SYSTEMIC SEISMIC VULNERABILITY AND RISK ASSESSMENT OF URBAN INFRASTRUCTURE AND UTILITY SYSTEMS

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ABSTRACT

The seismic vulnerability and risk assessment of infrastructure and utility systems are essential to prevent or mitigate sufficiently the negative consequences, implement resilience management strategies and recover efficiently after a major earthquake. In a complex urban environment, having multiple interacting and interdependent infrastructures becomes even more important. Earthquake hazards not only affect a single asset, but their impact is much greater because of the inter-and intra-dependences among various infrastructure, utility systems and lifelines. Therefore, we urgently need efficient tools to quantify and assess the systemic vulnerability and risk of urban infrastructure and utility systems. This is a challenging topic that is nowadays receiving more attention from the research community, the industry domain and the policymakers. This paper aims to review the available modelling approaches and tools for the seismic risk analysis of interconnected systems, including advantages and limitations. It focuses in particular on the European funded SYNER-G project that encompasses interdependencies, delivers a holistic methodology and implements a comprehensive framework based on the Object-Oriented Modelling paradigm. The capacities of the SYNER-G framework are illustrated through a selected application regarding the seismic risk analysis of interconnected infrastructure and utility systems in the city of Thessaloniki, Greece. Among other aspects, the paper discusses hazard modelling issues of the two common approaches, the probabilistic and the scenario-based procedure and illustrates in a specific example the impact of mitigation strategies, based on their effect on the performance of the interconnected systems and the overall loss reduction. The integration of interdependencies into the risk analysis and resilience strategies facilitates a better understanding of critical infrastructure operation and enables well-informed proactive and reactive decision-making and efficient disaster risk management, by infrastructure owners and operators, insurance companies, consulting agencies and local authorities.

Keywords: SYNER-G, infrastructure, utility systems, seismic hazard, systemic vulnerability and risk, fragility functions, performance indicators.

INTRODUCTION

Earthquakes have been one of the catastrophic hazards affecting the lives and economy of the world. It is of utmost importance to develop a safer and resilient built-up environment to tackle the consequences of the earthquake. Evidence and lessons learnt from past earthquakes highlights the vulnerability of infrastructure assets and contributed to the development of seismic risk models of various components of the built-up environment.

Vulnerability analysis of the different structures is one of the fundamental components to be studied for earthquake risk assessment and mitigation. However, while most available vulnerability models concern single structures or components of a system, the impact of the earthquake does not bound to the single structure only. It should be studied with the broad view by incorporating all the components of a complex system like for example a city environment, with inter and intra dependencies between them. Past earthquake events such as the 2012 Christchurch earthquake, or the 1995 Kobe earthquake, among many others, show that the increasing impact is significant due to the interdependencies of the critical infrastructures. Hence, a systemic vulnerability and risk assessment of the infrastructure is of paramount importance towards a holistic approach. Considering intra dependencies among components of the same system and the interdependencies between different systems is the key issue of the systemic approach and the main focus of this study. Addressing the issue, an integrated effort among a few is the SYNER-G project [15] that developed a comprehensive approach.

The following sections include a review of available methods to model interdependencies of critical infrastructure, a short description of SYNER-G methodology and its application to the infrastructure of Thessaloniki, Greece exposed to seismic hazard. The application embodies identification of the critical components, which is essential for decision-makers to prioritize investment in order to mitigate the risk.

The paper is focusing on the water supply system, which is generally designed for a long period of time and should be resilient enough to the occurrence of various hazards over its lifetime. Moreover, in addition to its own vulnerability, it is crucial to take into account the interaction with other infrastructures like the electric power network, as the interruptions of power supply might cause a further loss in the water supply system. Consequently, upgrading the performance of the power supply system is used as an example to analyze the potential impact of mitigation actions to improve the resilience of the water system.

MODELLING OF INTERDEPENDENCIES OF CRITICAL INFRASTRUCTURES (CIs)

PCCIP [12] defines infrastructure as “a network of independent, mostly privately-owned, man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services”. Among them, the ones whose destruction can have a debilitating impact on safety and economic security is considered to be critical. CIs in the past days tended to be overlooked until unexpected failures occur. The efficiency of the CIs due to the interdependencies is of less realization in the undisturbed situation, however, in the aftermath of an extreme event, the impact is much higher. External threats like natural disasters might significantly increase the damages due to the interdependencies by not limiting to the boundaries of a single infrastructure. For the mitigation of losses in any critical infrastructures due to all kinds of hazards, it is important to understand and assess existing vulnerabilities and interdependencies of assets and networks [3]. It should also be noted that, in the present context, the role of urbanization, climate change and increase of demand in services provided by CIs, adverse the impact of infrastructure failure to an even higher degree.

One of the foremost efforts to deliver the notion of critical infrastructures (CIs) not acting as isolated but highly interconnected to each other is found in Rinaldi et. al [16]. In this, dependencies are described in terms of physical (state of one infrastructure affects the material output of another), cyber (information flow among different infrastructure systems), geographic (effect of local environment effect to multiple infrastructures due to geographical proximity), and logical (dependencies except the other mentioned) categories. In Table 1 we summarize the systemic approach including the pros and cons of modelling CI interdependencies with the simulation techniques in the context of natural hazards. Some other methods of modelling interdependencies

Table 1: Approaches for modelling interdependencies of critical infrastructures

Methods	Description	Advantages	Limitations	Ref
Empirical methods	-Analysis is performed according to historic events and expert opinion	-Based on real-time data -Can represent physical, geographic, logical and cyber interdependencies -Relatively less computational cost -Can give a good form of validation in addition to other types of analysis	-Possibility of being biased due to unstandardized techniques of data collection -Reliance of the previous record to the new disaster	[9, 11]
Network based methods	-Graphical representation of the coupling phenomenon by the set of nodes and edges -Typology based or flow-based methods	-Classical and widely accepted model -Able to represent complex typologies of interdependence -Computation costs vary according to the requirement of the output -Can represent physical, logical, geographic and cyber interdependencies	-Doesn't support time stepped-simulation directly -Complicated to simulate or model all the complexities of the system or infrastructure	[7, 11, 20]
Agent based modelling	-Bottom-up approach, which emerges from the notion that the complexities are evolved due to the interaction of many individual agents in its environment based on a set of rules	-Gives good visualization and graphical representation of the behaviour -Can model uncertain characteristics of the components -Support time stepped simulation -Can represent physical, logical, geographic and cyber interdependencies	-Computational cost is relatively high -Complicated to simulate for macro-level analysis -Calibrations is often difficult due to the limited availability of information on CIs	[10,18]
System dynamics	-Top-down approach, with the help of casual-loop diagram showing influence among variables, and stock and flow diagram showing the flow of information	-Simulation in meso to macro level in comparison to agent-based method -Models dynamic behaviour of interdependence capturing cause and effect -Can represent physical, logical, and cyber interdependencies	-Unable to analyze component level dynamics -Semi-quantitative method that relies much on the subject expert -Requires a huge amount of data for calibration	[4, 11]

are input-output models, Petri-nets, Bayesian network-based models, high-level architecture, or artificial neural network approaches. Each approach has its significance, and the combination of these methods may result in better representation and understanding of the system performance. The hybrid modelling approach like object-oriented modelling (OOM), which is used in SYNER-G, can incorporate other methods providing the flexibility of maintenance and extension in the modelling according to future needs. In the OOM paradigm, systems and components are classified as classes and objects and the interaction/relationship is built upon from the main functional unit. OOM is one of the robust tools of simulation to solve the complex problem, as it can be centrally controlled where objects act only upon request, unlike agent-based modelling. This method is well proven for incorporating the complexity and the large size of the system of systems. Principles of the OOM paradigm, such as inheritance and composition, allow a high degree of abstraction and hierarchical decomposition in the model.

Also, it is important to notify that in most of the recent large scale efforts developing loss models at an urban and global scale, i.e. HAZUS, CAPRA, GEM, RISK-UE, LESSLOSS, IFRARISK, MAEviz, OPENRISK, RISKSCAPE, just to mention a few, the systemic approach for the complex network of infrastructures has not been addressed. One of the milestones achieved directly in the direction of systemic vulnerability is through the SYNER-G project [15].

THE SYNER-G METHODOLOGY

Infrastructure can be regarded as a complex system of systems. This means that the set of components that are themselves considered systems are arranged hierarchically and have a very large number of possible states in practice [15]. To address this comprehensively, SYNER-G methodology consists of three basic models, i.e. hazard model, components' physical vulnerability model and the system (functional and socio-economic) model. Details of the methodology can be found in Pitilakis et al. [15]. However, in a nutshell, the project delivers a holistic methodology and a comprehensive framework, which embraces: (i) a detailed taxonomy of infrastructure systems and components, including buildings, transportation and utility networks, and critical facilities, (ii) seismic hazard and intensity measures, appropriate for spatially distributed systems accounting for site effects and associated geotechnical hazards, (iii) fragility assessment of components, (iv) modelling of dependencies between the multiple component systems in the taxonomy and definition of systemic performance indicators, (v) socioeconomic impacts, (vi) relevant uncertainties.

SYNER-G comprises inhabited areas, utility and transportation systems, and critical infrastructures. Various systems are represented as a region-like system, network-like system and point-like system accordingly. These systems are evaluated by employing vulnerability, connectivity, capacity and fault tree analyses. The outcome of these analyses is expressed in terms of representative performance indicators (PI), which measure the performance of the system and its elements subjected to seismic hazard.

The analysis from SYNER-G not only give the overall impact of interdependencies on the performance of the city/region but also helps in identifying the critical components or system as a whole to be upgraded for the disaster mitigation measures. One can identify the topological insufficiency, functional vulnerability or the most sensitive component through correlation to the end metrics that are essential for strategic disaster planning. This realization and the impact of the mitigation strategies is one of the outcomes of this study.

SYSTEMIC VULNERABILITY OF UTILITY SYSTEMS

The performance of the water supply system (WSS) applying the SYNER-G approach includes hazard modelling, selection of fragility functions, consideration of interdependencies and evaluation with the performance indicators, briefly explained here.

Hazard: The method of "Shakefields" is applied to generate a sample of ground motions for a single deterministic scenario and set of stochastically generated events, which are required for probabilistic seismic risk analysis. Implementation of this procedure includes (i) generation of source event with a given magnitude and geometry (point, rupture surface), (ii) attenuation of the median ground motion field with appropriate ground motion prediction equation (GMPE), (iii) generation of the standard Gaussian field that represents spatial correlation structure of required intensity measure (IM), (iv) generation of ground motion values for different IM, (v) scaling of the ground motion considering the site condition and, (vi) definition of geotechnical hazard parameters, which is conditional upon estimated intensity at the site [19].

Fragility Functions: The evaluation of the vulnerability of WSS involves identifying the main typologies and components of WSS, defining adequate IM for each component or sub-components, defining the damage mechanisms, failure modes and damage states (DS) and selecting appropriate fragility function. The components of WSS includes water source, water treatment plants, pumping stations, storage tanks, pipes, tunnels, canals and supervisory control and data acquisition sub-system (SCADA) system. In the context of this paper, pumping stations, pipelines and demand nodes have been modelled, while pipelines have been considered as a vulnerable component to direct damage due to ground shaking and pumping stations vulnerable to power failure while considering the interdependencies with electric power substations. In this respect, and based on literature evidence, peak ground velocity (PGV) and permanent ground displacement (PGD) have been selected as the IM for pipelines [14]. Damage is generally expressed in terms of repair rate (RR), which defines the number of expected repairs per unit length of the pipelines for a given seismic intensity. Among different available fragility functions for buried pipelines, the ones proposed by ALA (2001) are employed in this study considering that they give a relatively good estimate of the vulnerability [15]. The repair rate RR (in km) as a function of PGV (in cm/sec) and PGD is given by equations (1) and (2),

$$RR = K_1 * 0.002416PGV \quad (1)$$

$$RR = K_2 * 2.5829PGD^{0.319} \quad (2)$$

Where, K_1, K_2 are the values used to adjust them based on the material type, connection type, soil type and pipe diameter and can be referred to [2, 15].

In the context of this paper, the interaction is considered with the electric transmission substations which will be described in the following sections. To check the damageability of substations the vulnerability of the electric power transmission substations has been evaluated in terms of peak ground acceleration (PGA) according to the results of a previous project [17]. EPN substation systems are classified according to voltage level with closed-type (sub-components entirely enclosed in the building of different vulnerability) or open-type. Fragility curves of the substations system are evaluated in terms of the fault tree/boolean approach, probabilistically combining the damage function of different sub-components like circuit breakers, power switches, transformers, and buildings (in case of closed-type).

For the mitigation of the impact of earthquakes, it is essential to focus on the robustness of the structure at the component level that is likely to be more critical due to the intensity of hazard at the site and level of correlation of its state to the overall performance. Mitigation strategies can be applied through the appropriate strengthening of the components, which would be reflected on upgraded fragility curves while doing the analysis. As this research is more concerned about the interdependencies of WSS to the EPN system, emphasis is given to check the upgrading of the EPN substations for the overall performance of WSS.

Systemic Vulnerability. The main interaction of WSS is with the electric power network (EPN), the building stock (BDG) and the health care system (HCS). The interdependency of WSS to EPN is physical as damage to EPN leads to the non-functionality of the pumping station. The interdependency of WSS to BDG is also physical as a lack of water supply leads to a displaced population and an increase in shelter demand. The interdependency of WSS to HCS is again, physical as a lack of water supply to hospitals hinders the emergency response over time. In this study, the interaction with EPN i.e. substations is only considered. As pumping stations require electric supply to operate, it is important to check the state of the electric power substations. The damage in the substations will directly affect the operation of the interconnected pumping stations and ultimately the whole system having end users deprived of the water supply. Therefore, it is simulated to interpret the connection of WSS pumping stations concerning specific EPN transmission substations. After the analysis, the most critical components are to be checked to understand its degree of interdependencies and its own vulnerability to decide on further mitigation strategies.

For the connectivity analysis, the connection between the supply and the demand node is checked by applying different performance indicators (PI) (i.e. damage ratio, service ratio, connectivity loss, redundancy ratio and reachability). In the flow analysis, the ability of the system to meet the needs at the demand node or the quantity of water supplied to the user is calculated. It is generally computed by the average value to head or flow rate at each node before and after the earthquake. In this research, water connectivity loss (WCL) is adopted as a single performance indicator given by,

$$WCL_i = 1 - N_i^s / N_o \text{..} \quad (3)$$

Where, N_i^s and N_o is the number of connected nodes in seismic and non-seismic conditions respectively.

The computation of metrics like WCL and other analyses from SYNER-G helps to understand the overall performance of the system after the earthquake. While allotting the interdependencies to the analysis, we can check the degree of the influence of other systems like EPN to WSS. This also helps to identify the mitigation strategies in terms of retrofitting the specific critical component, working on the topological insufficiency or supplementing the redundancies in case of extreme events.

APPLICATION TO THE CITY OF THESSALONIKI

The city of Thessaloniki, Greece, lies in a highly active seismic zone characterized by strong historical earthquakes of magnitude larger than 6.0, the most recent largest earthquake (M=6.5) occurred in 1978. To model the seismic hazard, the probabilistic and scenario-based procedure has been applied based on the results of the recent SHARE European research project [6]. Following a Monte-Carlo approach, 10,000 simulations were carried out to generate random earthquake events. Site conditions were considered according to Eurocode 8 classification, while liquefaction susceptibility is based on a previous study [17]. Intensity measure (PGV) is computed using GMPE proposed by Akkar and Bommer [1]. Spatial variability of ground motion is modelled using Jayaram and Baker model [8]. In the case of the scenario-based approach, an earthquake of M_w =6.5 at distance of approximately 20 km have been taken into consideration as shown in Figure 1.

Water is supplied to a population of about 1,000,000 in an area of 90 km^2 in the municipality of Thessaloniki. The WSS consists of 20 tanks with a capacity of 91,900 m^3. Transmission and distribution systems consist of approximately 71km and 1284km long pipelines. The network modelling consists of 477 nodes and 601 edges. The nodes are subdivided into 437 demand nodes, 21 pumping stations and 11 tanks. 24 different diameters pipelines (edges) ranging from 500mm to 3000mm are found. Material type includes asbestos cement, cast iron, PVC and welded steel. Figure 2 shows the main water supply system with source nodes, pipeline and demand nodes along with the electric transmission substations to which pumping stations are connected.

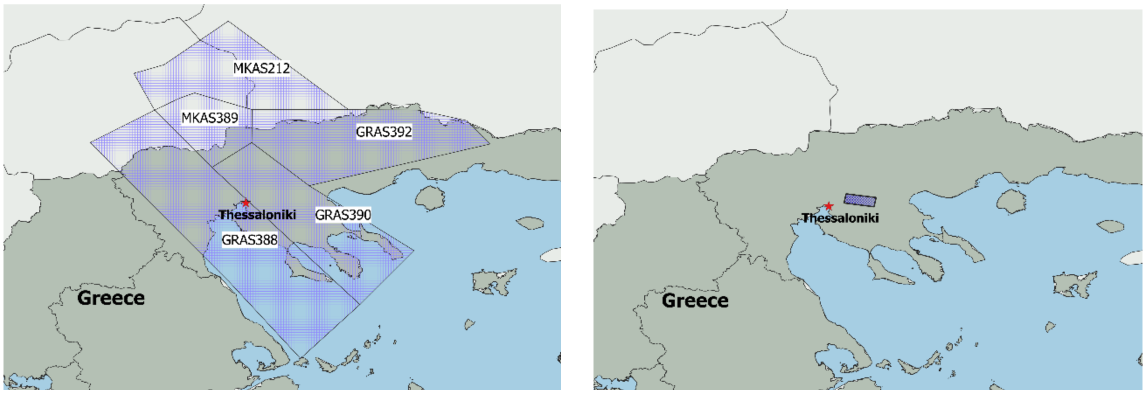

Figure 1: Seismic zones considered for probabilistic approach obtained from SHARE project [6] (left), Epicenter area considered for scenario-based approach [M=6.5, R=20km] (right).

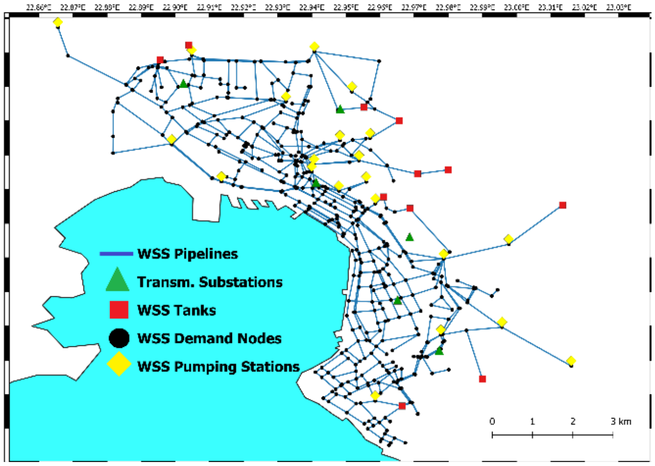

Figure 2: Water supply system of Thessaloniki and electric power transmission substations

As mentioned previously, interdependencies are modelled between transmission substations and pumping stations. In the context of this case study, open-type and closed-type (housed in building relatively lower and old seismic code) whose representative photographs are shown in Figure 3. As seen in Figure 4, closed-type substations are more vulnerable due to the vulnerability of the building enclosing them. Consequently, the loss of WSS connectivity was evaluated due to the direct damage of the pipelines and the interruption of power supply to pumping stations.

Three main cases were examined for the purpose of this research: (a) analysis without considering any interdependencies for two different hazard models, (b) analysis considering interdependencies between EPN and WSS, and (c) effect of strengthening actions undertaken to the most critical substations to the operation of the WSS prior to an earthquake. Simulations were carried out for both hazard models i.e. probabilistic and deterministic. In total, six different cases were carried (Table 2). The correlation between the electric transmission substations and WSS pipelines with the performance indicator (WCL), was assessed as shown in Figure 5. This figure assisted in identifying the critical components impacting the overall performance of the system. Since this research focuses on interdependencies, the mitigation measures were emphasized on the EPN substations rather than upgrading the components of WSS.

Figure 3: Representative open-type (left) and close-type (right) substations [Google Maps]

Table 2: Different cases considered

Cases	**Descriptions**
1	Without consideration of interdependencies (probabilistic model)
2	Without consideration of interdependencies (scenario-based model)
3	With consideration of interdependencies (probabilistic model)
4	With consideration of interdependencies (scenario-based model)
5	With consideration of interdependencies and strengthening measures (probabilistic model)
6	With consideration of interdependencies and strengthening measures (scenario-based model)

RESULTS

Cases 1 to 4, highlight the significant role that interdependencies play in both deterministic and probabilistic scenarios. In all the cases, consideration of interdependencies leads to an increased number of end-users deprived of water supply after an earthquake. As an example of the scenario simulated for cases 2 and 4, the functionality of the pumping stations and the consequent effect to damage nodes are shown in Figure 6.

For cases 3 and 4, the correlation of the WCL with pipelines and transmission substations are shown in Figures 5. It can be seen that the EPN substations are more correlated to the performance of the water supply system while considering the probabilistic model. Therefore, it is important to take into account the probabilistic model to understand the correlations of the functionality of all components to overall performance to facilitate the decision-makers or insurers to capture all the possible scenarios. Considering only the deterministic based approach might lead to a faulty impression about the criticality of the components.

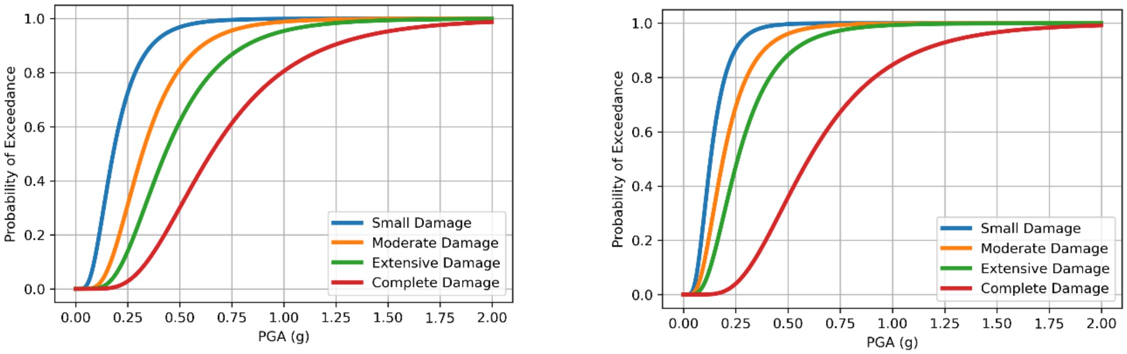

Figure 4: Fragility curve of open-type (left) and close-type (right) substations [17], {redrawn}

The analysis allows identifying the most critical substations, which have the highest correlation with the overall system performance. Their vulnerabilities were checked and the two EPN substations that have greater correlations and were more vulnerable were chosen to be upgraded

in terms of seismic performance marked with a circle in Figure 5 (right). Both substations were of close-type whose higher vulnerability is depending on the vulnerability of the building. To examine the effect of mitigation measures, the fragility function of these closed-type substations were modified to reflect the upgrading of the buildings before the occurrence of the earthquake.
Figure 6 (c) shows the functionality of the pumping stations and damage to the demand nodes for a scenario of case 6. From Figure 7, for a given damage scenario, it can be shown that upgrading the critical substations improves the performance of the WSS significantly.

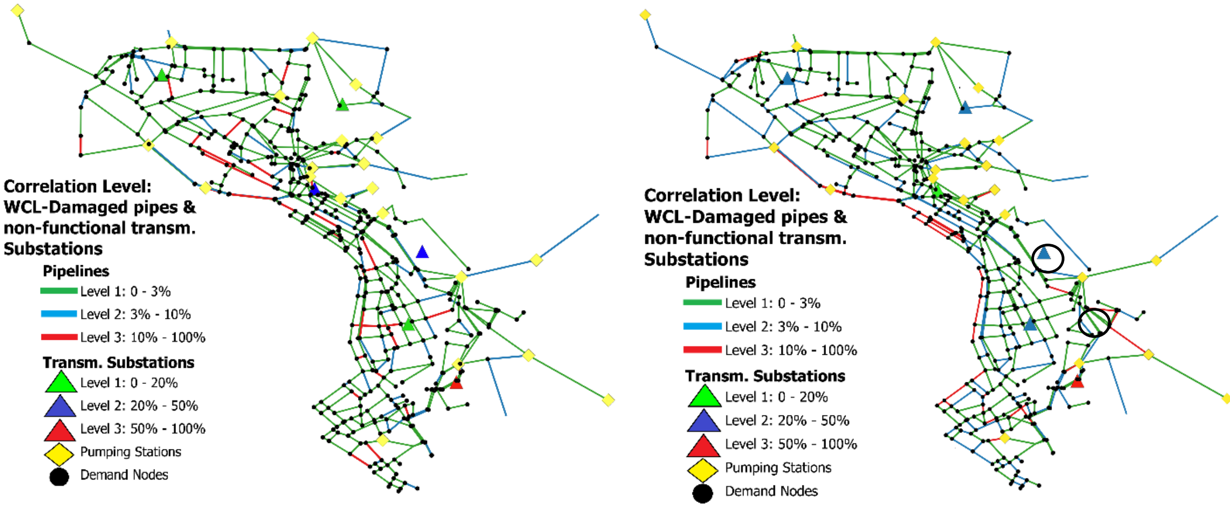

Figure 5: Correlation of damaged pipes and non-functional EPN transmission stations to water network connectivity for scenario-based (left) and probabilistic model (right)

The overall performance of the system in terms of the mean annual frequency curve of exceedance of water connectivity loss (WCL) for scenarios 1, 3 and 5 is shown in Figure 7. For the return period of 1000 years ($\lambda=10^{-3}$), the loss of connectivity in the present context is increased by almost more than 2.5 times when interactions are considered. Moreover, when proactive mitigation measures are undertaken to the critical substations, the loss of connectivity is decreased from 2.5% to 1.3% that approximate 25,000 to 14,000 end-users deprived of water supply in the population of 1,000,000.
While there might be other options for the mitigation strategies like upgrading the network configuration adding redundancies to both EPN and WSS, undemanding measures of upgrading the EPN substations have been chosen for this study. As mentioned earlier, this has been done through the modifications in fragility curves of critical EPN substations considering the strengthening of the enclosing buildings before an earthquake event. Furthermore, the performance of the WSS can be improved by applying upgrading measures to pipelines by anchoring the vulnerable cast-iron pipelines or changing it with the more flexible type like PVC which, however, is not in the context of this study.

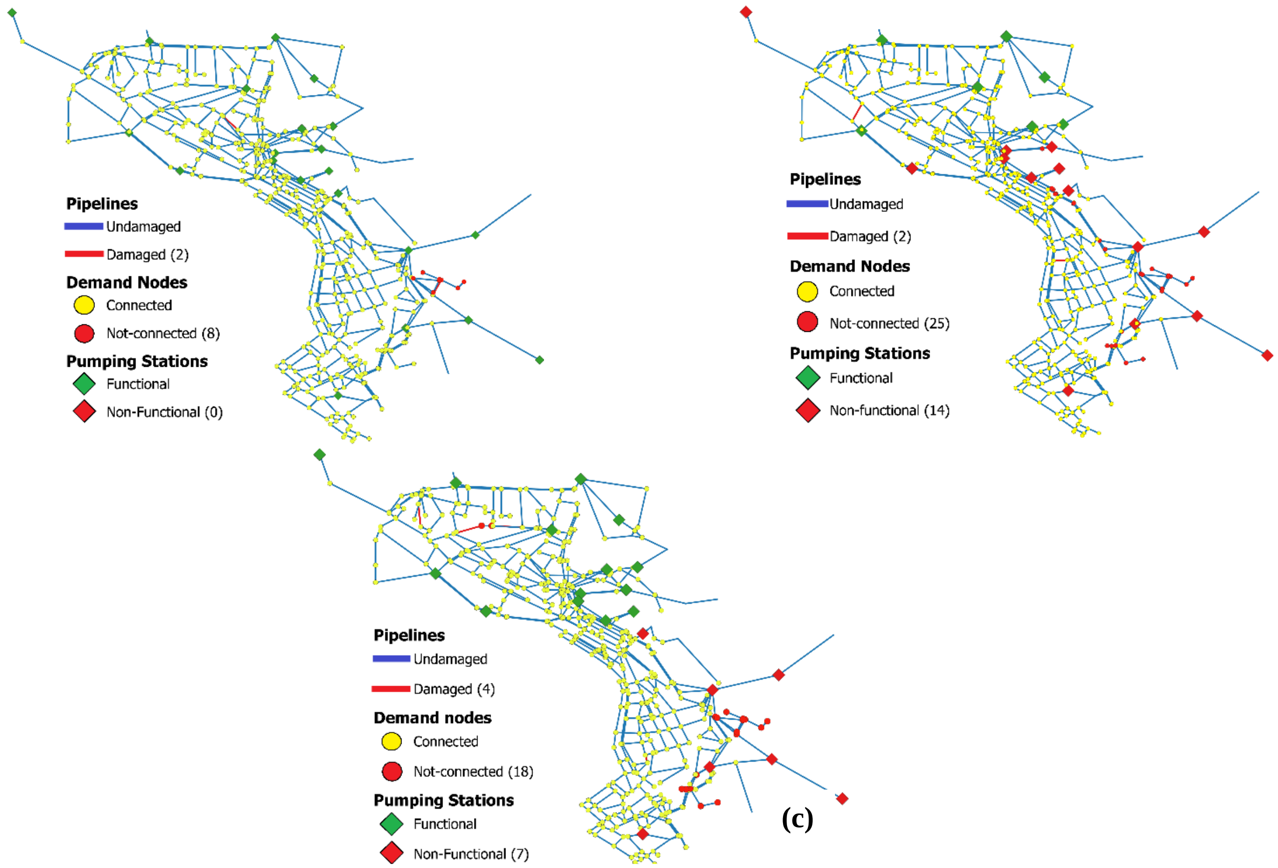

Figure 6: WSS damage for an event under case 2-(a), 4-(b), 6-(c) (Mw=6.5, R=20Km)

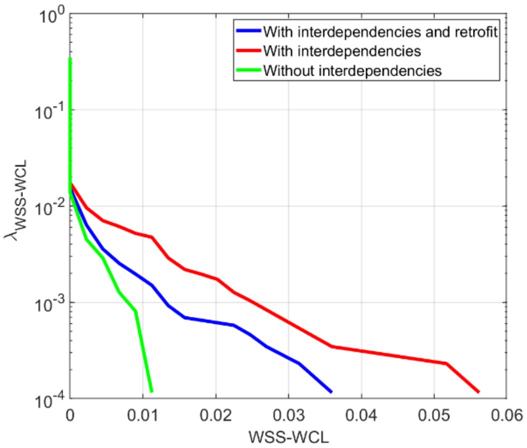

Figure 7: Mean annual frequency (MAF) curve for water connectivity loss (WCL) for scenarios 1, 3, 5

CONCLUSIONS

The paper first shortly discusses the different approaches of modelling the interdependencies in the context of physical infrastructures subjected to natural hazards. Then, we apply the SYNER-G approach to examine the effect of the seismic systemic approach in the water system of a large city like Thessaloniki in Greece, considering the interaction with the electrical power system. The aim is to check in the context of the systemic seismic approach concerning probabilistic and deterministic methods and then to describe an efficient and practical way to incorporate the effect of pre-earthquake strengthening measures to the most vulnerable and correlated component in the overall performance of the system. In particular, the conclusions and contributions of this study are as follows.

- Various existing approaches to compute the interdependencies have their own significance, and the combination of these methods may result in better representation and understanding of the system performance. SYNER-G based on the OOM paradigm, which acts as a hybrid modelling approach can incorporate other methods providing the flexibility of maintenance and extension in the modelling according to future needs.
- It is seen that the interaction of the electric power network and water supply system may significantly reduce the performance of the water system in case of an earthquake event. Therefore, it is important to identify the main interdependencies to evaluate the overall performance of the city. The study of the interdependencies not only help to realize the post-earthquake system performance but also to identify the most critical components and prioritize the investments for retrofitting measures.
- A pertinent mitigation action of the most critical substations (identified through the system analysis) may improve considerably the performance of the water system by reducing the detrimental effect due to the interaction between the water and the electric power systems. Thus, this systemic approach is a useful tool for well-informed decision-making toward more resilient city infrastructure.
- As in any type of vulnerability and risk assessment, the probabilistic model in the systemic approach gives a rational overview capturing the correlation of all the critical components to overall performance which might have been overlooked through the deterministic approach.

WAY FORWARD

In this study, the site effects implied in the hazard analyses are done in a simplified way based on the present Eurocode 8 site classification scheme, using $V_{s,30}$ as primary parameter. In case a more detailed classification scheme (e.g. Pitilakis et al. [13]) or when a detailed microzonation study is available, then the whole approach should be upgraded considering the detailed site effects and the spatial variability of the pertinent ground motion parameters (in this case being PGV and PGD). Considering that site effects are of paramount importance in the risk assessment of utility and lifeline systems, this is one of the ways that the present research will go forward.

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