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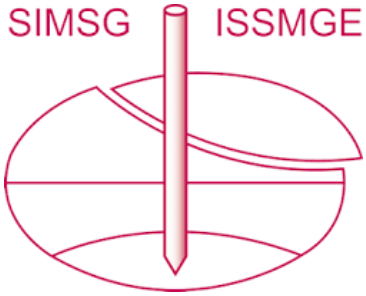

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SEISMIC PERFORMANCE AND RELIABILITY OF PORT FACILITIES – THE CASE OF THESSALONIKI (GREECE)

Kalliopi G. KAKDERI [1], Kyriazis D. PITILAKIS[2]

ABSTRACT

The paper presents a methodology for the seismic risk assessment and reliability performance of port facilities; key factors of the methodology are the inventory, the typology, the specific characteristics and the importance (global value) of the elements at risk, the interdependencies and functional relations between port components, as well as the development of seismic scenarios (seismic hazard) and the geotechnical characterization, with the detailed site response analysis. The port of Thessaloniki in Greece is used as a case study. The proposed methodology for the seismic vulnerability of the port facility is developed considering various uncertainties in the adopted fragility curves. Then an application is performed for Thessaloniki's port to estimate the expected damages for different earthquake scenarios, due to ground shaking and ground failure. The vulnerability assessment is based on a detailed inventory, typology, seismic hazard and vulnerability characteristics of the elements at risk, as well as the detailed site response of the area for the different seismic scenarios. The coupled behavior of the waterfront and other structures, especially cargo handling equipment and water pipelines, is examined through the definition of acceptable induced constraints due to the quay walls' direct damage. The "propagated" additional vulnerability is estimated on the basis of the spatial proximity. The estimation of direct losses and restoration time is then performed based on adequate models, local current practice and equipment. Finally, proposals for optimized pre-seismic retrofitting actions and post-seismic restoration process are provided, resulting in enhanced port earthquake sustainability and reliability.

Keywords: port facilities, seismic risk, reliability performance, waterfront structures

INTRODUCTION

Damages in port facilities during past earthquakes throughout the world, led to a wide range of direct and indirect losses, with very important economic and societal impacts. The uncertainties due to the spatial variability of the networks, the incomplete inventory data, the lack of well-validated damage data from past strong earthquakes and the uniform definition of damage states, make the vulnerability assessment of each particular component and of the network as a whole, a very difficult task. Furthermore, their complex structure requires an holistic approach and integrated tool for the evaluation of the seismic effect on their performance.

Loss assessment for a given seismic scenario refers to direct damages and indirect effects due to loss of functionality of lifeline components, networks and infrastructures inside port facilities. Indirect damages can be particularly important in complex systems such as port facilities. A representative example is the Port of Kobe (Japan) that suffered severe damage during the 1995 Great Hanshin earthquake; the port was

[1] Civil Engineer, MSc, Department of Civil Engineering, Aristotle University of Thessaloniki, Greece, e-mail: kakderi@civil.auth.gr
[2] Professor, Department of Civil Engineering, Aristotle University of Thessaloniki, Greece.

essentially shut down and required over two years to fully repair. Indirect financial losses were profound due to the "permanent" loss of the diverted traffic during the reconstruction phase (Chang, 2000).

We propose herein a methodology for the seismic risk analysis of a harbor infrastructure with an application to Thessaloniki's port. The final goal is the definition of reliable seismic scenarios for complex port facilities and the development of effective and efficient pre-earthquake mitigation plans, co and post seismic response and restoration efforts. Key role in the methodology has the detailed site response analysis, which is based on a detailed knowledge of the local seismicity, surface geology, topography and local soil conditions. Loss scenarios are generated for different seismic scenarios, taking into consideration the individual characteristics of the elements at risk, the typology and the vulnerability. The multiple interactions existing between different components of port facilities and the "propagated" additional vulnerability are estimated on the basis of the spatial proximity using a GIS tool. Moreover, taking into account the functional and social vulnerability of lifeline elements through a global value analysis, lifeline networks can be analyzed as an integrated part of the selected seismic risk scenario, and as a part of the urban system, considering human, material and immaterial assets. Thus, a prioritization of pre-earthquake retrofitting actions and quantification of the overall importance of port facilities could be performed, resulting in enhanced port earthquake sustainability and reliability.

METHODOLOGICAL FRAMEWORK

The general framework of the methodology developed for the vulnerability assessment and seismic risk management of lifeline systems and infrastructures is illustrated in figure 1 (SMRLIFE, 2003-2007). Loss estimates including direct and indirect losses, depend on the existing 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 thus 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 vulnerability assessment deals mainly with the quantification of damage of each element at risk, using appropriate fragility functions. Furthermore, a "global value analysis" of the elements at risk is proposed, taking into account different criteria such as the functional relations between them and with the urban or rural environment, in three periods (normal, crisis, recovery) in respect to the occurrence of an earthquake event, for the definition of lifeline's importance. 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. Multiple interactions between components and systems are taken into account for the definition of the final system's serviceability. Finally, combining the vulnerability assessment with the importance of different elements in pre and post seismic periods, a rigorous disaster management process including mitigation, preparedness, response and recovery actions could be assigned. The proposed modular methodology, when applied to complex systems such as port facilities, can lead to a rigorous seismic risk assessment and reliability performance, resulting in enhanced port earthquake sustainability. In the following, a description of the various steps of the methodology are described with an application to Thessaloniki's port, giving representative examples of the risk analysis results for different scenarios.

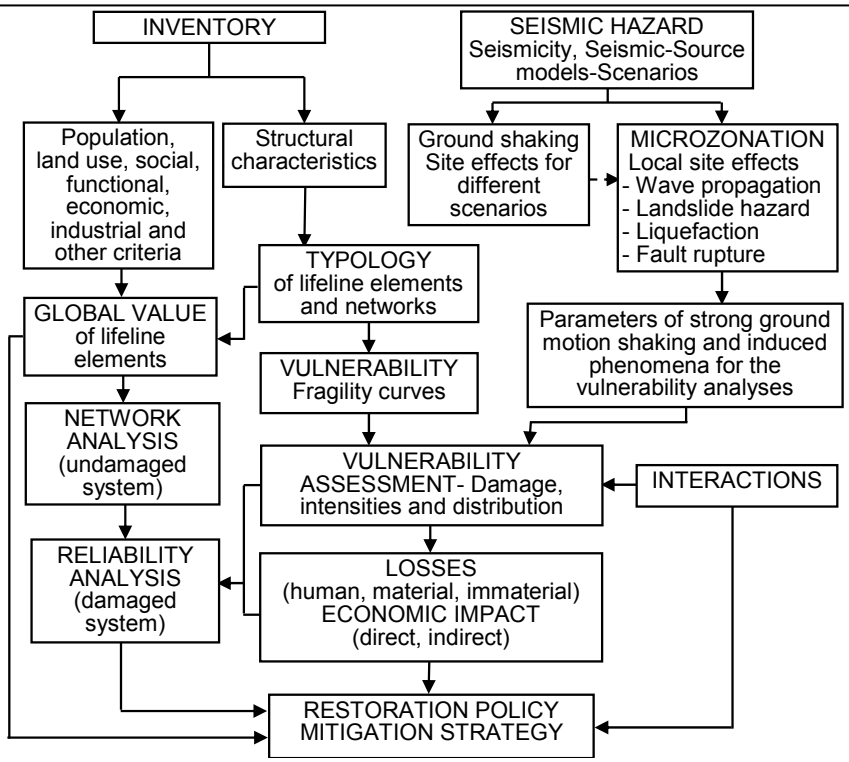


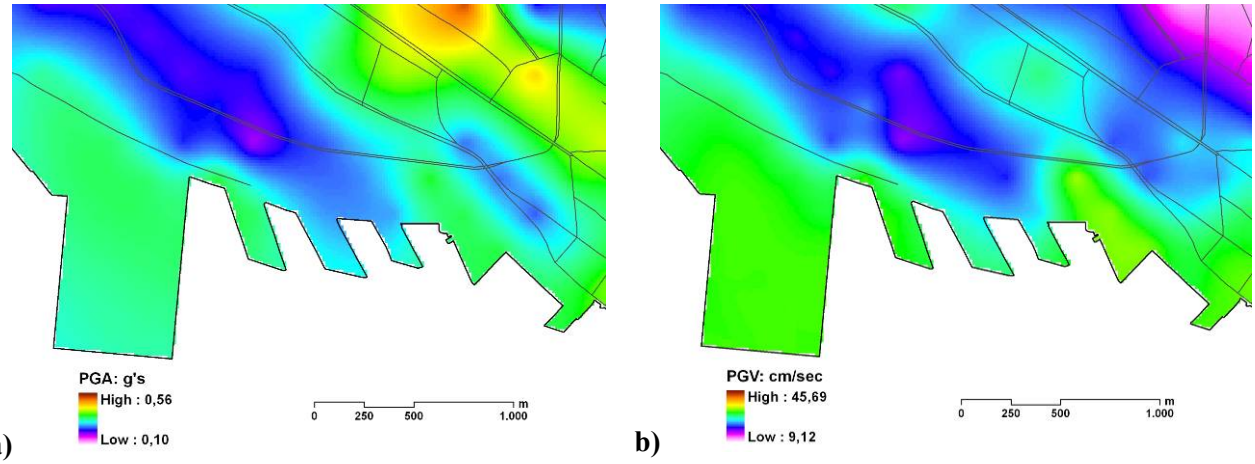
Figure 1. General flowchart of the proposed methodology (SMRLIFE, 2003-2007).

SEISMIC SCENARIOS – SITE SPECIFIC GROUND RESPONSE ANALYSIS

In Thessaloniki, a detailed microzonation study has been conducted for three different mean return periods of approximately T_m=100, 475 and 1000 years (Pitilakis et al., 2010). 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 (RISKUE, 2001-2004; SRMLIFE, 2003-2007). A detailed model of the surface geology and geotechnical characteristics, for site effect studies, was also generated for the whole city. Site effects are calculated performing a great number of 1D linear equivalent response analyses, and few 2D analyses in selected cross sections, in order to take into account the influence of geotechnical characteristics and dynamic properties of the main soil formations, on the expected seismic ground motion. The analysis is conducted for five different scaled real accelerograms (for bed rock motions), which were selected according to the seismic hazard study, for the three scenarios. Using Geographical Information Systems (GIS), thematic maps with the spatial distribution of strong motion parameters (e.g. Peak Ground Accelaration - PGA, Peak Ground Velocity - PGV, Peak Ground Displacement - PGD, ground strains, response spectra, etc) have been generated for all seismic scenarios in the study area. Finally, in order to account for the liquefaction-induced phenomena, the evaluation of permanent ground horizontal and vertical displacements (PGD), (lateral spreading and settlements), has been performed for the three scenarios using empirical and analytical procedures. Figure 2 illustrates the spatial distribution of the mean peak ground acceleration and mean peak ground velocity studying the Thessaloniki's port area, and for the earthquake scenario with 10% probability of exceedance in 50 years (mean return period of 475 years).

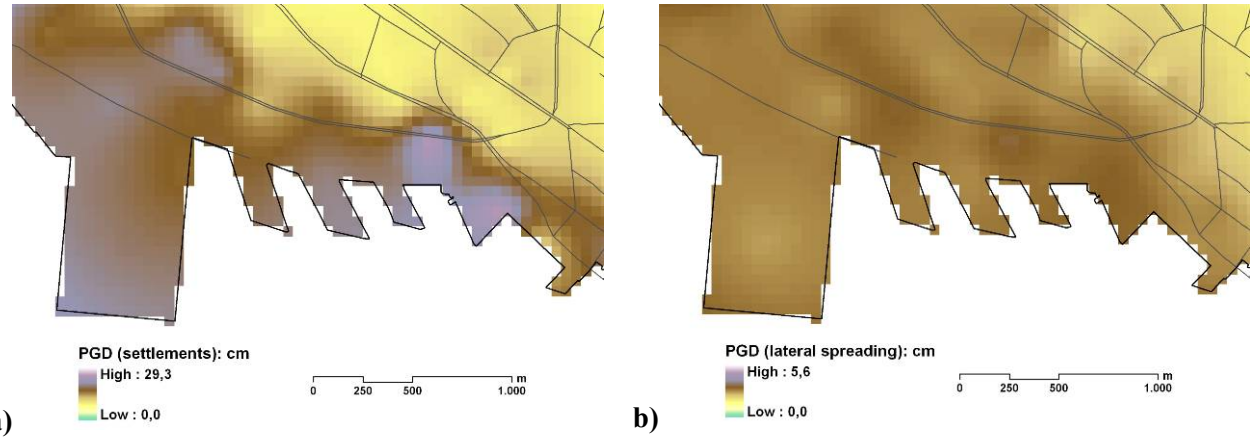
The spatial distribution of the mean values of "peak" permanent ground deformations (settlements and lateral spreading) due to the occurrence of liquefaction phenomena is given in figure 3 for the same seismic scenario. Loose, saturated silty sand deposits susceptible to liquefaction appear along the

coastland; as a result relatively high values of permanent ground displacements are estimated, ranging up to 31 cm for the 1000 years seismic scenario. It should be noticed that the occurrence of liquefaction phenomena is the most widespread source of earthquake-induced damage to port facilities and especially waterfront structures (Werner, 1998).



a) **b)**

Figure 2. Spatial distribution of (a) mean peak ground acceleration (PGA: g's) and (b) mean peak ground velocity (PGV: cm/s) in Thessaloniki's port (T_m=475 years).



a) **b)**

Figure 3. Spatial distribution of (a) permanent ground displacements/ settlements due to liquefaction and (b) horizontal permanent ground displacements due to lateral spreading in Thessaloniki's port (T_m=475 years).

VULNERABILITY ASSESSMENT AND SEISMIC SCENARIOS

The port of Thessaloniki covers an area of 1,500,000 m^2 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 (transmission and distribution lines, substations), potable and waste water (pipelines), telecommunication (lines and stations), railway (tracks) and roadway (roads and bridge) systems as well as buildings and critical facilities. The presence of all the above utilities and infrastructures in a limited area enables the complete application of the methodology for the seismic risk assessment of lifelines and infrastructures, also taking

into account the multiple interactions existing between them, and the specification of possible weak or critical points for the operation of the whole system.

Loss estimations are performed for the port facilities, utility networks, transportation systems and buildings of Thessaloniki's port based on the results of the site specific study of ground motion, for 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. They may be classified in category C of EC8. 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. Damages based on both ground shaking (peak ground strain and peak ground velocity) and permanent ground deformation were accounted for, depending on each element typology and appropriate seismic parameters. The type, extent and spatial distribution of induced earthquake damage were specified and illustrated in GIS thematic maps. In the following, some examples of the vulnerability assessment and estimated direct damages of port facilities (waterfront structures, cargo and handling equipment) and potable water system of Thessaloniki's port are provided for selected seismic scenarios.

Port facilities (Cargo handling equipment/ Waterfront structures)

The inventory developed for the waterfront structures includes several attributes such as name, location, operational depth, year of construction, equipment, material, type, foundation type, maintenance, damages in previous earthquakes and length. Existing fragility curves have been validated using data from recent European earthquakes (Kakderi et al., 2006). The empirical vulnerability functions proposed in HAZUS (NIBS, 2004) have been used for the vulnerability assessment of waterfront structures due to ground failure. For the case of ground shaking, the analytical fragility curves proposed by Kakderi and Pitilakis (2010) have been applied (for soil type C of EC8). Peak ground acceleration on rock and permanent ground displacement due to liquefaction are the input parameters describing the seismic intensity.

For cranes and cargo handling equipment the available inventory data include their type, capacity, working range, year of construction, source, location, anchorage, type of cargo and energy, alternative energy sources, maintenance and damages in previous earthquakes. The HAZUS fragility curves (NIBS, 2004) have also been used in this case for the estimation of direct induced damage due to the effect of ground shaking and failure. Seismic input parameters are the peak ground acceleration (PGA) and permanent ground displacement (PGD) respectively.

The majority of the waterfront structures (63%) are expected to remain practically undamaged for the 475 years scenario, while the rest 37% will have minor to slight damages [damage states according to HAZUS (NIBS, 2004)], when considering only the effect of ground failure. If the effect of ground shaking is also taken into consideration, and using the damage states proposed by PIANC (2001), the whole length of waterfront components is expected to sustain minor damages for the 475 and 1000 scenarios. On the other hand, moderate level damages are expected for 42 out of the 49 elements of cargo handling equipment due to their sensibility in differential ground settlements. In this case the anticipated damages are attributed mainly to the occurrence of liquefaction induced phenomena. Estimated direct economic losses can be easily assessed by the estimated damage levels as a percentage of the components' replacement cost. Figure 4 presents the results of the vulnerability assessment (estimated worst probable damage state, i.e. exceeding probability >50%) for the waterfront structures and cargo handling equipment for the 475 years scenario when considering both the effect of ground failure and shaking.

Lifeline and infrastructure systems

Thessaloniki's port potable water system comprises about 19.3 km of pipes. It is a highly redundant system, with closed loops, which is connected to the urban water supply system in four independent locations. The current inventory database includes several structural and functional attributes such as

length, material, diameter, depth and type of seating. The vulnerability assessment of potable water pipes is based on the estimation of the expected Repair Rate per pipe km (RR/km). 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), where the seismic loading is described in terms of peak ground velocity (PGV). The expected damages due to ground failure, expressed in terms of ground settlements, are assessed based on the Honegger and Eguchi (1992) fragility relation. Prior to their application, these empirical vulnerability functions have been validated with well documented data, from recent earthquakes in Lefkas-Greece, (2003) and in Düzce-Turkey, (1999) (Alexoudi, 2005).

Figure 5 presents the spatial distribution and the intensity of estimated damages for the water supply network within the port area for the 1000 years scenario. Their number, intensity and location are related to the spatial distribution of seismic ground motion, for the specific scenario as well as the individual characteristics of the examined elements. The occurrence of liquefaction induced phenomena is the determinant factor of the pipelines' anticipated seismic performance, in all three seismic scenarios.

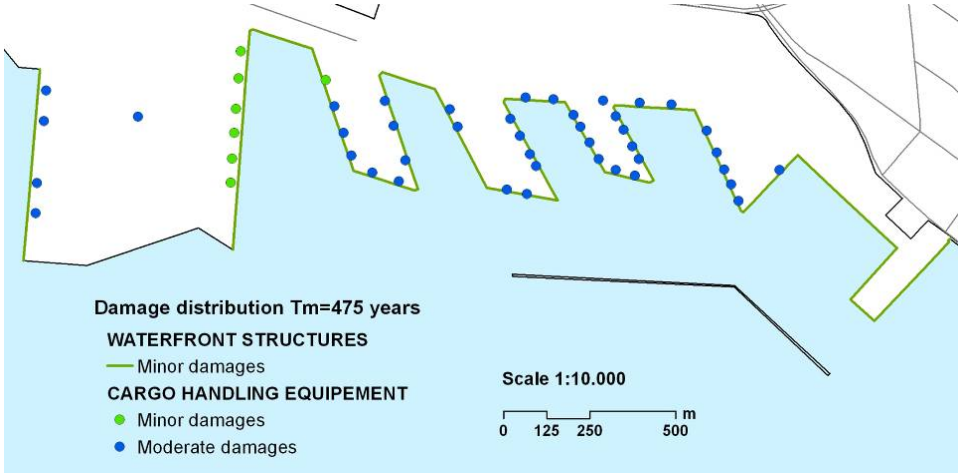


Figure 4. Damage distribution of waterfront structures and cargo handling equipment in Thessaloniki's port due to the effect of both ground failure and shaking (T_m=475 years).

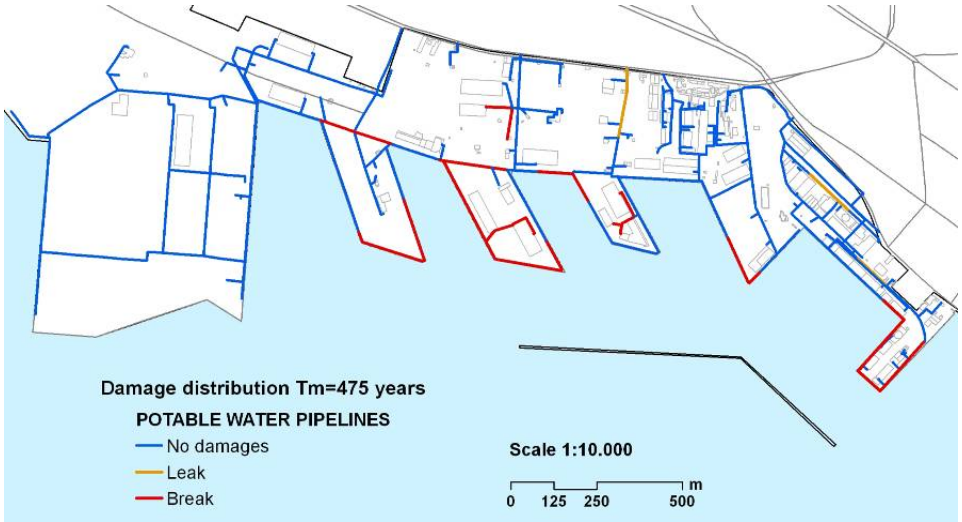


Figure 5. Damage distribution of water system in Thessaloniki's port (T_m=1000 years).

TREATMENT OF INTERACTIONS

Port facilities are complex systems, consisting of different structural and non structural components, utilities and infrastructures, thus concentrating various activities in a limited area. In general, there is a strong level of dependence between all components of a port facility. The multiple interactions existing between them are described by Alexoudi et al. (2009) for the three periods in respect to the occurrence of an earthquake event (normal, crisis and recovery). According to the type and level of interaction, their global seismic performance can be greatly influenced, as a result of their different response for a given level of earthquake intensity. In order to estimate the "propagated" additional vulnerability, a rigorous methodology accounting for all inter and intra dependencies of port components is generally required; the final output should be the assessment of the global performance and reliability of such a complex system under the effect of an earthquake event.

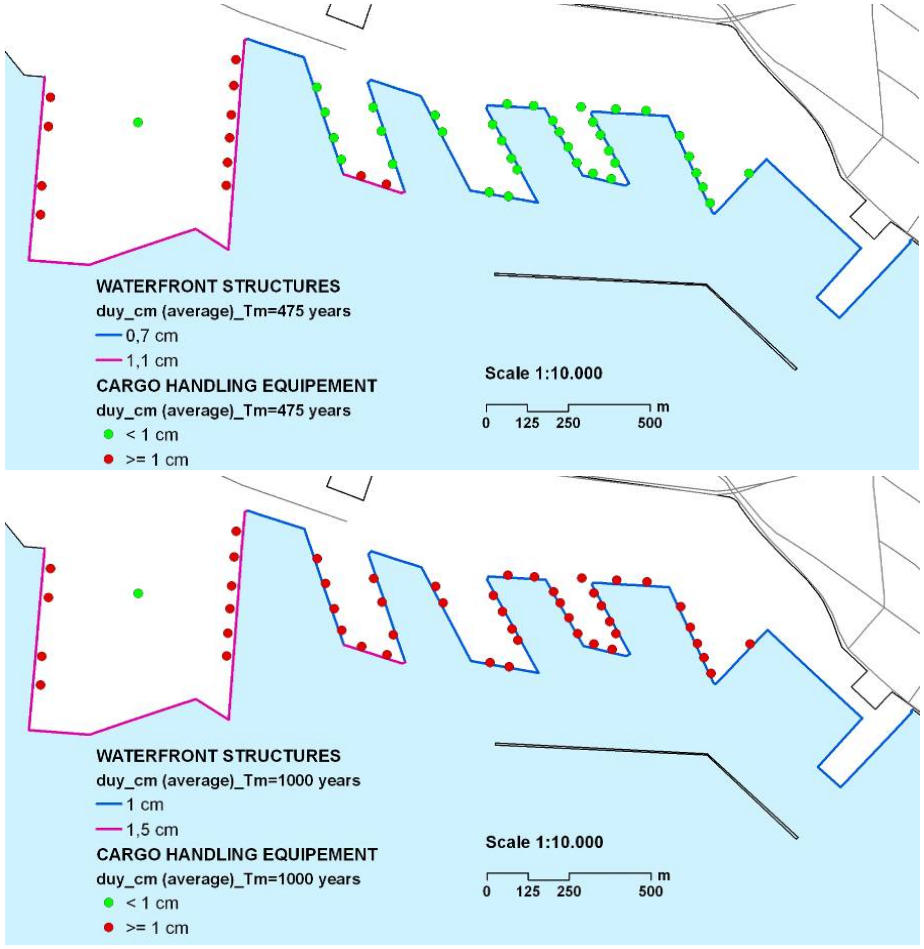


Figure 6. Distribution of differential settlements for the cargo handling equipment of Thessaloniki's port for the seismic scenario with mean return period of (a) 475 and (b) 1000 years.

Herein the interactions due to spatial proximity, and in particular the coupled behavior of the waterfront and other structures are assessed. Typical effects of ground shaking to gravity type quay walls are related to residual movement and tilting of the wall, along with the induced differential displacements behind them and damage to the apron (Pachakis and Kiremidjian, 2004; Werner, 1998). On the other hand, cargo handling equipment components are designed in order to be able to sustain limited differential movements (settlements and/or horizontal displacements) along each crane rail and between waterside and landside

crane rails. Using Geographical Information Systems (GIS), the distribution of anticipated residual differential displacements behind the quay walls (at a 1.0-1.5m distance) is defined for the three seismic scenarios (T_m=100, 475, 1000 years). For this, a relationship between expected values of PGA at outcrop rock conditions and residual differential settlements (average values) is established based on the results of numerical analyses of typical cases (Kakderi and Pitilakis, 2010). Estimated values of residual differential horizontal movements behind the quay walls are negligible; in this case the permanent seaward movements are critical for the functionality of the cranes, especially for the case of the occurrence of liquefaction phenomena, and are previously assessed with the use of fragility curves. Acceptable values of differential movements for the rail mounted jumbo cranes located to the sixth pier of Thessaloniki's port have been provided by the Port Authority (1 cm for differential settlements and 4 cm for differential horizontal displacements). Design information for the components of cargo handling equipment located along the rest of the port's waterfront are not available; thus the conservative assumption of the same values of acceptable displacements is made also for this older pieces of equipment.

Figure 6 illustrates the distribution of differential settlements for the cargo handling equipment of Thessaloniki's port for the seismic scenarios with mean return period of 475 and 1000 years. Despite the fact that for the 475 years scenario, the port's cranes are expected to have only minor to moderate damages when only the effect of seismic shaking and ground failure are taken into consideration, the coupled behaviour of cargo handling equipment with the supporting waterfront structures renders some components non-functional due to the induced differential displacements. For the 1000 years scenario, all equipment components have non-acceptable values of induced differential displacements hampering their functionality. Finally, the small values of residual differential displacements are not expected to induce extra vulnerability to the water supply pipelines located along the port's waterfront structures.

SEISMIC RISK MANAGEMENT

Global value analysis

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 (direct and indirect) that describe the role of each element in the urban system. 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. 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.

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, crisis and post crisis period, 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 (figure 7).

Table 1. Indicators used for the global value analysis and classification of importance of cargo handling equipment of Thessaloniki's port.

CARGO HANDLING EQUIPMENT			PERIOD		
Components	Indicators	Description	Normal	Crisis	Recovery
Operation	1.Capacity	Lifting capacity in tons.	•	•	•
Operation	2.Location	Location / dock-pier located	•	•	•
Operation	3.Cargo capacity	Type of cargo that can be handled (conventional, containers)	•	•	•
Operation	4.Redundancy	Alternative equipment to cover the activity.	-	•	•

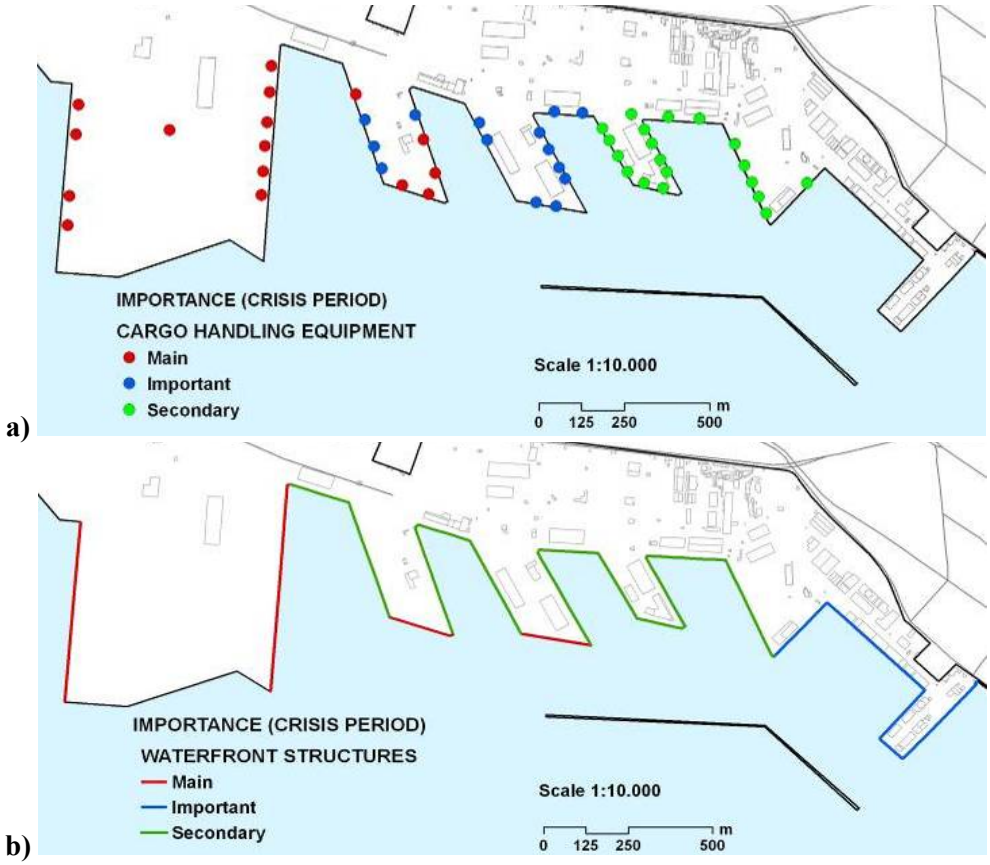


Figure 7. Classification of the importance of (a) cargo handling equipment and (b) waterfront structures of Thessaloniki's port during the crisis period.

Restoration policies and mitigation strategies

One of the main features of an efficient seismic risk management plan is the definition of restoration priorities in order to minimize the necessary time, efforts and cost, providing at the same time optimum serviceability and system reliability and functionality. For the achievement of reliable estimates of the required time for recovery, lifeline owing and operating companies in collaboration with local actors should define restoration curves for every component in each lifeline system, with lifelines experts using basically qualitative evaluations. Respectively, 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" elements at risk provides a prioritization according to the importance of the activities, the socioeconomic values and the daily demand for serviceability. In this way the reliability of the systems is enhanced, allowing a rapid restoration procedure and return to the initial operating conditions.

Table 2. Risk analysis matrix showing cargo handling equipment seismic retrofit priorities.

URBAN RISK/ SEISMIC HAZARD	PRIORITIES		
	Main	Important	Secondary
Complete/ Extensive damages	1st priority	1st priority	2nd priority
Moderate damages	1st priority	2nd priority	3rd priority
Slight/ minor damages	1st priority	2nd priority	4th priority

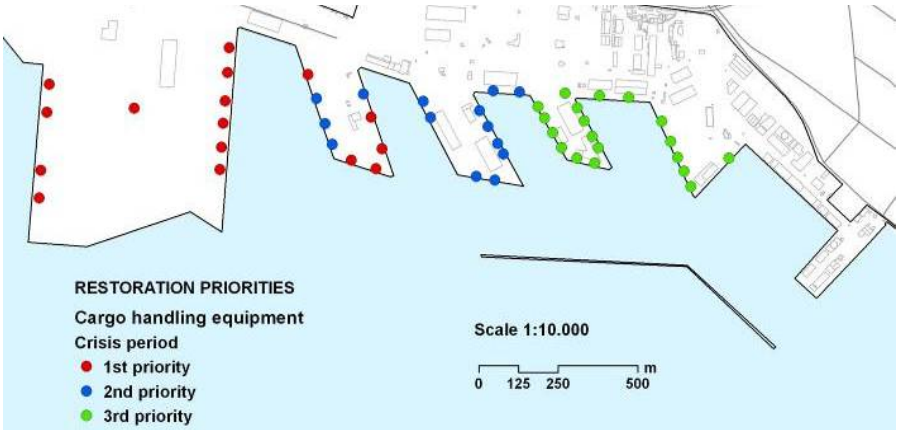


Figure 8. Restoration priorities of cargo handling equipment of Thessaloniki's port during the crisis period (T_m=475 years).

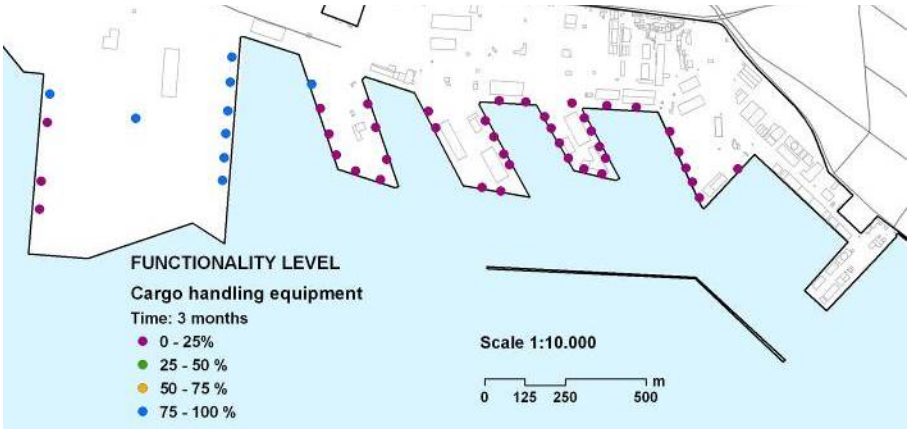


Figure 9. Functionality percentage of cargo handling equipment of Thessaloniki's port in three months time (90 days) after the seismic event (T_m=475 years).

The developed methodology makes use of the "global value" approach for the classification of the importance of lifeline system components (main, important and secondary), in the three periods. 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 given seismic scenario. Nevertheless, the managing company and/or operating organization of each lifeline system plays the determinant role for the definition of priorities, as specific issues should be taken into consideration like financial sources, available material and technical means and managing policies.

Table 2 summarizes the application of the proposed methodology in the cargo handling equipment. Figure 8 illustrates the restoration priorities defined for the same cargo handling equipment during the crisis period, for the 475 years scenario. Restoration curves have been defined in collaboration with the port authority, based on available man power, and capabilities, local experience and expertise. They refer to the

recovery of equipment which has sustained minor to extensive damages; in case of complete damages the component is usually replaced. In figure 9, the functionality level of cargo handling equipment 90 days after the seismic event is illustrated, supposing that the restoration process starts immediately after the earthquake. Assuming that there are only two available teams that could work together, the time requested for the full recovery of all damaged equipment for the 475 years scenario reaches the 6 years, which of course is completely unacceptable, leading to an obvious ex-ante policy decision. Of course in case of severe and spatially expanded earthquake damage to such costly pieces of equipment, a cost-benefit analysis of replacement – recovery is generally foregone. If the effect of interactions with the supporting waterfront structures is also taken into consideration, the need for the application of properly oriented and specified mitigation measures both to waterfront structures and cargo handling equipment is emerged. Alternatively, a post-earthquake management plan could be specified by the Port Authority for the minimization of short and long-term earthquake effects, based on the estimated direct losses and functionality of critical equipment, estimates of restoration time and of course available resources and "acceptable performance criteria" that are set by the Authority for different seismic level inputs.

CONCLUSIONS

Vulnerability assessment and seismic risk management using advanced methodologies is of major importance for the reduction of seismic risk in complex infrastructure systems. When it comes to port facilities, the creation of reliable seismic risk scenarios can lead to efficient pre and post seismic mitigation measures and restoration policies, for the reduction of direct and indirect losses and maximization of port serviceability and system reliability.

In this research paper, the application of a general methodology for the reduction and management of seismic risk of lifelines and infrastructures is presented for the Thessaloniki's port in Greece. 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 three seismic scenarios with mean return periods T_m=100, 475 and 1000 years. Thus, vulnerability and loss estimates for port facilities 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 play the key role in the vulnerability analysis and loss assessment.

Examples of the assessment of potential earthquake losses are presented for selected components and systems within the port facilities, taking also into consideration the multiple interactions existing between them. It is shown that the coupled effect of interacting port components can play a crucial role in their functionality and the system's reliability. On the basis of a global value analysis the different elements at risk, the classification of their importance in different periods is performed. This leads in a prioritization, in a more efficient way, of the pre-earthquake retrofitting actions, and post earthquake restoration efforts. Furthermore, efficient disaster management plans aiming at the minimization of the restoration time, the efforts and the cost, could be implemented.

Based on the previous applications, the development of an advanced and integrated methodological tool for the efficient seismic risk management of complex infrastructures is presented. The actual vulnerability and the associated risk of any element at risk may be reduced with appropriate mitigation countermeasures. The accurate evaluation of the input motion in terms of ground shaking characteristics, for a given probability of occurrence of a specific magnitude seismic event, always plays the decisive role in the risk assessment. The ultimate goal is the minimization of losses and restoration time and cost and the maximization of port functionality and system reliability.

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