6ICEGE
6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch, New Zealand

Effect of Spatial Correlations of Ground Motion Intensities in the Seismic Risk Assessment of Interconnected Lifeline Networks and Transportation Infrastructures

S. Argyroudis[1], J. Selva[2], K. Kakderi[3] and K. Pitilakis[4]

ABSTRACT

A sensitivity study of probabilistic systemic risk analysis of interconnected urban networks to spatially correlated seismic hazard intensities is presented. Probabilistic evaluation of the performance of networks is carried out by means of Monte Carlo simulations. In particular, a scalar random field of a so-called primary Intensity Measure (IM) on rock is sampled, on a regular grid covering the study region, as a function of the sampled magnitude and epicenter location, employing a ground motion prediction equation (GMPE) with spatially correlated residuals. The primary IM is interpolated to all sites and the secondary IMs are sampled from their distribution conditional on the primary IM value. All values are then amplified on the basis of local soil conditions. A geotechnical hazard model is used to sample geotechnical IMs such as permanent ground deformations for components whose fragility model requires one. For each sampled IM set, physical damages to each vulnerable component are sampled from their specific fragility curves, for all the components considered, and the system performance is assessed through systemic analysis. In this case study, we assess Performance Indicators (PIs) for electric power, water and transportation systems (i.e. road and harbor). The overall performance of each network is expressed through the Mean Annual Frequency (MAF) of exceedance of the PIs values (performance curve). Disaggregation and correlation procedures are used to define the contribution of damaged components, seismic zones and magnitudes to the total seismic loss. The sensitivity to spatial correlations is evaluated by analyzing the impact on performance curves and critical components designation when spatial correlations are not taken into consideration.

Introduction

Lifeline and transportation infrastructures are geographically distributed systems that play a vital role for any society, especially in the aftermath of a devastating earthquake. Experience from past earthquakes indicates that they can be particularly vulnerable. The presence of synergies between components within the same system (intra-dependencies) or between different systems (interdependencies) can considerably increase the total losses, making risk models particularly challenging. This assessment is useful for the seismic risk mitigation (e.g., retrofit programs), post-earthquake decision making (e.g., prioritization of restorations), insurance modeling and post-disaster management planning. Due to their spatial extent, lifeline systems are exposed to variable seismic ground motions, often presenting important incoherency (shaking effects) and to

[1]Researcher, PhD, Depart. of Civil Engineering, Aristotle University, Thessaloniki, Greece, sarg@civil.auth.gr
[2]Researcher, PhD, Instituto Nazionale di Geofisica e Vulcanologia (INGV), Bologna, Italy, jacopo.selva@ingv.it
[3]Researcher, PhD, Depart. of Civil Engineering, Aristotle University, Thessaloniki, Greece, kakderi@civil.auth.gr
[4]Professor, Depart. of Civil Engineering, Aristotle University, Thessaloniki, Greece, kpitilak@civil.auth.gr

geotechnical hazards such as liquefaction, landslides and fault ruptures. Seismic risk analysis of such networks requires the consideration of the ground motion spatial correlation that forms the basis for the systemic risk analysis. In the most common probabilistic approach the performance of a network is computed for a significantly large sample of earthquake ground motion events using Monte Carlo simulation (MCS) (e.g., Crowley and Bommer 2006; Stergiou and Kiremidjian 2006; Jayaram and Baker 2010).

In this paper, we apply the general framework developed in the SYNER-G project (Pitilakis et al., 2014) for the seismic vulnerability assessment of infrastructures of urban/regional extension, accounting for inter- and intra-dependencies, as well as for the uncertainties characterizing the problem. Two main steps are considered: 1) the seismic hazard characterization through realizations of ground motions and 2) the probabilistic evaluation of the target system's performance conditional on such realizations. The application includes two systems with different dimensions: i) the overall city of Thessaloniki (Greece), including the electric power network (EPN), the water supply system (WSS), the roadway network (RDN), and ii) the harbor (HBR) along with the EPN. Systemic analysis is performed considering specific interdependencies between systems. Disaggregation and correlation between components' damages and system performance are used to define the contribution of each component, seismic zone and magnitude to the total seismic loss. A sensitivity test to spatial correlations is then performed, by analyzing the impact on the total loss curves and on the definition of 'critical components' when spatial correlations are removed from the model.

Methodology

The objective of the analysis is to evaluate probabilities or mean annual frequency of events defined in terms of loss in performance of networks. The analysis is based on an object-oriented paradigm where systems are described through a set of classes, characterized in terms of attributes and methods, interacting with each other. The physical model for each network starts from the SYNER-G taxonomy and requires: a) for each system within the taxonomy, a description of the functioning of the system (intra-dependencies) under undisturbed and disturbed conditions (i.e., in the damaged state following an earthquake); b) a model for the physical and functional damageability of each component (fragility functions); c) identification of all dependencies between the systems (inter-dependencies); and d) definition of adequate Performance Indicators (PIs) for components and systems (Pitilakis et al. 2014).

The computational modules include the following main models: a) *seismic hazard class* modeling earthquake events and corresponding seismic intensity parameters, b) *network class* modeling physical damages of networks' components and the overall system's performance, c) *interdependencies models* simulating specific interactions between systems. The hazard model provides the means for: 1) sampling events in terms of location (epicentre), magnitude and faulting style according to the seismicity of the study region and 2) maps of sampled correlated seismic intensities at the sites of the vulnerable components in the infrastructure ('shakefields' method, Weatherill et al. 2014). When the fragility of components is expressed with different IMs, the model assesses them consistently. Probabilistic evaluation of the performance of networks is carried out by means of Monte Carlo simulations. For simplicity, the methodology is focused on performance without reparations (emergency phase). The final goal is to assess the exceedance probability of different levels of performance loss for each system under the effect of any possible seismic input. This output, represents the performance curve, and is the equivalent of risk curves for non-systemic probabilistic assessments in single (e.g., PEER formula, Cornell and Krawinkler, 2000) and/or multi-risk (e.g., Selva, 2013) analysis. Further specifications for each physical system are given in Pitilakis et al. (2014).

Description of the Case Study

Seismic Hazard

Five seismic zones with M_{min}=5.5 and M_{max}=7.5 are selected based on the results of SHARE European research project (Giardini et al. 2013). In addition, a seismic source representing the destructive earthquake (M=6.4, 20 June 1978) that caused extensive damage in the study area is adopted for a specific scenario analysis. A Monte Carlo simulation (MCS) is carried out sampling seismic events for the considered zones following the ‘shakefield’ approach. In particular, earthquakes are sampled from the seismic zones in terms of localization and magnitude and local intensity values at the sites of vulnerable components are evaluated. First, a scalar random field of a so-called primary Intensity Measure (IM) on rock is sampled (i.e. peak ground acceleration, PGA) on a regular grid covering the study region, as a function of the sampled magnitude and epicenter location, employing the ground motion prediction equation (GMPE) by Akkar and Bommer (2010). The spatial variability for PGA is modelled using the correlation models provided by Jayaram and Baker (2009) as adapted for European events consistently with the selected GMPE (Esposito and Iervolino, 2011). For each site of the grid, the averages of primary IM from the specified GMPE are calculated, and the residuals are sampled from a random field of spatially correlated Gaussian variables. Then, the primary IM is interpolated to all vulnerable sites and the secondary IMs are sampled from their distribution conditional on the primary IM value. All values are amplified on the basis of local soil conditions using the amplification factors proposed in EC8 (2004). The geotechnical hazard approach proposed in HAZUS is used to sample permanent ground deformations (PGD) due to liquefaction for components whose fragility model requires one (e.g. pipelines, quaywalls). In case of the specific scenario analysis, only shakefields are sampled for the selected event.

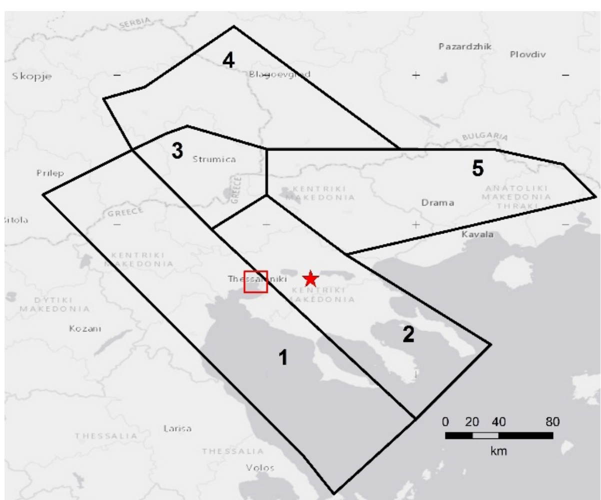

Figure 1. Seismic zones, epicenter of M6.4, 1978 event (red star) and study area (red rectangle).

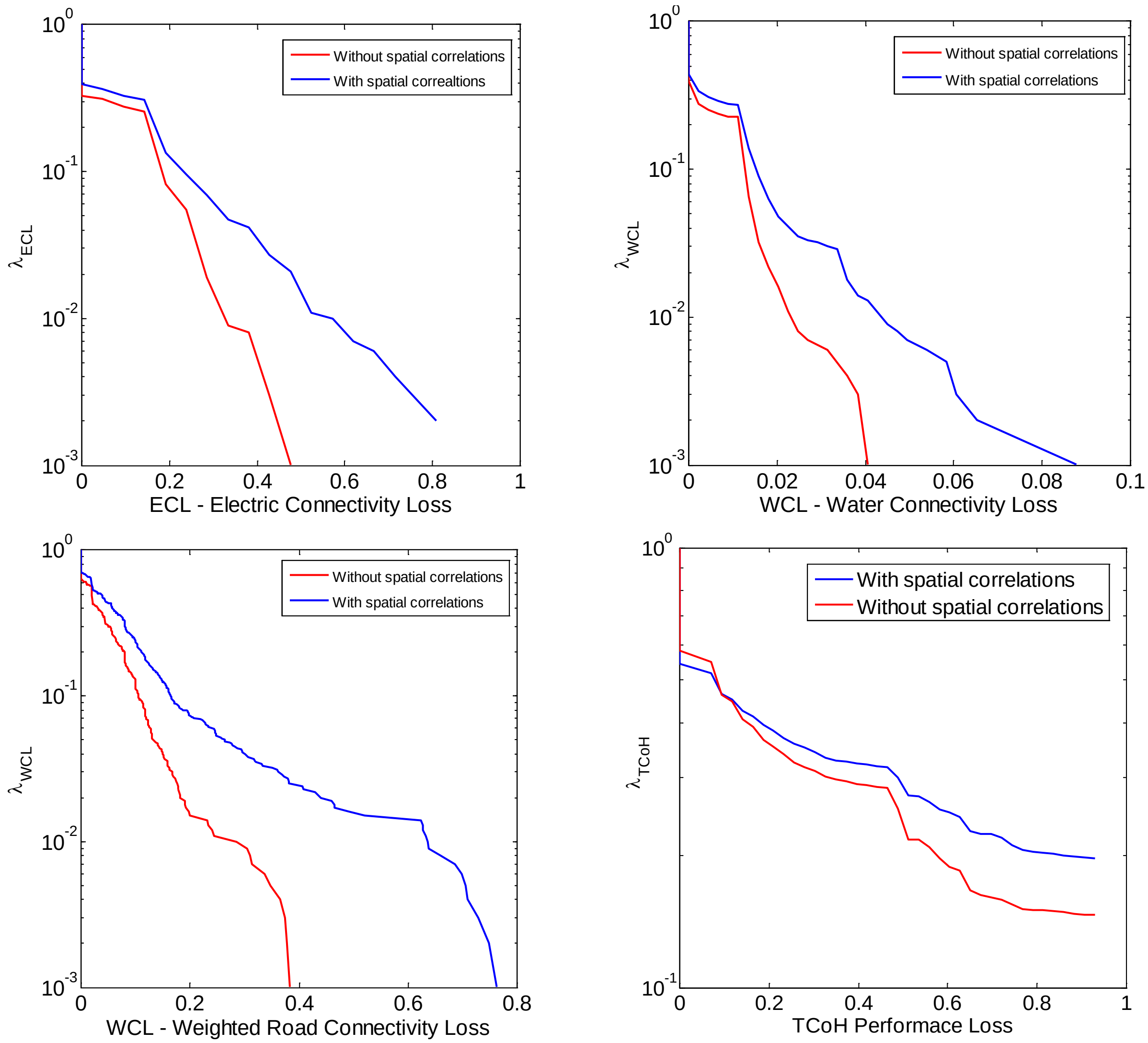

Figure 2. MAF curves for performance loss (λ for EPN, WSS, RDN, HBR) with and without considering spatial correlations of IMs (1000 runs, one seismic scenario, M=6.5).

Systems' Specifications

Electric Power Network (EPN) is composed of 30 nodes and 29 edges. Nodes consists of 1 generator, 8 transmission substations and 21 demand points located at WSS pumping stations. Only substations are considered as vulnerable components, while edges are non-vulnerable transmission lines connecting the generator with the substations and the substations with the demand points. The adopted PI is the Electric power Connectivity Loss (ECL), which relates the number of connected nodes in seismic and non-seismic conditions. *Water Supply System (WSS)* is comprised of 477 nodes and 601 edges with total length of about 280 km. The nodes consist of 445 demand nodes, 21 pumping stations and 11 tanks; the latter considered as water sources for the system. Pipelines are the vulnerable elements; their repair rate (RR) is correlated to peak ground velocity (PGV) and permanent ground deformation (PGD). The considered PI is the Water Connectivity Loss (WCL), which relates the number of connected nodes in seismic and non-seismic conditions. *Roadway Network (RDN)* is composed of 594 nodes, divided to 15 external nodes, 127 Traffic Analysis Zone (TAZ) centroids and 452 simple intersections, and 674 edges. Road segments and bridges are vulnerable due to liquefaction (PGD) and ground shaking (PGA) respectively. The effect of collapsed overpasses and buildings to the road functionality is considered. The PI is the Weighted Connectivity Loss (WCL), which measures the average reduction in the ability of sinks to receive flow from sources and weights the number of sources connected to each sink. *Harbor (HBR)* includes 72 nodes (pier-ends and cranes) and 17 edges (gravity type waterfronts). Cranes and waterfronts are vulnerable due to PGD and PGA. In addition, the EPN sub-network within the HBR is considered, consisting of 17 distribution substations (vulnerable components), 74 edges and 48 demand nodes (cranes). This sub-network is supplied by the EPN of the city and supplies electric power to cranes. The PI demonstrated here is the Total Containers Handled (TCoH) per day (more details in Pitilakis et al. 2014).

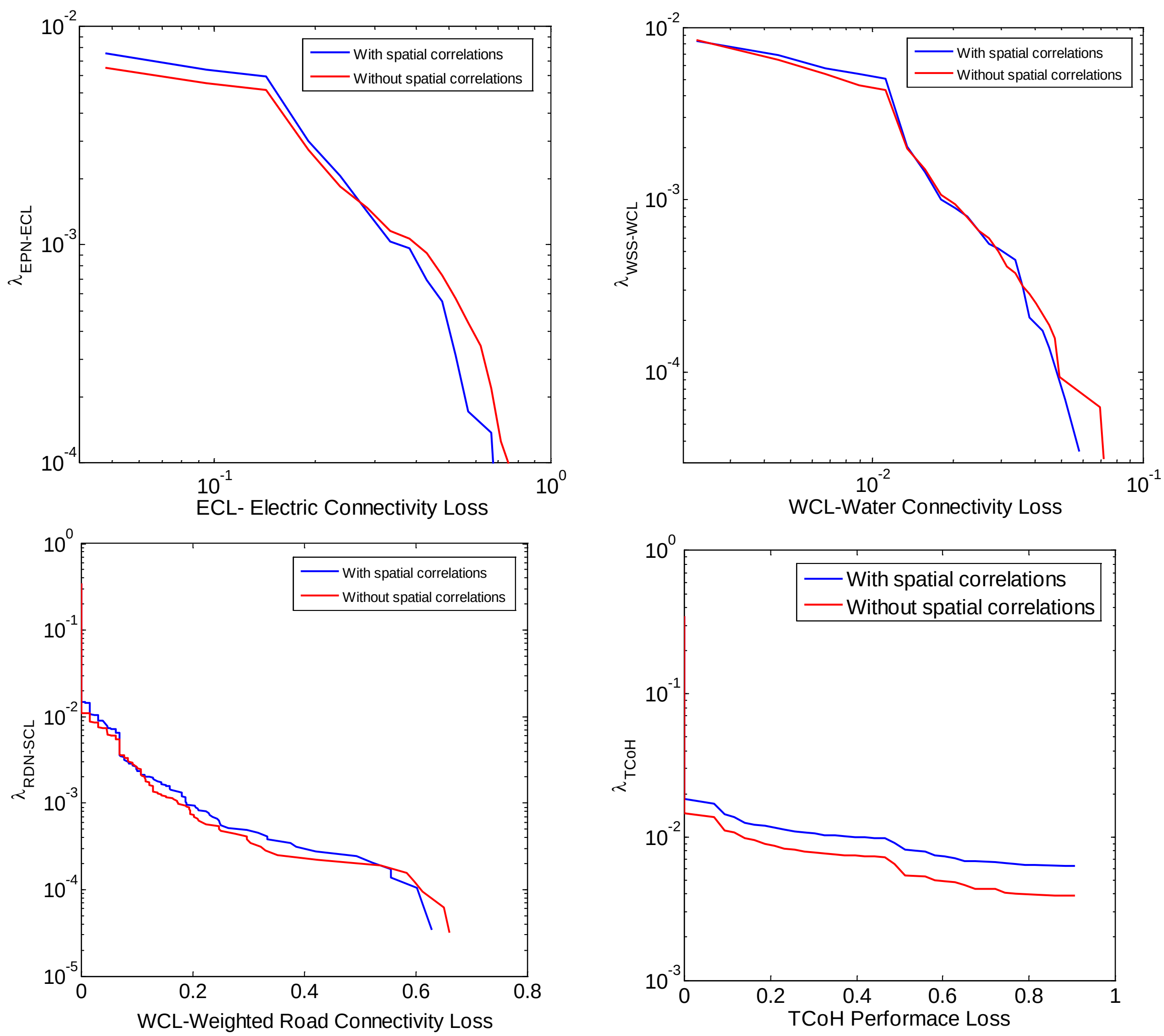

Figure 3. MAF curves for performance loss (λ for EPN, WSS, RDN, HBR) with and without considering spatial correlations of IMs (10000 runs, 5 seismic zones, M=5.5-7.5).

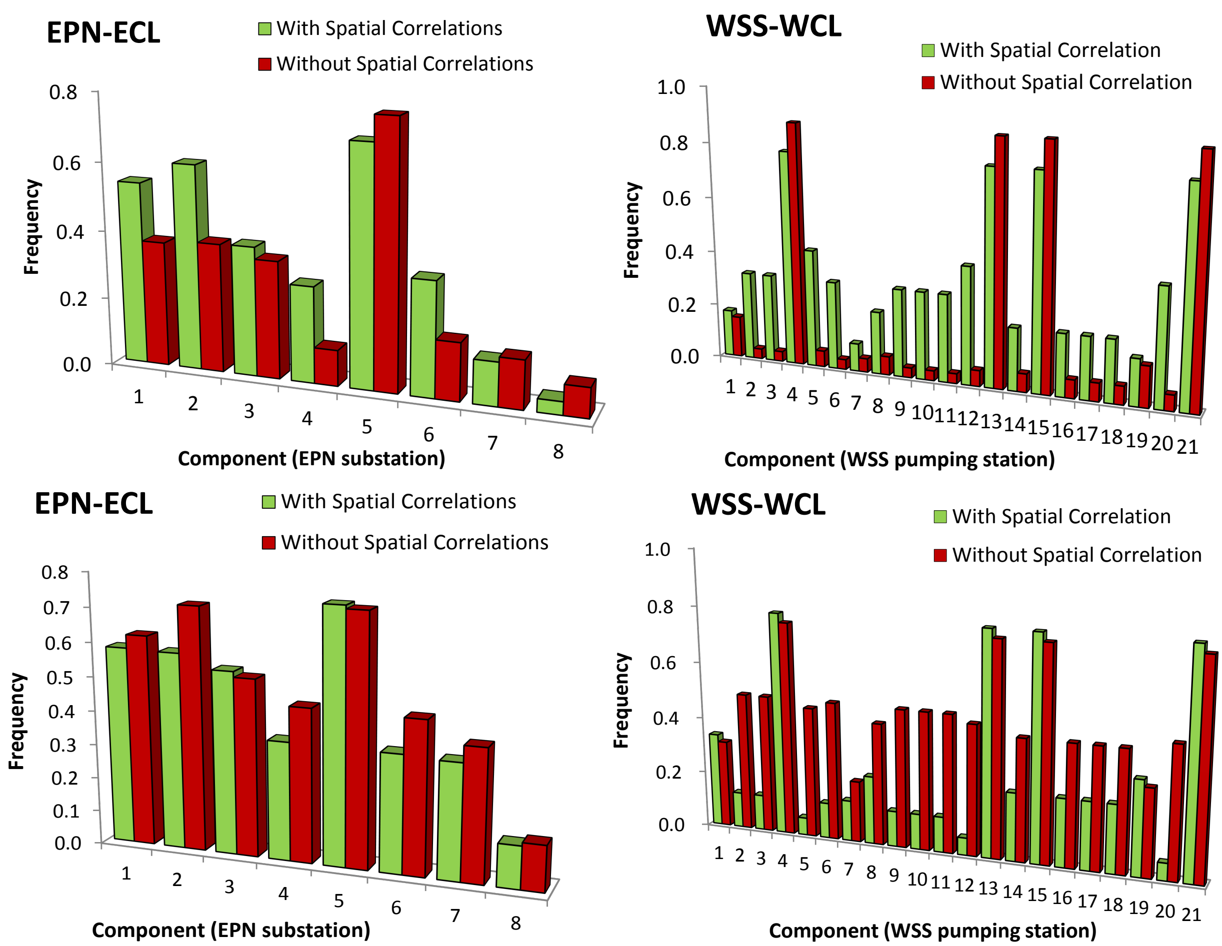

Figure 4. Correlation of components' functionality to system PI with and without considering spatial correlations of IMs (up: 1 seismic scenario, down: 5 seismic zones)

Application Results

In Figures 2 and 3 we show the differences in the estimated Mean Annual Frequency (MAF) of exceedance for EPN, WSS and RDN connectivity loss and HBR performance loss, with and without considering spatial correlations of the IMs. The results are based on 1,000 runs for a specific seismic scenario (M=6.5) (Fig. 2) and on 10,000 runs (MCS) for the five seismic zones (M=5.5-7.5) (Fig. 3). In Figure 3 we show the correlation of non-functional components (water pumping stations and electric power substations) to the corresponding system's PI, with and without considering spatial correlations of the IMs. In this way the most correlated components to the system's PI can be defined for all possible events or for a specific seismic scenario, that is, the components that mostly control the performance of the system. In Figure 4 we show the contribution of various magnitudes and seismic zones to the probability of exceeding a specific loss threshold, with and without considering spatial correlations of the IMs.

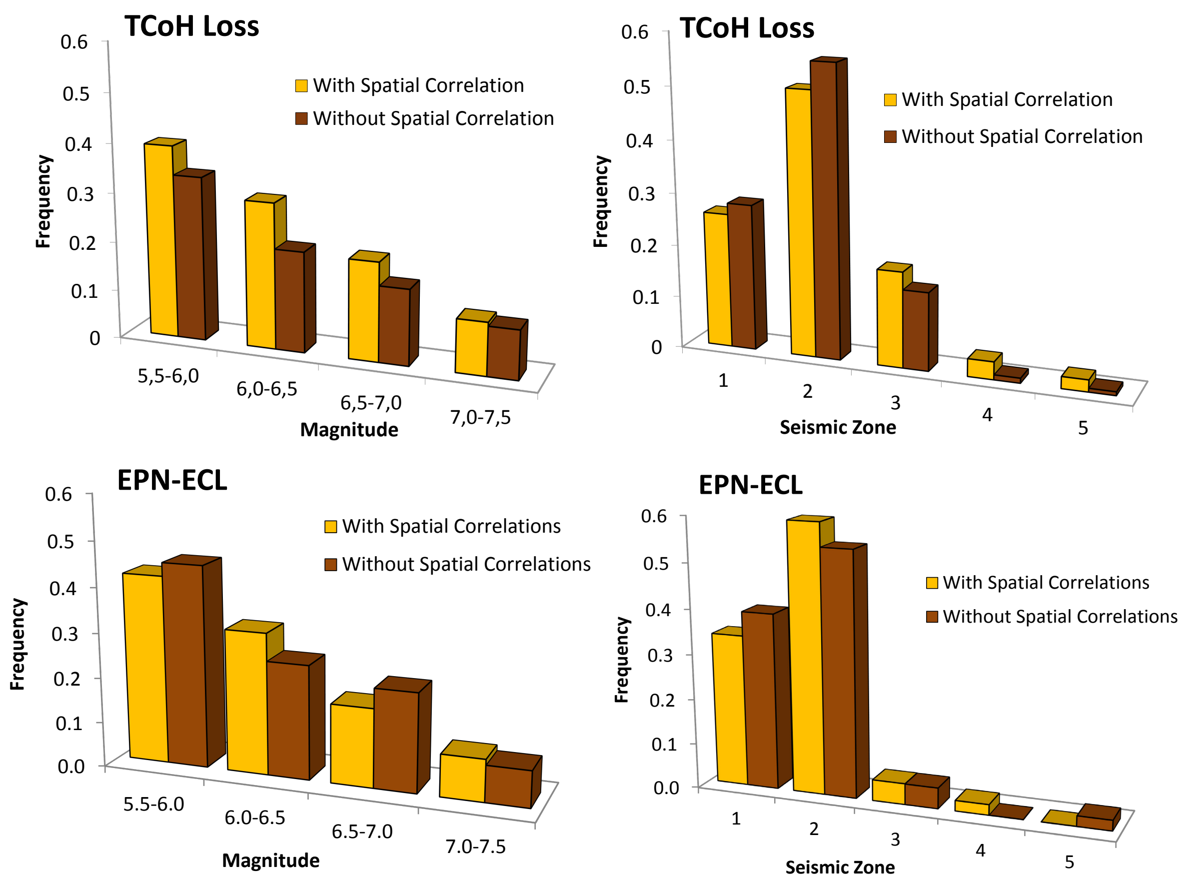

Figure 5. Disaggregation to magnitudes and seismic zones for given PI exceedance (5% for TCoH, 20% for ECL), with and without considering spatial correlations of IMs.

Discussion and Conclusions

In case of one seismic scenario it is observed that when spatial correlations of IMs are not considered, the expected losses can be underestimated (Figure 2). In particular, neglecting spatial correlations results to considerably lower losses at lower annual probabilities of exceedance. In this case random IMs are computed (based on the GMPE), which are not correlated for adjacent cells/components, and consequently the estimated damages and losses are also not correlated. For example, two adjacent components can have completely different seismic demand (IM), and thus completely different damages, which is rather not realistic, resulting to bias of the expected losses. It is also observed (Figure 4 up) that, in both cases (with/without spatial correlations) the most correlated (e.g. the four most correlated) components are identical. However, the 'critical' components seem to emerge better when no spatial correlations are considered. This is maybe related to the fact that correlated damages for spatially proximate components may induce a 'false' correlation between the PI and a component that is not relevant for the system performance, but it is spatially close to another component that is actually relevant for the system. In case of all possible seismic scenarios (Figure 3) the differences in MAF curves are not as clear as before for the EPN, WSS and RDN which are systems distributed in a large area (up to 180 sq. km) with the exception of the HBR that is extended in a smaller area (3 sq. km). This may be due to the fact that the most important sources for the hazard are the local ones (Zone 1

& 2, Figure 5), and most of components of the larger systems are quite far away to each other and spread all over the city. Thus, earthquakes occurring within the city area may dominate the performance loss, and systems' components are spread around the epicenters. On the opposite, HBR is localized, with components very close to each other, and earthquakes have a small chance of being localized within such a limited area. Similar observations on the reduced impact of spatial correlations for larger spatial 'footprint' of an exposure portfolio have been made by Weatherill et al. (2015). The same trends for the most correlated components are derived from Figure 3 (down) as for the case of the single scenario. The disaggregation also shows (Figure 5) that for both cases (with and without spatial correlations) smaller magnitudes contribute more to the loss (for the considered low thresholds), since those events are more probable than larger ones. However, the likelihood of seismic scenarios depends on the considered loss threshold, the proximity of networks to the seismic zones and the seismicity of the zones. On the other hand, different magnitudes and seismic sources can have similar contribution to a given loss exceedance; therefore a single scenario cannot be determined as the most probable one.

Acknowledgments

We would like to thank the support provided by the General Secretariat for Research and Technology, Greece (Grant No: 11ΣΥΝ_8_1577, ESPA 2007-2013).

References

Akkar S, Bommer JJ. Empirical equations for the prediction of PGA, PGV and spectral accelerations in Europe, the Mediterranean region and the Middle East. *Seismological Research Letters* 2010; **812**:195-206.

Cornell C, Krawinkler H. Progress and challenges in seismic performance assessment. *PEER News* 2000; **3**(2).

Crowley H, Bommer J. Modelling seismic hazard in earthquake loss models with spatially distributed exposure. *Bulletin of Earthquake Engineering* 2006; **4**(3):249–273.

Esposito S, Iervolino, I. PGA and PGV spatial correlation models based on European multi-event datasets. *Bulletin of the Seismological Society of America* 2011; **101**(5):2532-2541.

Eurocode 8, EC8. *Design of structures for earthquake resistance*. European Committee for Standardisation. The European Standard EN 1998-1, 2008.

Giardini D et al. Seismic Hazard Harmonization in Europe (SHARE). Online Data Resource, http://portal.share-eu.org:8080/jetspeed/portal/, doi: 10.12686/SED-00000001-SHARE, 2013.

Jayaram N, Baker J. Correlation model of spatially distributed ground motion intensities. *Earthquake Engineering and Structural Dynamics* 2009; **38**:1687-1708.

Jayaram N, Baker J. Efficient sampling and data reduction techniques for probabilistic seismic lifeline risk assessment. *Earthquake Engineering & Structural Dynamics* 2010; **39**(10): 1109-1131.

Pitilakis K, Franchin P, Khazai B, Wenzel H (eds). SYNER-G: Systemic seismic vulnerability and risk assessment of complex urban, utility, lifeline systems and critical facilities. Methodology and applications. Series*: Geotechnical, Geological and Earthquake Eng*., **31**, Springer, Netherlands, 2014.

Selva J. Long-term multi-risk assessment: statistical treatment of interaction among risks, *Natural Hazards* 2013; **67**(2):701-722.

Stergiou E, Kiremidjian AS. *Treatment of uncertainties in seismic risk analysis of transportation systems*. Engineer Thesis, Stanford University, 2006.

Weatherill G, Esposito S, Iervolino I, Franchin P, Cavalieri F. Framework for seismic hazard analysis of spatially distributed systems, in: K. Pitilakis et al. (eds). *SYNER-G: Systemic seismic vulnerability and risk assessment of* *complex urban, utility, lifeline systems and critical facilities. Methodology and applications*. Springer, Netherlands, 2014.

Weatherill G, Silva V, Crowley H, Bazzurro P. Exploring the impact of spatial correlations and uncertainties for portfolio analysis in probabilistic seismic loss estimation, *Bull Earthquake Eng* 2015; **13**: 957-981.