated (Pitilakis et al., 2007a). Some of the most advanced models also account for the system behaviour of the networks (e.g. Augusti and Ciampoli, 1997; 1998; Kunreuther et al., 2001;

Chang, 2003; Seligson et al., 2003). However, whether particular mitigation measures will be viewed as worth adopting is not a foregone conclusion but requires a detailed assessment of the costs and benefits under various hazard scenarios. The final decision is conditional to the available budget and the desirable level of the intervention and of course the anticipated level of physical damage for the specific seismic scenario. Finally, it is pointed out that a rigorous and effective risk management plan should be based on the comparative consideration of estimated losses through the assessment of the relative effects of different mitigation actions.

Real-time mitigation of seismic risk

Finally, an important progress is expected to the risk management of lifelines by applying real-time damage estimation data under GIS platforms. More accurate, and thus much more reliable data could be the basis for emergency services, predictions of damages intensity and spatial distribution for future events, loss estimations for each material and immaterial element at risk and mitigation strategies. Earthquake Early Warning (EEW) systems are mainly involved in the co-seismic phase. These involve the generation of real time ground motion estimation maps as products of real-time seismology and/or generation of alarm signals directly from on-line instrumental data. The Rapid Response Systems take part immediately after the earthquake and provide assessment of the distribution of ground shaking intensity (Shake Maps) or physical damage and casualties (Loss Maps). These maps can serve to direct the search and rescue teams to the areas most needed and assist civil protection authorities in the emergency action.

Few efforts made so far (i.e. Eguchi et al., 1997; Shimizu and Yamazaki, 1998; Nakayama et al., 2004), proved that these systems are probably the most powerful and efficient way to mitigate seismic risk reducing the uncertainties involved in all other methodologies. A summary of the work done over last decades regarding the development of new approaches and setting up of new applications for earthquake rapid response systems that function to estimate earthquake losses in quasi real time after an earthquake is provided by Erdik et al. (2010). Currently operating near real time loss estimation tools can be classified under two main categories depending on the size of area they cover: Global and Local Systems. Global or regional near real time loss estimation systems include the Global Disaster Alert and Coordination System (GDACS, <http://www.gdacs.org>), World Agency of Planetary Monitoring Earthquake Risk Reduction (WAPMERR, <http://www.wapmerr.org>), Prompt Assessment of Global Earthquakes for Response (PAGER, <http://earthquake.usgs.gov/eqcenter/pager/>) system of USGS and NERIES-ELER (<http://www.neries-eu.org>) methodologies. Several local systems (country-, city- or, facility-specific) capable of computing damage and casualties in near real time already exist in several regions of the world. For example the Taiwan Earthquake Rapid Reporting System, the Real-time Earthquake Assessment Disaster System in Yokohama (READY), The Real Time Earthquake Disaster Mitigation System of the Tokyo Gas Co. (SUPREME) and the Istanbul Earthquake Rapid Response System (IERRS) provide near-real time damage estimation after major earthquakes (Erdik and Fahjan, 2006). Almost all of these systems are based on the assessment of demand in real time from dense strong motion instrument arrays and the estimation of damage on the basis of known inventory of elements exposed to hazard and the related vulnerability relationships. After an earthquake the shaking and damage distribution maps are automatically generated on the basis of the ground motion intensity measure data received from the field stations, building inventory and the vulnerability relationships. The latter is probably one of the weak points, as they are not actually time dependent, while both structures' quality and strength, and hazard are time dependent. Thus, the development of reliable inventory data and system time dependent vulnerability and loss assessment methodologies is a pre-requisite.

CONCLUSIONS

A rigorous disaster management process includes mitigation, preparedness, response and recovery actions in three periods: normal, crisis and recovery. A breakdown between the different processes and periods can help to evaluate the contribution of each phase to the overall safety management. A reliability earthquake risk reduction policy needs a multidisciplinary approach to estimate the likely emergency response resource needs and socioeconomic impacts of large earthquakes in urban areas. The expected economical (direct, indirect) and social consequences of an earthquake should be compromised with the level of tolerable risk.

Seismic vulnerability assessment is used to quantify potential losses in a given region or to a particular portfolio of lifelines, utilities and infrastructures, due to future earthquakes. The existence of preparedness plans based on the assessment of the impact of earthquakes and the minimization of their consequences are the most important tasks of civil protection. To fulfill these tasks, comprehensive earthquake loss scenarios have to be developed, in order to reduce the expected losses and improve the recovery actions.

Seismic risk scenarios take into consideration the inventory, the typology and vulnerability characteristics of different elements at risk, as well as the seismic hazard, geotechnical characterization and site response of the main soil formations for different seismic scenarios. Thus, vulnerability and loss estimates for lifelines and infrastructures are evaluated on the basis of site specific seismic hazard analysis using available inventory data and adequate fragility curves. Local site conditions and specific seismic ground response, conventionally referred as “zoning study”, plays the key role in the vulnerability analysis and loss assessment.

Analyzing physical infrastructure systems in terms of the dimensions of systems interdependencies, namely infrastructure system characteristics, inter-system and intra-system causal relationships, environmental impact such as climate change, response behavior, failure types, state of operation and interdependency risks, yields new insights into infrastructure systems behavior and a consequent expanded thinking on risk informed decision making of critical infrastructure. Interdependent analysis can enhance loss estimation methodologies and indicate strategies for robust design and growth of infrastructures.

The identification of “main”, “important” and “secondary” element at risk in “normal” period provides a prioritization according to the importance of the activities, the social and economical values and the daily demand for serviceability. A disaster management plan can enhance the pre-earthquake activities for retrofitting important and critical components in the urban environment and prepare an efficient organization of public services and local authorities for “crisis” period. For the “recovery” period an efficient management plan must minimize the restoration time, the efforts and the cost.

Earthquake hazard has in general low probability but high social and economic impact. The aim of a risk management strategy, especially for lifelines, is to maintain community safety and also to reduce physical damage and social and economic disruption. All decisions are based on the selection of the acceptable risk for the estimated seismic scenario. The selection of the acceptable risk and the appropriate seismic scenario or scenarios should combine the level of detail of the seismic hazard (microzonation study), the will of central and local actors, the available funds, the financial capability of the community and the country without neglecting the epistemic and physical uncertainties involved in every path of the any earthquake risk reduction policy.

The actual vulnerability and the associated risk of any element at risk may be reduced with appropriate mitigation countermeasures. The decision for mitigation of lifelines against seismic hazard is a quite complex issue as different parts such as government, local authorities, lifeline companies or insurance industry are involved. Moreover the decision by its self is very difficult because it should be made based

on the results of the seismic risk assessment of lifelines which includes various uncertainties, owing to seismic hazard, vulnerability, performance and loss estimation procedures. The loss results can be used in order to prioritize the pre-earthquake mitigation measures, such as the retrofitting or redundancy of the elements with greater risk. Moreover, the loss results are considered to be the guide for an effective restoration policy.

Finally, potential impact of large earthquakes on urban societies can be reduced by timely and correct action after a disastrous earthquake. Modern technology permits measurements of strong ground shaking in near real-time for urban areas exposed to earthquake risk and should be further developed.

REFERENCES

- Alexoudi M.N., Kakderi, K. and Pitilakis, K.D. (2008c). Seismic Risk of Interdependent Lifeline System Using Fuzzy Reasoning. Proc. 14th World Conference on Earthquake Engineering (14WCEE).
- Alexoudi, M. (2005). Contribution to seismic assessment of lifelines in urban areas. Development of a holistic methodology for seismic risk. PhD Thesis, Civil Engineering Department, Aristotle University of Thessaloniki (in Greek).
- Alexoudi, M., Manou, D. and Pitilakis, K. (2008a). Seismic vulnerability analysis of waste-water system. Methodology and application for Düzce and Kocaeli earthquakes. Proc. 14th World Conference on Earthquake Engineering (14WCEE), Beijing, China.
- Alexoudi, M., Manou, D., Chatzigogos, Th. and Pitilakis, K. (2010). Influence Of Local Site Conditions In The Seismic Risk Assessment of The Water System in Düzce (Turkey). Proc. 6th National Conference of Geotechnical and Environmental Engineering, Volos, Greece (in Greek).
- Alexoudi, M.N., Kakderi, K.G. and Pitilakis, K.D. (2008b). Advanced Fragility Curves of Interdependent Lifelines Using Decision Making Process. Proc. 1st International Symposium on Life-Cycle Civil Engineering (IALCCE'08).
- Amin, M. (2001). Toward Self-Healing Energy Infrastructure Systems. IEEE Computer Applications in Power, Vol. 14, No. 1, pp. 20-28.
- Anastasiadis, A. (1994). Contribution to the determination of the dynamic properties of natural Greek soils. Ph.D. Thesis, Department of Civil Engineering, Aristotle University of Thessaloniki (in Greek).
- Anastasiadis, A., Raptakis, D. and Pitilakis, K. (2001). Thessaloniki's Detailed Microzoning: Subsurface Structure as basis for Site Response Analysis. Pure and Applied Geophysics – PAGEOPH, Vol. 158 No. 12, pp. 2597-2633.
- Anastasiadis, A.J. and Argyroudis, S.A. (2007). Seismic Vulnerability Analysis in Urban Systems and Road Networks. Application to the City of Thessaloniki, Greece. Sustainable Development and Planning, Vol. 2, No. 3, pp. 287-301.
- Anderson, E. (2008). Central American Probabilistic Risk Assessment (CAPRA): objectives, applications and potential benefits of an open access architecture. Global Risk Forum, GRF Davos, Switzerland.
- Apostolidis, P., Raptakis, D., Roumelioti, Z. and Pitilakis, K. (2004). Determination of S-wave velocity structure using microtremor and SPAC method applied in Thessaloniki (Greece). Journal of Soil Dynamics and Earthquake Engineering, Vol. 24, pp. 49-67.
- Applied Technology Council (1985). Earthquake Damage Evaluation Data for California. Report ATC-13, Applied Technology Council, Redwood City, California, U.S.A.
- Argyroudis, S. (2010). Contribution to seismic vulnerability and risk of transportation networks in urban environment. PhD Thesis, Department of Civil Engineering, Aristotle University of Thessaloniki, Greece (in Greek).
- Argyroudis, S., Pitilakis, K. and Anastasiadis, A. (2005). Roadway Network Seismic Risk Analysis in Urban Areas: The case of Thessaloniki - Greece. Proc. International Symposium of GEOLINE, Lyon.

- Augusti, G. and Ciampoli, M. (1997). Optimal distribution of seismic upgrading interventions to maximize the expected flow in a road network. VII IFIP WG 7.5. Boulder, CO: VII IFIP WG 7.5.
- Augusti, G. and Ciampoli, M. (1998). Multi objective optimal allocation of resources to increase the seismic reliability of highways. *Mathematical Methods of Operations Research*, Vol. 47, No. 1, pp. 33–49.
- Badal, J. and Samardzhieva, E. (2003). Prognostic estimations of casualties caused by strong seismic impacts. EGS-AGU-EUG Joint Assembly, Nice, France.
- Bal, I.E., Crowley, H. and Pinho, R. (2008a). Displacement-Based Earthquake Loss Assessment for an Earthquake Scenario in Istanbul. *Journal of Earthquake Engineering*, Vol. 11 No. 2, pp. 12-22.
- Bal, I.E., Crowley, H., Pinho, R. and Gülten Gülay, F. (2008b). Detailed assessment of structural characteristics of Turkish RC building stock for loss assessment models. *Soil Dynamics and Earthquake Engineering*, Vol. 28, No. 10-11, pp. 914-932.
- Basoz, N., and Kiremidjian, A. (1996). Risk Assessment for Highway Transportation Systems. Stanford, Calif.: J.A. Blume Earthquake Engineering Center, Department of Civil Engineering, Stanford University, Report No. 118.
- Bernhardt, K.L.S. and McNeil, S. (2004). An Agent Based Approach to Modeling the Behavior of Civil Infrastructure Systems. Engineering Systems Symposium, Tang Center, MIT.
- Brown, Th., Beyeler, W. and Barton, D. (2004). Assessing Infrastructure Interdependencies: the Challenge of Risk Analysis for Complex Adaptive Systems. *International Journal of Critical Infrastructures*, Vol. 1, No. 1, pp. 108-117.
- Chang, S.E. (2003). Evaluating disaster mitigations: Methodology for urban infrastructure systems. *Natural Hazards Review*, Vol. 4, No. 4, pp. 186–196.
- Chang, S.E. and Shinozouka, M. (1996). Life-cycle cost analysis with natural hazard risk. *Journal of Infrastructure Systems*, ASCE, Vol. 2, No. 3, pp. 62–78.
- Coburn, A. and Spence, R. (2002). *Earthquake protection*, Second edition, John Wiley & Sons Ltd, ISBN: 0-471-49614-6.
- Der Kiureghian, A. and Song, J. (2008). Multi-scale Reliability Analysis and Updating of Complex Systems by use of Linear Programming. *Reliability Engineering and System Safety*, Vol. 93, No. 2, pp. 288-297.
- Ditlevsen, O. and Madsen, H.O (1996). *Structural Reliability Methods*. John Wiley & Sons Ltd, Chichester.
- Douglas, J., Serrano, J.J., Comte, J., Bouc, O., Arnal, C., Robida, F., Modaressi, H., Logtmeijer, C., Vowles, G. and Holt, I. (2007). Risk Assessment for the Road Network in the French-Italian Border Region using web Services. Seventh IIASA-DPRI Forum on Integrated Disaster Risk Management - Stresa - Italie.
- Dueñas-Osorio, L., Craig, J.I. and Goodno, B.J. (2007). Seismic Response of Critical Interdependent Networks. *Earthquake Engineering and Structural Dynamics*, Special Issue on Earthquake Engineering for Electric Power Equipment and Lifeline Systems, Vol. 36, No. 2, pp. 285-306.
- EC8 (1998). Eurocode 8 - Design of structures for earthquake resistance -Part 5: Foundations, retaining structures and geotechnical aspects.
- Eguchi, R.T., Goltz, J.D., Seligson, H.A., Flores, P.J., Blais, N.C., Heaton, T.H. and Bortugno, E. (1997). Real Time Loss Estimation as an Emergency Response Decision Support System: The Early Post-Earthquake Damage Assessment Tool (EPEDAT). *Earthquake Spectra*, Vol. 13, No. 4, pp. 815-832.
- Eidinger, J. (1993). Fire Conflagration and Post-Earthquake Response of Power and Water Lifelines. Proc. 4th DOE of Energy Natural Phenomena Hazards Mitigation Conference, Atlanta, GA.
- Elgamal, A., Yang, Z., Parra, E. and Ragheb, A. (2001). CYCLIC 1D. UCSD.
- Erdik, M. and Aydinoglu, N. (2002). Earthquake performance and vulnerability of buildings in Turkey. Report prepared for World Bank Disaster Management Facility, Washington, DC.

-
- Erdik, M. and Fahjan, Y. (2006). Damage scenarios and damage evaluation in 'assessing and managing earthquake risk.' In: Oliveira CS, Roca A, Goula X (eds), Assessing and managing earthquake risk. Springer, Netherlands, pp. 213–237.
- Erdik, M., Aydinoglu, N., Fahjan, Y., Sesetyan, K., Demircioglu, M., Siyahi, B., Durukal, E., Ozbey, C., Biro, Y., Akman, H. and Yuzugullu, O. (2003). Earthquake risk assessment for Istanbul metropolitan area. *Earthquake Engineering and Engineering Vibration*, Vol. 2, No. 1, pp. 1–25.
- Erdik, M., Sesetyan, K., Demircioglu, M.B., Hancilar, U. and Zulfikar C. (2010). Rapid Earthquake Loss Assessment After Damaging Earthquakes. Chapter 21, in *Earthquake Engineering in Europe*, Garevski, M. and Ansal, A. (Eds), Geotechnical, Geological, and Earthquake Engineering, Vol. 17, Part 6, pp. 523-547, DOI: 10.1007/978-90-481-9544-2_21.
- FEMA (1992). A benefit–cost model for the seismic rehabilitation of buildings, FEMA-227Vols. 1 and 2. Sacramento, CA: Federal Emergency Management Report, 1992.
- Franchin, P., Lupoi, A. and Pinto, P.E. (2006). On the Role of Road Networks in Reducing Human Losses after Earthquakes. *Journal of Earthquake Engineering*, Vol. 10, No. 2, pp.195-206.
- Giannini, R. and Vanzi, A. (2000). Seismic Reliability of Electric Networks and Interaction with other Damage Indicators. Proc. 12th World Conference on Earthquake Engineering.
- Giannini, R., Pinto, P.E. and Vanzi, I. (1999). Earthquake Hazard Analysis Software: ASKxELP. Assessment of Seismic Risk for Electric Power Networks and Interaction with other Indicators of Seismic Damage. National Information Service for Earthquake Engineering, University of California, Berkeley, U.S.A.
- Goretti, A. (2005). A Probabilistic Model Able to Handle Interaction Among Road Network, Buildings and Emergency Services in Urban Areas. Proc. IX International Conference on Structural Safety and Reliability, ICOSSAR'05, Rome.
- Hada, Y., and Meguro, K. (2000). Optimum Restoration Model Considering Interactions among Lifeline Systems-Interactions Among Restoration Activities of Lifeline Utilities. Proc. 12th World Conference on Earthquake Engineering.
- Haimes, Y.Y., and Jiang, P. (2001). Leontief-based model of risk in complex interconnected infrastructures. *Journal of Infrastructure Systems*, Vol. 7, No. 1, pp. 1-12.
- Hoshiya, M. and Ohno, H. (1985). A System Dynamic Model in Seismic Performance Assessment of Electric Power and Water Supply Networks. Proc. Trilateral Seminar – Workshop on Lifeline Earthquake Engineering, Taipei, Taiwan, pp. 181-189.
- Ishihara, K. and Yoshimine, M. (1992). Evaluation of settlements in sand deposits following liquefaction during earthquakes, *Soils and Foundations*, Vol. 32, No. 1, pp. 173-188.
- JCSS, (2008). Risk Assessment in Engineering Principles, System Representation & Risk Criteria. Joint Committee for Structural Safety, <http://www.jcss.ethz.ch/>.
- Kakderi, K. and Pitilakis, K. (2011). Seismic performance and reliability of port facilities – The case of Thessaloniki (Greece). Proc. 5th International Conference on Earthquake Geotechnical Engineering, Santiago, Chile.
- Kakderi, K., Alexoudi, M. and Pitilakis, K. (2007). Seismic Risk Analysis of Interdependent Lifeline systems. Proc. 4th International Conference on Geotechnical Earthquake Engineering.
- Kakderi, K., Alexoudi, M. and Pitilakis, K. (2008). Seismic Risk Analysis of Interdependent Lifeline Systems. Proc. 3rd Greek Conference on Earthquake Engineering and Engineering Seismology (in Greek).
- Kameda, H. (2000). Engineering Management of Lifeline Systems Under Earthquake Risk. Proc. 12th World Conference on Earthquake Engineering.
- Kanda, J. and Shah, H. (1997). Engineering role in failure cost evaluation for 790 buildings. *Structural Safety*, Vol. 19, No. 1, pp. 79–90.

-
- Kappos, A., Panagopoulos, G., Panagiotopoulos, Ch. and Penelis, Gr. (2006). A hybrid method for the vulnerability assessment of R/C and URM buildings. *Bulletin of Earthquake Engineering*, Vol. 4, No. 4, pp. 391-413.
- Karaca, E. (2005). Regional Earthquake Loss Estimation: Role of Transportation Network, Sensitivity and Uncertainty, and Risk Mitigation. PhD thesis, MIT, Cambridge, MA.
- Kim, Y.S., Spencer, B.F., Song, J., Elnashai, A.S. and Stokes, T. (2007). Seismic Performance Assessment of Interdependent Lifeline Systems. MAEC Report, Mid America Earthquake Research Center, University of Illinois, Urbana-Champaign, CD Release 07-16.
- Kunreuther, H., Cyr, C., Grossi, P. and Tao, W. (2001). Using cost-benefit analysis to evaluate mitigation for lifeline systems. MCEER research projects and accomplishments:2000–2001.
- LESSLOSS, (2004-2007). Risk Mitigation for Earthquakes and Landslides. Research Project, European Commission, Sixth Framework Programme, Priority 1.1.6.3, Global Change and Ecosystems, Contract Number: GOCE-CT-2003-505448.
- Li, J., and He. J. (2002). A recursive decomposition algorithm for network seismic reliability evaluation. *Journal of Earthquake Engineering and Structural Dynamics*, Vol. 31, No. 8, pp. 1525-1539.
- Little, R.G. (2002). Controlling Cascading Failure: Understanding the Vulnerabilities of Interconnected Infrastructures. *Journal of Urban Technology*, Vol. 9, No. 1, pp. 109–123.
- Liu, G.-Y., Liu, C.-W., Wang, Y.-J. and Jean, W.-Y. (2004). Seismic Risk Analysis of Power Transmission System. Proc. 3rd Taiwan-Japan Workshop on Lifeline Performance and Disaster Mitigation.
- Lupoi, G., Franchin, P., Lupoi, A., Pinto, P.E. and Calvi, G.M. (2008). Probabilistic Seismic Assessment for Hospitals and Complex-Social Systems. IUSS Press, Pavia, Italy.
- Manou, D., Alexoudi, M., Raptakis, D. and Pitilakis, K. (2007). Düzce (M7.2, 1999) earthquake: Damage Correlation with the microzonation study and vulnerability assessment of the water system in Düzce, Turkey. Proc. 4th International Conference on Earthquake Geotechnical Engineering (4ICEGE), Thessaloniki, Greece Paper No. 1621.
- Manou, D., Manakou, M., Alexoudi, M., Anastasiadis, A. and Pitilakis, K. (2010). Microzonation study of Düzce, Turkey. Proc. 5th International conference on recent advances in Geotechnical Earthquake engineering and Soil Dynamics and Symposium in honour of professor I. M. Idriss, San Diego, CA, Paper No. 7.12b.
- Menoni, S. (2001). Chains of damages and failures in a metropolitan environment: some observations on the Kobe earthquake in 1995. *Journal of Hazardous Materials*, Vol. 86, No. 1, pp. 101–119.
- MERP, (2002-2005). Marmara Earthquake Rehabilitation Programme - An Integrated intervention for the Rehabilitation of Düzce, Research Project, European Commission, Republic of Turkey, Prime Minister Project, Implementation Project, PIU-ID-MERP-2002-2004, 2002-2005.
- Mid-America Earthquake Center (MAEC) (2009). MAEviz Software. <http://mae.cee.uiuc.edu/software_and_tools/maeviz.html>.
- Nakayama, W., Shimizu, Y. and Koganemaru K. (2004). Development of super dense realtime disaster mitigation system for urban gas supply network. *Journal of Japan Association for Earthquake Engineering*, Special Issue.
- NIBS (2004). HAZUS: Hazard US: Earthquake Loss Estimation Methodology. National Institute of Building Sciences, NIBS document 5200-03, Washington, DC.
- Nojima, N. and Kameda, H. (1991). Cross Impact Analysis for Lifeline Interactions. Proc. 3rd US Conference on Lifeline Earthquake Engineering, Los Angeles, California, TCLEE/ASCE, Monograph No. 4, edited by M. A. Cassaro, pp. 629- 638.
- Nuti, C. and Vanzi, I. (1998). Assessment of Post-Earthquake Availability of Hospital System and Upgrading Strategies. *Earthquake Engineering and Structural Dynamics*, Vol. 27, No. 12, pp. 1403-1423.

5th International Conference on Earthquake Geotechnical Engineering

January 2011, 10-13

Santiago, Chile

-
- Nuti, C., Rasulo, A. And Vanzi, I. (2007). Structural Safety Evaluation of Electric Power Supply at Urban Level. *Earthquake Engineering and Structural Dynamics, Special Issue on Earthquake Engineering for Electric Power Equipment and Lifeline Systems*, Vol. 36, No. 2, pp. 245-263.
- O'Rourke, M.J. and Ayala, G. (1993). Pipeline damage due to wave propagation. *Journal of Geotechnical Engineering*, ASCE, Vol. 119, No. 9, pp. 1490-1498.
- Ostrom, D.K. (2003). SERA II. Proc. 6th U.S. Conference and Workshop on Lifeline Earthquake Engineering, TCLEE, Monograph No. 25, pp. 587-596.
- Pachakis, D. and Kiremidjian, A. (2003). The use of Simulation in Disaster Response Planning and Risk Management of Ports and Harbors. Proc. 6th U.S. Conference and Workshop on Lifeline Earthquake Engineering, TCLEE, Monograph No. 25.
- Pachakis, D. and Kiremidjian, A. (2004). Estimation of Downtime-Related Revenue Losses in Seaports Following Scenario Earthquakes. *Earthquake Spectra*, Vol. 20, No. 2, pp. 427-449.
- Paolucci, R. and Ptilakis, K., (2007). Seismic Risk Assessment of Underground Structures under Transient Ground Deformations. in Ptilakis K. (Ed.). *Earthquake Geotechnical Engineering*, Chap. 18, pp. 433-459, Springer.
- Papaioannou, Ch. (2004). Technical Report Research Program SRM-LIFE, Seismic Hazard Scenarios: Probabilistic Analysis of Seismic Hazard. Coord. K.Ptilakis, Thessaloniki.
- Park, J. (2004). Development and application of probabilistic decision support framework for seismic rehabilitation of structural systems. Thesis, Georgia Institute of Technology.
- Peerenboom, J., Fisher, R. and Whitfield, R. (2001). Recovering from disruptions of interdependent critical infrastructures. Proc. Workshop on Mitigating the Vulnerability of Critical Infrastructures to Catastrophic Failures, Lyceum, Alexandria, Virginia.
- Penelis, Gr.G., Kappos, A.J., Stylianidis, K.C. and Panagiotopoulos, C. (2002). 2nd level analysis and vulnerability assessment of URM buildings. Proc. International Conference on Earthquake Loss Estimation and Risk Reduction, Bucharest, Romania.
- Ptilakis, K. and Anastasiadis, A. (1998). Soil and site characterization for seismic response analysis. Proc. XI ECEE, Paris, Invited Lecture, pp.65-90.
- Ptilakis, K., Alexoudi, A., Argyroudis, S., Monge O. and Martin, C. (2005a). Chapter 9: Vulnerability assessment of lifelines. C.S. Oliveira, A. Roca and X. Goula ed. *Assessing and Managing Earthquake Risk. Geo-Scientific and Engineering Knowledge for Earthquake Risk mitigation: Developments, Tools and Techniques*. Springer Publ.
- Ptilakis, K., Alexoudi, A., Argyroudis, S., Monge, O. and Martin, C. (2006a). Earthquake Risk Assessment of Lifelines. *Bulletin of Earthquake Engineering*, Vol. 4 No.4, Special Issue: The Risk-Use Project (Ed. Atilla Ansal), pp. 365-390.
- Ptilakis, K., Alexoudi, M., Argyroudis, S. and Anastasiadis, A. (2006b). Seismic Risk Scenarios for an Efficient Risk Management: The Case of Thessaloniki (Greece). In *Advances in Earthquake Engineering for Urban Risk Reduction*, Eds. S.T. Wasti and G. Ozcebe, Springer, pp.229-244.
- Ptilakis, K., Alexoudi, M., Kakderi, K., Manou, D., Batum, E. and Raptakis, D. (2005b). Vulnerability analysis of water systems in strong earthquakes. The case of Lefkas (Greece) and Düzce (Turkey). Proc. International Symposium on the Geodynamics of Eastern Mediterranean: Active Tectonics of the Aegean, Istanbul.
- Ptilakis, K., Anastasiadis, A. and Raptakis, D. (1992). Field and Laboratory Determination of Dynamic Properties of Natural Soil Deposits. Proc. 10th World Conference on Earthquake Engineering, Madrid, Vol. 5, pp.1275-1280.
- Ptilakis, K., Anastasiadis, A., Kakderi, K., Alexoudi, M. and Argyroudis, S. (2010c). The role of soil and site conditions in the vulnerability and risk assessment of lifelines and infrastructures. The case of Thessaloniki (Greece). Proc. 5th International conference on recent advances in Geotechnical Earthquake engineering and Soil Dynamics and Symposium in honour of professor I. M. Idriss, San Diego, CA.

5th International Conference on Earthquake Geotechnical Engineering

January 2011, 10-13

Santiago, Chile

-
- Pitilakis, K., Anastasiadis, A., Kakderi, K., Argyroudis, S. and Alexoudi M. (2007a). Seismic Zonation, Vulnerability Assessment and Loss Scenarios in Thessaloniki. Proc. 2nd Japan-Greece Workshop on Seismic Design, Observation, and Retrofit of Foundations, Tokyo, Japan.
- Pitilakis, K., Anastasiadis, A., Kakderi, K., Argyroudis, S. and Alexoudi M. (2007b). Vulnerability Assessment and Risk Management of Lifelines, Infrastructures and Critical Facilities. The case of Thessaloniki's Metropolitan area. Proc. 4th International Conference on Geotechnical Earthquake Engineering, June 25-28, Thessaloniki, Greece, paper ID: 1774.
- Pitilakis, K., Makra, K. and Raptakis, D. (2001). 2D vs 1D site effects with potential applications to seismic norms: The cases of EURO-SEISTEST and Thessaloniki. Invited lecture in XVth International Conference on Soil Mechanics & Geotechnical Engineering, pp. 123-133, Istanbul – Turkey.
- Pitilakis, K., Raptakis, D., Makra, K., Manakou, M. and Chávez-García, F.J. (2010b). EUROSEISTEST 3D Array for the Study of Complex Site Effects. Akkar, D. Sinan; Gülkan, Polat; Eck, Torild van (Eds.), Earthquake Data in Engineering Seismology, Predictive Models, Data Management and Networks. Series: Geotechnical, Geological, and Earthquake Engineering, Vol. 14.
- Pitilakis, K.D., Anastasiadis, A.I., Kakderi, K.G., Manakou, M.V., Manou, D.K., Alexoudi, M.N., Fotopoulou, S.D., Argyroudis, S.A. and Senetakis, K.G. (2010a). Development of comprehensive earthquake loss scenarios for a Greek and a Turkish city: Seismic hazard, Geotechnical and Lifeline Aspects. Earthquakes and Structures, submitted for review.
- Porter, K., Jaiswal, K., Wald, D., Earle, P. and Hearne, M. (2008a). Fatality models for the U.S. Geological Survey's Prompt Assessment of Global Earthquake for Response (PAGER) system. Proc. 14th World Conference on Earthquake Engineering, Beijing, China, 8 pp.
- Porter, K.A., Jaiswal, K.S., Wald, D.J., Greene, M. and Comartin, C. (2008b). WHE-PAGER Project: a new initiative in estimating global building inventory and its seismic vulnerability. Proc. 14th World Conference on Earthquake Engineering, Beijing, China 8 pp. Porter et al. (2008).
- Raptakis, D. (1995). Contribution to the determination of the geometry and the dynamic characteristics of soil formations and their seismic response. Ph.D. Thesis, Department of Civil Engineering, Aristotle University of Thessaloniki (in Greek).
- Raptakis, D.G., Anastasiadis, A.J., Pitilakis, K.D. and Lontzetidis, K.S. (1994a). Shear wave velocities and damping of Greek natural soils. Proc. 10th European Conference on Earthquake Engineering, Vienna, Austria, Vol. 1, pp. 477-482.
- Raptakis, D.G., Karaolani, E., Pitilakis, K. and Theodulidis, N. (1994b). Horizontal to vertical spectral ratio and site effects: The case of a down-hole array in Thessaloniki (Greece). Proc. XXIV General Assembly, ESC, Athens, Vol. 3, pp.1570-1578.
- Rinaldi, S.M., Peerendoom, P. and Kelly, T.K. (2001). Identifying, Understanding, and Analyzing Critical infrastructure interdependencies. IEEE Control Systems Magazine, Vol. 21, No. 6, pp. 11-25.
- RISK-UE, (2001-2004). An Advanced Approach to Earthquake Risk Scenarios with Applications to Different European Towns. Research Project, European Commission, DG XII2001-2004, CEC Contract Number: EVK4-CT-2000-00014.
- Rubinstein, R.Y. (1981). Simulation and Monte Carlo Method. Wiley, New York.
- Rubinstein, R.Y. and Melamed, B. (1998). Modern Simulation and Modeling. Wiley, New York (ISBN 0-471-17077-1).
- Santos, J.R., and Haimes, Y.Y. (2004). Modeling the Demand Reduction Input-Output (I-O) Inoperability Due to Terrorism of Interconnected Infrastructures. Risk Analysis, Vol. 24, No. 6, pp. 1437-1451.
- Scawthorn, C. (1992). Lifeline Interaction and Post- Earthquake Functionality. Proc. 5th U.S.- Japan Workshop on Earthquake Disaster Prevention for Lifeline Systems, pp. 441- 450.
- Seed, R.B., Cetin, K.O., Moss, R.E.S., Kammerer, A.M., Wu, J. and Pestana, J.M. (2003). Recent Advances in Soil Liquefaction Engineering: A Unified and Consistent Frame work. Proc. 26th Annual ASCE Los Angeles Geotechnical Spring Seminar, Keynote Presentation, H.M.S. Queen Mary, Long Beach, California.

5th International Conference on Earthquake Geotechnical Engineering

January 2011, 10-13

Santiago, Chile

-
- Seligson, H.A., Ballantyne, D.B., Huyck, C.K., Eguchi, R.T., Bucknam, S. and Bortugno, E. (2003). URAMP (utilities regional assessment of mitigation priorities) – a benefit-cost analysis tool for water, wastewater and drainage utilities: Methodology development. Proc. 6th U.S. Conference on Lifeline Earthquake Engineering, ASCE, TCLEE, Long Beach, California.
- Selva, J., Kakderi, K., Alexoudi, M. and Pitilakis, K. (2010). Serviceability of a system of interdependent components (submitted).
- Shimizu, Y. and Yamazaki, F. (1998). Real-Time City Gas Network Damage Estimation System-SIGNAL. Proc. 11th European Conference on Earthquake Engineering, Balkema, Rotterdam.
- Shinozuka, M. and Tanaka, S. (1996). Effects of Lifeline Interaction Under Seismic Conditions. Proc. 11th World Conference on Earthquake Engineering.
- Shinozuka, M., Cheng, T.C., Feng, M. and Mau, S.T. (1999). Seismic performance analysis of electric power systems. Research Progress and Accomplishments 1997–1999, MCEER, pp. 61–69.
- Shinozuka, M., Hwang, H. and Tanaka, S. (1993). GIS - Based Assessment of the Seismic Performance of Water Delivery System. Proc. 5th US-Japan Workshop on Earthquake Disaster Prevention for Lifeline Systems, edited by K. Kawashima, H. Sugita and T. Nakajima, PWRI 3198, Public Works Research Institute, Tsukuba, Japan, pp. 233-249.
- Shinozuka, M., Murachi, Y., Dong, X., Zhu, Y. And Orlikowski, M.J. (2003). Seismic performance of highway transportation networks. Proc. China-US Workshop on protection of urban infrastructure and public buildings against earthquakes and man-made disasters, Beijing, China.
- Song, J. and Der Kiureghian, A. (2003). Bounds on system reliability by linear programming. Journal of Engineering Mechanics, ASCE, Vol. 129, No. 6, pp. 627-636.
- Sousa, M.L., Campos Costa, A., Carvalho, A. and Coelho, E. (2004). An automatic seismic scenario loss methodology integrated on a geographic information system. Proc. 13th World Conference on Earthquake Engineering, Vancouver, BC, Canada.
- Spence, R. Ed (2007). Earthquake disaster scenario predictions and loss modelling for urban areas. LESSLOSS Report 7, IUSS Press, Pavia, Italy.
- SRM-DGC, (2006-2008). Development and proposition for implementation of an efficient methodology and appropriate local instruments for the management, prevention and reduction of seismic risk in Düzce -Turkey, Grevena - Greece and Catania – Italy. Research project, Interreg III B Archimed, Code Number. A.1.010.
- SRMLIFE, (2003-2007). Development of a global methodology for the vulnerability assessment and risk management of lifelines, infrastructures and critical facilities. Application to the metropolitan area of Thessaloniki. Research Project, General Secretariat for Research and Technology, Greece.
- SYNER-G, (2009-2011). Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain. Research Project, European Commission, 7th Framework Programme, Contract Number: 244061.
- Tadday, K. and Sahin, M. (2001). Situation analysis and recommendations related to improvement measures for drinking water supply system in Düzce. Proc. Symposium on Water Supply Situation in Earthquake Affected Region, Düzce.
- Tang, A., and Wen, A. (2009). An intelligent simulation system for earthquake disaster assessment. Computers and Geosciences, Vol. 35, No. 5, pp. 871-879.
- Tang, A.P., Ou, J.W.A. and Tao, X. (2004). Lifeline Systems Interaction and their Seismic Performance Assessment. Proc. 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada.
- Tolone, W.J., Wilson, D., Raja, A., Xiang, W.-N., Hao, H., Phelps, S. and Johnson, E.W. (2004). Critical Infrastructure Integration Modeling and Simulation. Proc. 2nd Symposium in Intelligence and Security Informatics, Tucson, Arizona.
- Tromans, J. (2004). Behaviour of buried water supply pipelines in earthquake zones. PhD Thesis, Imperial College of Science, Department of Civil and Environmental Engineering, University of London.
- Vanzi, I. (1996). Seismic Reliability of Electric Power Networks: Methodology and Application. Structural Safety, Vol. 18, No. 4, pp. 311–327.

5th International Conference on Earthquake Geotechnical Engineering

January 2011, 10-13

Santiago, Chile

- Vanzi, I. (2000). Structural upgrading strategy for Electric Power Networks under Seismic Action. *International Journal of Earthquake Engineering and Structural Dynamics*, Vol. 29, No. 7, pp. 1053–1073.
- Veneziano, D., Sussman, J., Gupta, U. and Kunnumkal, S.M. (2002). Earthquake Loss under Limited Transportation Capacity: Assessment, Sensitivity and Remediation. Proc. 7th USNCEE, Boston, MA, USA.
- Werner, S.D., Taylor, C E. and Ferritto, J.M. (1999). Seismic Risk Reduction Planning for Ports Lifelines. Proc. 5th U.S. Conference on Lifeline Earthquake Engineering, TCLEE, Monograph No. 16.
- Wong, F.S. and Isenberg, J. (1995). Effects of Lifeline Interaction on Seismic Performance of Communications Networks. Proc. 4th U.S. Conference on Lifeline Earthquake Engineering, TCLEE/ASCE, Monograph No.6, edited by J. O' Rourke, pp. 557-564.
- Yao, B., Xie, L. and Huo, E. (2004). Study Effect on Lifeline Interaction under Seismic Conditions. Proc. 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada.
- Youd, T.L., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian, J.T., Dobry, R., Liam Finn, W.D., Harder Jr., L.F., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.S.C., Marcuson, W.F., Martin, G.R., Mitchell, J.K., Moriwaki, Y., Power, M.S., Robertson, P.K., Seed, R.B. and Stokoe, K.H. (2001). Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 127, No. 10, pp. 817-833.