6th European Transport Research Conference
MOVING FORWARD:
Innovative Solutions for Tomorrow's Mobility
PGE Narodowy, Warsaw, Poland - 18-21 April 2016

Proceedings of 6th Transport Research Arena, April 18-21, 2016, Warsaw, Poland

Systemic vulnerability and risk assessment of transportation systems under natural hazards towards more resilient and robust infrastructures

K. Pitilakis [a,]*, S. Argyroudis [a], K. Kakderi [a], J. Selva [b]

[a]*Aristotle University, Thessaloniki, Greece*
[b]*Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy*

Abstract

Transportation infrastructures are complex systems of various connected components like bridges, roads, tunnels, embankments, retaining walls in case of a highway system or wharfs, cranes, buildings, utility systems in case of port facilities. Due to their spatial extent, they are exposed to variable natural hazards such as earthquakes, tsunami or landslides. Experience from past disastrous events shows that transportation infrastructures are quite vulnerable due to the lack of redundancy, the lengthy repair time, the rerouting difficulties or the cascading failures and interdependencies. Their damage could be greatly disruptive in terms of safety of life, business disruption, access to emergency services and key lifelines utilities, rescue operations and socio-economic impacts. Therefore, in terms of resilience it is important to recognize and quantify the risks and global losses associated to damages of transportation systems and to establish efficient risk mitigation strategies. These include, among others, enhancement of emergency preparedness, strengthening of existing structures and improvement of the recovery planning.
Herein an integrated framework for the probabilistic systemic vulnerability and risk assessment of transportation and utility networks is presented, based on the achievements of the recently completed EC project SYNER-G (www.syner-g.eu) and the ongoing EC project STREST (www.strest-eu.org). The infrastructure is modeled according to a detailed taxonomy. The framework encompasses in an integrated fashion all aspects in the chain, from regional hazard to fragility assessment of components to the socio-economic impacts of a natural disaster, accounting for relevant uncertainties within an efficient quantitative simulation scheme, and modeling interactions between multiple component systems in the taxonomy. Selected Performance Indicators (PIs) are calculated for each network based on the estimated damages and functionality losses of the different components under the given hazards.
The methodology and tools are demonstrated through case studies in the road network and the harbor of Thessaloniki city, Greece, under seismic hazard and associated geotechnical hazards (i.e. soil liquefaction). The applications include assessments of systems' performance considering the spatial seismic hazard with correlation of ground motion intensities, the vulnerability of the network components, and the effect of interactions within the system, as well as, between components of different systems. In particular, road disruptions can be caused due to direct damage of road segments and bridges, as well as building and overpass

* Corresponding author. Tel.: +30.2310.995693; fax: +30.2310.995619.
E-mail address: kpitilak@civil.auth.gr

collapses. Harbor operations can be disturbed due to failures of waterfront structures and cargo handling equipment, as well as disruptions to the electric power supply and building collapses. The systemic risk for the road network and harbor is calculated, specifically focusing on the short-term impact of seismic events (just after the earthquake) and the risk curves (i.e. mean annual rates of exceedance for loss in performance of the infrastructures) are provided. The significant elements for the functionality of each system are defined through correlation factors to the system PIs. Such results can contribute to the decision-making regarding the enhancement of existing and the robust development of new infrastructures in the frame of safety and resiliency.

Keywords: Transportation infrastructures; interdependencies; risk assessment; roadway; harbor

1. Introduction

Infrastructure resilience, particularly related to transportation networks, is essential to any society, especially when considering natural (and man-made) disasters. Serious disruption to transportation infrastructure can have catastrophic impact on the ability of the community, business and economy to respond to and recover from a disaster. The world's dependence on transportation systems is continually growing as regional, national, and international societal interaction and economic activities become more fully integrated and interdependent. Recent events around the globe, including significant seismic events in developed countries such as New Zealand, Chile and Japan, have increased the awareness and importance of this fact. Hence, it is of utmost importance for researchers and stakeholders to address the issue of designing resilient transportation infrastructures.

In particular, transportation infrastructures must be able to withstand stress, maintain baseline service levels, and be stout in physical design and operational concept in order to provide restoration to the system. Resilient transportation systems may reduce the probability of failure within the system as well as reduce the consequences of any failure that may occur, thus improving the time for recovery. Moreover, analyzing the resilience of a transportation network will aid decision-makers in identifying specific weaknesses within the network, thus allowing the proper prioritization of investments and mitigation actions (Freckleton et al., 2012).

The concept of resilience is broadly applied throughout many different fields of study (e.g., engineering, psychology, sociology, and economics). In earthquake engineering, researchers have defined seismic resilience, particularly, as the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and reduce the effects of future earthquakes (Bruneau et al., 2003; Tierney and Bruneau, 2007). Cimellaro et al. (2010) define resilience as "a function indicating the capability to sustain a level of functionality or performance for a given building, bridge, lifeline network, or community, over a period defined as the control time that is usually decided by owners, or society". Freckleton et al. (2012) gathered all conceptual frameworks that have been created in order to define and "measure" resilience within the area of transportation. Thus, transportation resilience can be defined in different ways:

- The ability for the system to maintain its demonstrated level of service or to restore itself to that level of service in a specified timeframe (Heaslip et al., 2009).
- A characteristic that enables the system to compensate for losses and allows the system to function even when infrastructure is damaged or destroyed (Battelle, 2007).
- A system's ability to accommodate variable and unexpected conditions without catastrophic failure (Litman, 2010).
- The ability for the system to absorb the consequences of disruptions to reduce the impacts of disruptions and maintain freight mobility (Ta et al., 2009).

In general, it is observed that there is no widely accepted measure for resilience of transportation infrastructure for any mode of transportation. The review on disaster resilience of transportation infrastructure and seaports made by Madhusudan and Ganapathy (2011) exposes the lack of systematic research on the impact of disasters on the resilience of transportation and port infrastructure. Previous studies are limited to setting levels of service or performance measures for specific elements (e.g. roads, Brabhaharan et al., 2006) or qualitative measurements of resilience (Bruneau et al., 2003; Murray-Tuite, 2006; Heaslip et al., 2009; Mostashari et al., 2009; Dantas and Giovinazzi, 2010; Freckleton et al., 2012; Pant, 2012; Lee et al., 2013; Hughes and Healy, 2014). On the other hand, those which have attempted to develop quantitative metrics (indices) through more detailed analysis and modeling (Hamad and Kikuchi, 2002; Brenkert and Malone, 2004; Mayunga, 2007; Heaslip et al., 2010) do not take into consideration important issues, like specific typologies of network components, spatial variability of ground motion and secondary induced hazards (e.g., geotechnical hazards) observed in geographically distributed systems, interdependencies between networks, system-level performance measures and uncertainties. Moreover, in the majority of previous studies, focus has been given to roadway system as main type of transportation infrastructure, leaving behind other transportation systems like railways, harbor facilities, etc.

Herein, an integrated framework for the probabilistic systemic vulnerability and risk assessment of transportation and utility networks is presented, based on the achievements of the recently completed EC project SYNER-G (www.syner-g.eu) and the ongoing EC project STREST (www.strest-eu.org). The framework encompasses in an integrated fashion all aspects in the chain, from regional hazard to fragility assessment of components to the socio-economic impacts of a natural disaster, accounting for relevant uncertainties within an efficient quantitative simulation scheme, and modeling interactions between multiple component systems in the taxonomy. Selected Performance Indicators (PIs) are calculated for each network based on the estimated damages and functionality losses of the different components under the given hazards. Ultimately, this research contributes to the assessment of the impact of disasters on the resilience and robustness of transportation and port infrastructure through a risk-based performance analysis on system level and through identification of significant components and functions for minimizing losses and social effects.

In the following paragraphs, the main methodological framework is presented and then the methodology and tools are demonstrated through case studies in the road network and the harbor of Thessaloniki city, Greece, under seismic hazard and associated geotechnical hazards (i.e. soil liquefaction).

2. 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 intensities measures (IMs) 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).

This methodology potentially accounts also for epistemic uncertainty, taking into consideration uncertainty in models' parameters (through a hierarchical acyclical chain of probabilistic distributions). In addition, it can be applied within techniques like Logic Trees or Ensemble Modeling (Selva et al., 2015) to quantify also epistemic uncertainty. Even though the original methodology has been specifically designed for seismic hazard only (Cavalieri et al., 2012; Argyroudis et al., 2015), it can be straightforwardly extended to other single natural hazards. On the contrary, further developments are required if multiple hazards should be considered.

Transportation networks, due to their wide and spatial extent are exposed to multiple natural hazards, namely earthquakes, volcanic eruptions, landslides, tsunamis, river floods, wildfires, winter storms, fluvial and coastal flooding. In case of earthquakes, they are exposed to variable seismic ground motions often with important incoherency (shaking effects) and also to geotechnical hazards (permanent ground deformations), resulted from fault crossing, landslides and liquefaction (e.g. lateral spreading, settlements, buoyancy effects). In particular, slope failures due to earthquakes or intense precipitation may trigger permanent ground displacements and massive soil movements in landslide prone areas resulting to severe damages and losses to transportation infrastructures. Therefore the vulnerability of transportation components (e.g. roads, tunnels, embankments, retaining walls, railway tracks) exposed to slope failures should be evaluated based on models that correlate damage with intensity measures accounting for slope geometry and soil properties. A review of predictive models for co-seismic slope displacements is made by Pitilakis and Fotopoulou (2015), together with a coherent approach to evaluate seismic vulnerability of structures founded on precarious landslide slopes. Winter et al. (2014) developed an expert judgement approach to determine the physical vulnerability of roads to debris flow. Finally, available fragility models for seismic and geotechnical hazards are presented by Argyroudis and Kaynia (2014) for highway and railway components and by Kakderi and Pitilakis (2014) for harbor infrastructures.

3. Case study 1: Road network of Thessaloniki city

3.1. Seismic hazard

Five seismic zones with Mmin = 5.5 and Mmax = 7.5 are selected based on the results of SHARE European research project (Giardini et al., 2013). A Monte Carlo Simulation (MCS) is carried out sampling seismic events for these zones in terms of localization and magnitude. The selected primary IM is peak ground acceleration (PGA) since most of the fragility models used in the analysis are given as a function of this IM. The ground motion prediction equation (GMPE) introduced by Akkar and Bommer (2010) is applied for the estimation of the ground motion parameters on rock. The spatial variability for PGA is modeled using the correlation models provided by Jayaram and Baker (2009) as adapted for European events consistently with the selected GMPE (Esposito and Iervolino, 2011). The primary IM is then retrieved at vulnerable sites by distance-based interpolation and finally the local IM is sampled conditionally on primary IM. Site conditions are considered through the amplification factors proposed in EC8 (2004) in accordance with the site classes that were defined in the study area. The approach proposed in HAZUS (NIBS, 2004) is used to sample permanent ground deformations (PGD) due to liquefaction for components whose fragility model requires one (e.g. pavements or quaywalls).

3.2. System characteristics

In this case study the main road network (RDN) of the urban area is considered together with the ring road and the main exits of the city where the majority of bridges and overpasses are located. The road network is composed of 594 nodes and 674 edges. The nodes are subdivided into 15 external nodes, 127 traffic analysis zones (TAZs) centroids and 452 simple intersections; 495 edges are two-ways roads, while 179 are one-way roads. Edges are the vulnerable components, classified into road pavements and bridges, with fragility models expressed in terms of permanent ground deformation (PGD) due to liquefaction and PGA for ground shaking, respectively. The building stock is also included in the analysis in order to estimate the road blockages due to collapses of adjacent buildings. The performance of the network is measured based on the connectivity loss that expresses the average reduction in the ability of sinks to receive flow from sources. Simple connectivity loss (SCL) measures the connected nodes (TAZs), while weighted connectivity loss (WCL) weights the number of connected nodes based on the travel time. More details on the system configuration, the fragility models and the analysis models are given in Argyroudis et al. (2015).

3.3. Application and results

The analysis results as obtained from a plain MCS are presented in Fig. 1 with reference to the 'closed' road network due to building and overpass collapses as well as direct damage to pavements and bridges. In practice, the network is analysed for each sampled event and the results are aggregated all over the sampled events, in order to numerically obtain the marginal distribution of performance loss. The same figure compares the estimated mean annual frequency (MAF) of exceedance curves for SCL when the road blockage due to collapsed building is not considered in the analysis. This interaction has a significant impact, especially for low annual rates. Fig. 2 shows the level of correlation between the connectivity loss and road blockages due to building collapses and damages in bridges and road segments. This correlation analysis is performed in order to identify components that specifically tend to control PIs, and thus, that can be considered critical for the performance of RDN. Relatively higher correlations are found for RDN edges blocked by building collapse, demonstrating the importance of this failure mechanism for RDN analysis. In particular, the most correlated blocked roads are mainly in the historical centre of the city, where the vulnerability of buildings (mostly built with the oldest seismic code in Greece) is higher and the road-to-building distances are shorter. Several road segments in the city centre and the southeast part of the study area present a medium correlation due to building collapses. The high correlation of broken edges near the coast is instead related to ground failure due to liquefaction, while the other broken edges are mainly damaged bridges. The latter is attributed to highly vulnerable bridges (i.e. older structures with poor seismic design).

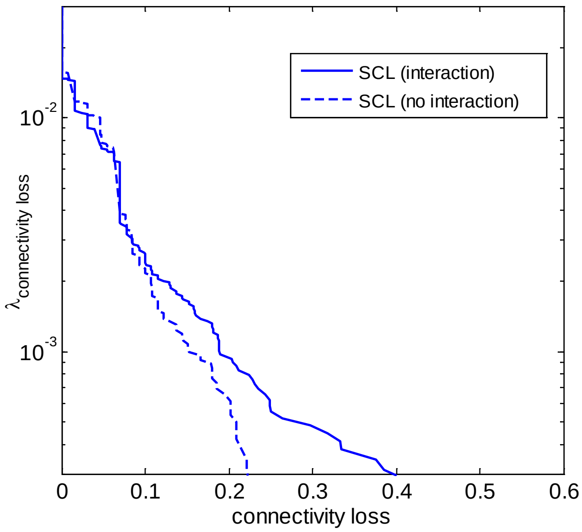

Fig. 1. MAF curves for simple connectivity loss (SCL) with and without interaction with building collapses.

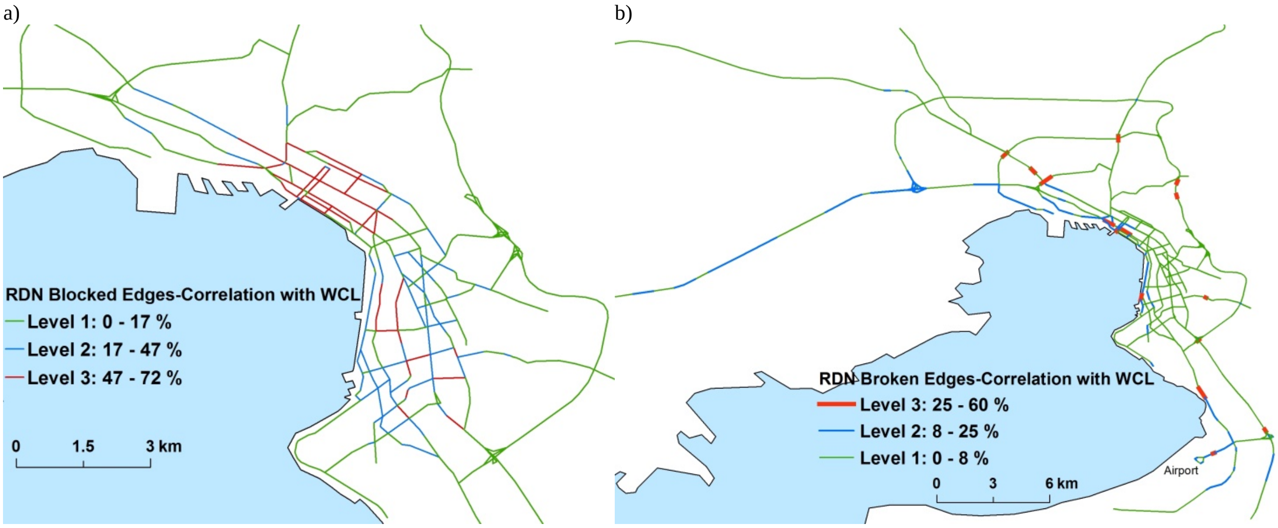

Fig. 2. Correlation of a) blocked by buildings edges and b) broken edges (damaged bridges and road segments) to road network connectivity.

4. Case study 2: Harbor of Thessaloniki city

The port of Thessaloniki constitutes the most important port in Northern Greece and one of the most important ports in Southeast Europe. The installations include 6 piers spreading on a 6,200 meter-long quay and a sea depth down to 12 meters, with open and indoors storage areas spreading on a total of 600,000 square meters, suitable for servicing all types of cargo as well as passenger traffic. It trades approximately 16,000,000 tons of cargo annually, and has a capacity of 370,000 containers. The port also has a variety of utilities and infrastructural components, 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. What is of major importance is that soil formations are characterized by very high liquefaction susceptibility, mainly due to loose, saturated, silty-sandy soils that prevail at the area. The seismic and liquefaction hazards are assessed as in road network case study.

4.1. System characteristics

Following the methodological framework for the systemic analysis, waterfront structures, cargo handling equipment, power supply system, roadway system and buildings are examined. Harbor's class modelling (HBR) includes 72 nodes (pier-ends and cranes) and 17 edges (gravity type waterfronts). Cranes and waterfronts are vulnerable due to Permanent Ground Deformation (PGD) and Peak Ground Acceleration (PGA). In addition, the Electric Power Network (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. Fragility models used are provided in Pitilakis et al. (2014).

The functionality of the harbor is assessed through several system-level Performance Indicators (PIs), as evaluated starting from the effects of seismic events. The PIs demonstrated here are the Total Number of Containers (TCoH) and the Total Cargo (TCaH) Handled per day (more details in Pitilakis et al., 2014).

4.2. Application and results

The assessment of the systemic risk of Thessaloniki's port is based on a MCS scheme where 10,000 runs are carried out. The system's "performance curve" is one of the main results of the analysis performed. The Mean Annual Frequency (MAF) of exceedance values for all PIs are given in terms of normalized performance loss (1-PI/PImax) in Fig. 3a which shows the MAF of exceedance curves ("performance curve") for TCoH and TCaH.

For performance loss values below 20% TCaH yields higher values of exceedance frequency, while for performance loss over 20% TCoH yields higher values of exceedance frequency. The importance of interactions between components is also pertained from the analysis results. Fig. 3b compares the estimated MAF of exceedance curves for TCoH when all and no interactions are taken into consideration in the analysis. The effect of this interaction can be very important for performance loss levels over 10% for TCoH. The TCoH performance loss is increased from about 20% to about 50% for λ=0.01 (TR= 100 years) when interactions are included in the analysis.

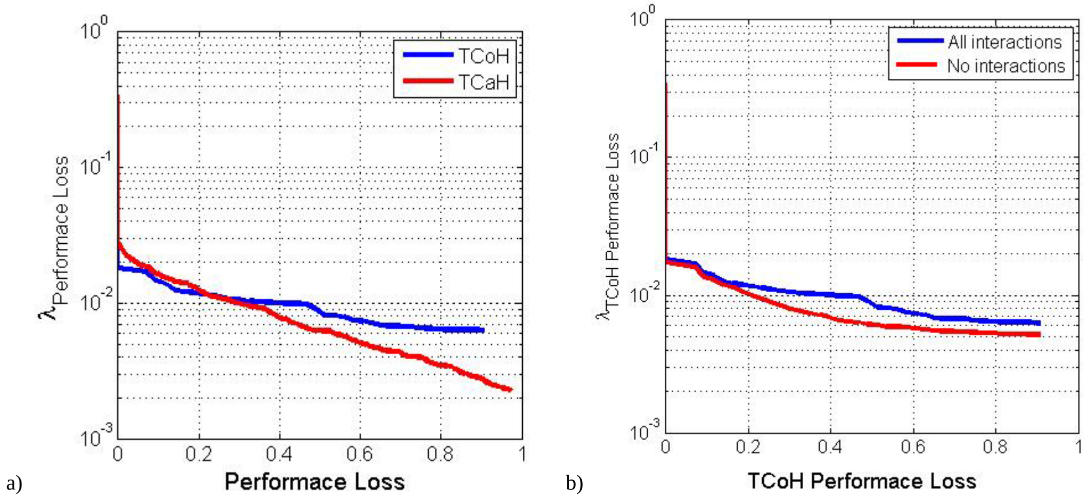

Fig. 3. MAF curves for a) TCoH and TCaH performance loss and b) TCoH for Thessaloniki's port, with and without interaction with EPN and building collapses.

Figs 4 and 5 show the level of correlation between the TCaH and the distribution of damages in cranes and non-functionality of electric power distribution substations respectively. In this way the most critical components can be identified in relation with their contribution to the performance loss of the system. All cranes have medium (40-70%) to high (over 70%) levels of correlation, indicating their great importance to the functionality of the overall port system. A higher level of correlation is estimated for the EPN distribution substations, with 40% of the components having values greater than 70%. Based on this results appropriate mitigation measures can be designed and implemented, resulting to more resilient and robust port infrastructures and operations.

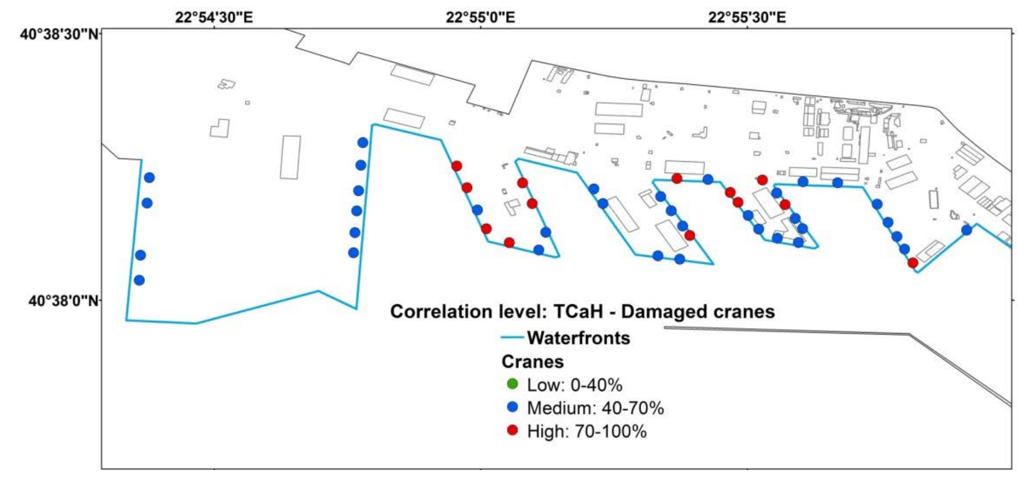

Fig. 4. Correlation of damaged cranes to port performance (PI=TCaH).

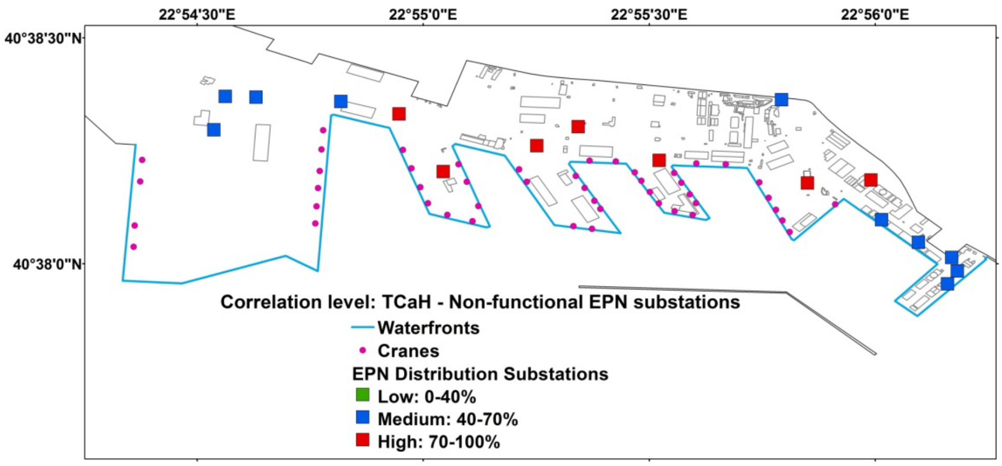

Fig. 5. Correlation of non-functional electric power distribution substations to port performance (PI=TCaH).

4.3. Addressing resilience through stress tests

A safer and more resilient society requires improved and standardized tools for hazard and risk assessment of low-probability-high-consequences events (so-called extreme events) and the systematic application of these new tools to whole classes of critical infrastructures (CIs). Among the most important tools are the stress tests, designed to test the vulnerability and resilience of CIs. The on-going European research project STREST: Harmonized approach to stress tests for critical infrastructures against natural hazards (www.strest-eu.org) aims at designing an innovative stress test framework for non-nuclear CIs, with the development of a common CI taxonomy, of rigorous models for the hazard, vulnerability, risk and resilience assessment of extreme events. The Harbor of Thessaloniki is one of the case studies; a characteristic example of distributed and/or geographically extended infrastructures with potentially high economic and environmental impact. In this particular application, the harbor infrastructures are exposed to seismic, geotechnical (i.e. liquefaction) and tsunami hazards. In this framework, SYNER-G models and tools will be extended and applied.

An important aspect of a stress test methodology is the definition of acceptable risk-based performance objectives, in order to verify the response of the CI to extreme events, and decide whether the CI pass or fail the test. Different levels of stress tests are proposed, based on the methodology adopted for the computation of risk (probabilistic or scenario based), the consideration of extreme events (multi hazard), the inclusion of the analysis of epistemic uncertainty and the use of expert elicitation (Esposito and Stojadinovic, 2015).

5. Discussion and conclusions

Analyzing and enforcing the resilience of critical infrastructures, like transportation networks, encompasses the study of the capabilities of a system to resist and react to such events as natural hazards, artificial threats, unscheduled discontinuities of service, outages and a plethora of other context-dependent classes of adverse circumstances and perturbations, which are generally referred as disruptive events. Since an infrastructure is constituted by an interconnection of assets, the characterization of the complex relationship between the existing linkages and the resulting overall behavior of the system is a natural challenge.

The issue of designing resilient transportation infrastructures is of utmost importance. Transportation infrastructures must be able to withstand stress, maintaining baseline service levels, in order to provide restoration to the system, as well as reduce the consequences of any failure that may occur, thus improving the time for recovery. Analyzing the resilience of a transportation network will aid decision-makers in identifying specific weaknesses within the network, thus allowing the proper prioritization of investments and mitigation actions.

Herein, a generalized and comprehensive model that accounts for seismic statistical characterization of seismic input acting on the components, intra-dependencies among the network components, and inter-dependencies with external systems, as the built environment or electric power supply is applied to road network and harbor facilities in the city of Thessaloniki, Greece. All sources of aleatory uncertainty are formally treated within a probabilistic framework, leading to a fully probabilistic risk assessment. Through the applications it is shown that the performance of the systems is highly controlled by inter-dependencies. Indeed, such interactive effects strongly modify the performance curves (exceedance probability of loss in performance). This means that an unbiased systemic analysis should include a complex system-of-system analysis, including all the systems that may potentially induce non-functionalities to the transportation network.

Ultimately, this research contributes to the assessment of the impact of disasters on the resilience and robustness of transportation and port infrastructure through a risk-based performance analysis on system level and through identification of significant components and functions for minimizing losses and social effects. Final goal is to have an indication of the resilience margins of existing critical infrastructures and evaluate resilience improvement measures.

Acknowledgements

The research is supported from the European Commission, Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 603389.

References

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

Argyroudis, S., Kaynia, A.M., 2014. Fragility functions of highway and railway infrastructure. In: Pitilakis K, Crowley H, Kaynia AM (eds) SYNER-G: Typology definition and fragility functions for physical elements at seismic risk. Geotechnical, Geological and Earthquake Engineering 27, doi: 10.1007/978-94-007-7872-6_10, Springer Netherlands.

Argyroudis, S., Selva, J., Gehl, P., Pitilakis, K., 2015. Systemic seismic risk assessment of road networks considering interactions with the built environment. Computer-Aided Civil and Infrastructure Engineering 30, 524–540.

Battelle, 2007. Evaluation of the systems' available redundancy to compensate for loss of transportation assets resulting from natural disasters or terrorist attacks. http://ntl.bts.gov/lib/33000/33400/33441/final_report/pdf/volume_3/technical_issue_papers/paper4e_02.pdf.

Brabhaharan, P., Wiles, L.M., Frietag, S., 2006. Natural Hazard Road Risk Management Part III: Performance Criteria. Land Transport New Zealand Research Report 296. 126pp.

Brenkert, A., Malone, E., 2004. Modeling vulnerability and resilience to climate change: a case study of India and Indian States. Climatic Change 72, 57–102.

Bruneau, M., Chang, S.E., Eguchi, R.T., Lee, G.C., O'Rourke, T.D., Reinhorn, A.M., Shinozuka, M., Tierney, K., Wallace, W.A., Winterfeldt, D.V., 2003. A framework to qualitatively assess and enhance the seismic resilience of communities. Earthquake Spectra 19(4), 733-752.

Cavalieri, F., Franchin, P., Gehl, P., Khazai, B., 2012. Quantitative assessment of social losses based on physical damage and interaction with infrastructural systems. Earthquake Engineering and Structural Dynamics 41(11), 1569–89.

Cimellaro, G.P., Reinhorn, A.M., Bruneau, M., 2010. Framework for Analytical Quantification of Disaster Resilience, Engineering Structures 32, 3939-3649.

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

Dantas, A., Giovinazzi, S., 2010. Benchmarking the readiness of road controlling authorities to meet their obligations under the Civil Defence and Emergency Management (CDEM) Act 2002. NZ Transport Agency research report 409, 90pp.

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

Esposito, S., Stojadinovic, B., 2015. Designing stress tests for CIs. Draft report. STREST project: Harmonized approach to stress tests for critical infrastructures against natural hazards (www.strest-eu.org).

Freckleton, D., Heaslip, K., Louisell, W., Collura, J., 2012. Evaluation of transportation network resiliency with consideration for disaster magnitude. 91st Annual Meeting of the Transportation Research Board, Washington, D.C.

Giardini, D., et al., 2013. Seismic Hazard Harmonization in Europe (SHARE). Online Data Resource, doi: 10.12686/SED-00000001-SHARE

Hamad, K., Kikuchi, S., 2002. Developing a measure of traffic congestion: fuzzy inference approach. Transportation research record 1802, 77–85.

Heaslip, K., Louisell, W., Collura, J., 2009. A methodology to evaluate transportation resiliency for regional networks. 88th Annual Transportation Research Board Annual Meeting, Washington, DC.

Heaslip, K., Louisell, W., Collura, J., 2009. A methodology to evaluate transportation resiliency for regional network. 88th Transportation Research Board Annual Meeting. Washington DC.

Heaslip, K., Louisell, W., Collura, J., Urena Serulle, N., 2010. An evaluation of network transportation resiliency for disasters and other events. 89th Annual Meeting of the Transportation Research Board. Washington DC.

Hughes, J.F., Healy, K., 2014. Measuring the resilience of transport infrastructure. New Zealand Transport Agency research report 546, 82pp.

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

Kakderi, K., Pitilakis, K., 2014. Fragility functions of harbor elements. In: Pitilakis K, Crowley H, Kaynia AM (eds) SYNER-G: Typology definition and fragility functions for physical elements at seismic risk. Geotechnical, Geological and Earthquake Engineering 27, doi: 10.1007/978-94-007-7872-6_11, Springer Netherlands.

Lee, A., Vargo, J., Seville, E., 2013. Developing a tool to measure and compare organisations' resilience. Natural Hazards Review 14(1), 29–41.

Litman, T. 2010. Evaluating Accessibility for Transportation Planning. http://www.vtpi.org/access.pdf.

Madhusudan, C., Ganapathy, G.P., 2011. Disaster resilience of transportation infrastructure and ports – An overview. International Journal of Geomatics and Geosciences 2(2), 443-455.

Mayunga, J., 2007. Understanding and applying the concept of community disaster resilience: a capital-based approach. www.ehs.unu.edu/file/get/3761.

Mostashari, A., Omer, M., Nilchiani, R., 2009. Assessing resilience in a regional road based transportation network. Hoboken, NJ: Stevens Institute of Technology.

Murray-Tuite, P., 2006. A comparison of transportation network resilience under simulated system optimum and user equilibrium conditions. 2006 Winter Simulation Conference, Monterey, CA.

National Institute of Building Sciences (NIBS) 2004. HAZUS-MH: Users's Manual and Technical Manuals. Report prepared for the Federal Emergency Management Agency, Washing-ton, D.C.

Pant, S.B., 2012. Transportation network resiliency: a study of self-annealing. Utah State University, Graduate Theses and Dissertations. Paper 1434.

Pitilakis, K., Fotopoulou, S., 2015. Vulnerability assessment of buildings exposed to co-seismic permanent slope displacements. In Proceedings of the XVI ECSMGE Geotechnical Engineering for Infrastructure and Development, 13-17 September, Edinburgh.

Pitilakis, K., Franchin, P., Khazai, B., Wenzel, H., 2014. 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.

Selva, J., 2000. Long-term multi-risk assessment: statistical treatment of interaction among risks, Natural Hazards 67(2), 701-722.

Selva, J., Sarfraz, M.I., Taroni, M., Marzocchi, W., Cotton, F., Courage, W., Abspoel-Bukman, L., Miraglia, S., Mignan, A., Pitilakis, K., Argyroudis, S., Kakderi, K., Pitilakis, D., Tsinidis, G., Smerzini, C., 2015. D3.1 – Report on the effects of epistemic uncertainties on the definition of LP-HC events. STREST project: Harmonized approach to stress tests for critical infrastructures against natural hazards.

Ta, C., Goodchild, A.V., Pitera, K. 2009. Structuring a Definition of Resilience for the Freight Transportation System. Transportation Research Record: Journal of the Transporation Research Board 2097, 19-25.

Tierney, K., Bruneau, M., 2007. Conceptualising and measuring resilience: a key to disaster loss reduction, TR News, MayJune 2007, pp 1417.

Weatherill, G., Esposito, S., Iervolino, I., Franchin, P., Cavalieri, F., 2014. 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.

Winter, M.G., Smith, J.T., Fotopoulou, S., Pitilakis, K., Mavrouli, O-C., Corominas, J., Argyroudis, S. 2014. An expert judgement approach to determining the physical vulnerability of roads to debris flow. Bulletin of Engineering Geology and the Environment, 73: 291-305.