SYNER-G+: PROSPECT OF SYSTEMIC SEISMIC RISK ASSESSMENT OF INTERCONNECTED SYSTEM

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Abstract: Critical infrastructures are on the verge of increasing risk due to extreme events like earthquakes. In the complex world of today where no system is independent, it is important to realize that a systemic approach, considering the interdependencies between the systems, is an indispensable tool to address the risk and the resilience of the critical infrastructures. Among various efforts, the framework developed in the SYNER-G project has delivered a systemic approach for the integrated seismic risk assessment considering the interaction among different components of a system as well as between systems at different urban and regional scales. Even though it is a powerful framework with a comprehensive approach, its current practical usage is limited, mainly due to the complexity of the tool that cannot be easily understood and applied by many end-users. In this regard, in this paper we discuss the future perspectives of the SYNER-G methodology for a more extensive usage by the disaster risk reduction community, through a possible integration of its framework in a widely accepted, well-calibrated, user-friendly and open-source software like the OpenQuake-Engine. Additionally, we present an application to highlight its efficiency and usefulness to assess the real impact when considering interdependencies among interacting systems, like for example the water supply system and electric power network at city scale.

Keywords: Critical Infrastructure, Systemic approach, Interdependencies, SYNER-G

1. Introduction

It is coming to the realization that interdependent infrastructures are on the verge of increasing risk due to extreme events like earthquakes. Research in reliability and resilience of critical infrastructure exposed to multiple natural hazards is the urgent need of present and future demand and at the same time a challenging endeavour both in terms of physical and socio-economic aspects. Addressing the issue is not straightforward due to the growing complexity of interdependencies and the rigidity of the organization of the infrastructures itself, which might not be flexible enough to be easily adapted to the demanding resiliency requirement when treated interdependently. In our complex world, no system is independent anymore; each one depends more or less on the performance of other interconnected components and systems. Consequently, the systemic approach is an indispensable and vital tool to accurately address the risk and the resilience of the critical infrastructures and utility systems subjected to natural and anthropogenic hazards.

While there are important achievements towards seismic hazard, vulnerability and loss assessment of independent exposed elements at risk, as well as towards its efficient mitigation and management, it is necessary now to formulate all these interactions and bring them together in a way to address the issue in a holistic manner with a systemic approach at different levels in urban, regional, national and international scale. This systemic approach would help to analyse the overall performance of the various critical infrastructures and utility systems both comprehensively and strategically. This formulation would also help to look back into the individual components and evaluate the impact they pose to other systems and help in building a broader mindset for researchers, practitioners and decision-makers.

The pioneering work in HAZUS (followed by ATC-25 and ATC-13) is among the important guidelines that include the risk assessment of critical infrastructures (ATC, 1985, 1991; National Institute of Building Sciences (NIBS), 2004). Even though it is one of the milestones in terms of risk assessment and is widely used, intra- and interdependencies between components and systems have not been adequately addressed so far. There are several efforts towards this direction but due to the complexity of the problems involved, an efficient and friendly technology to account for the systemic approach of systems like lifelines and critical infrastructures is still missing. Among these efforts, the work in the framework of the SYNER-G project (Pitilakis et al., 2014) is probably the most ambitious; intra- and inter-dependencies between the components of a system and between different interconnected systems have been included in a comprehensive methodology to account for the systemic approach. The methodology incorporates the definition of the taxonomy and typologies, hazard computation, vulnerability assessment, intra- and inter-dependencies modelling, definition of systemic performance indicators, socioeconomic impact, incorporating also relevant uncertainties. Even though the SYNER-G methodology is powerful, its practical implication to assess the systemic risk in urban or regional scale including possible intra- and inter-dependencies is still limited. As in many other scientific fields, extensive usage and practical applications are only possible when properly acknowledged by the larger community, in this case the community in the field of disaster risk reduction, which can be generally done through embracing the methodological framework to a widely accepted open-source tool.

This paper describes shortly the scope and prospect of the incorporation of the SYNER-G methodology in the presently most widely accepted and open-source tool for seismic hazard and risk assessment, i.e. the OpenQuake platform. Introducing the SYNER-G methodology in OpenQuake, it is reasonably expected that it would be more efficient to highlight its efficiency and usefulness to assess the real impact when considering interdependencies among interacting systems, for example at the city scale. In the present work, the potential of this introduction and its efficiency are demonstrated considering the interdependencies between the water supply system and the transmission substations of the electric power network in the city of Thessaloniki, Greece for a specific seismic scenario.

2. Modelling of Interdependencies of Interconnected Systems

The operation of critical infrastructures, including the transportation system, water supply system, electric power network, wastewater system and many more, is crucial for the normal functioning of society. The notion of critical infrastructures and systems acting interdependently is described by Rinaldi et al., (2001). According to it, interdependencies can be classified as physical, geographical, cyber and logical. Unidirectional relationships between the systems are known as dependencies whereas, bidirectional relationships are called interdependencies. However, as practised in many other works, both dependency and interdependency are termed as ‘interdependency’ here. As an example, the water supply system, which is the focus of the application presented in this study, is interdependent primarily with electric power networks, but also with the building stock and other systems like for example the health care system. The interdependencies between them are physical, i.e. the state of one infrastructure affects the other.

Interdependencies can be of less importance under ordinary operational conditions but are more vivid, even crucial, in case of extreme events like strong earthquakes. Tohoku earthquake in 2011, Christchurch earthquake in 2011, Central Sulawesi earthquake in 2018 are only some of the examples signifying the serious impact that interdependencies between the systems can have. There exist various modelling and simulation approaches for modelling interdependencies, grouped mainly into six types: empirical, agent-based, system- dynamics-based, economic theory-based, network-based and others (Ouyang, 2014). Each one of them has its own significance and limitations. A better representation of the systemic effects, i.e. considering the whole rather than parts of the system, can be possible only through the combination of two or more of these approaches (Poudel et al., 2021)

3. The SYNER-G Methodology

In SYNER-G, the integrated seismic risk approach provides the impact of earthquakes holistically, considering the interactions among different systems and infrastructures at different scales. The methodology incorporates in an integrated way all aspects in the chain, from hazard to the physical vulnerability and loss assessment of components and systems, as well as to the socio-economic impacts, accounting for relevant uncertainties and modelling the interactions between the multiple components and system. The methodological framework of SYNER-G is shown in Figure 1.

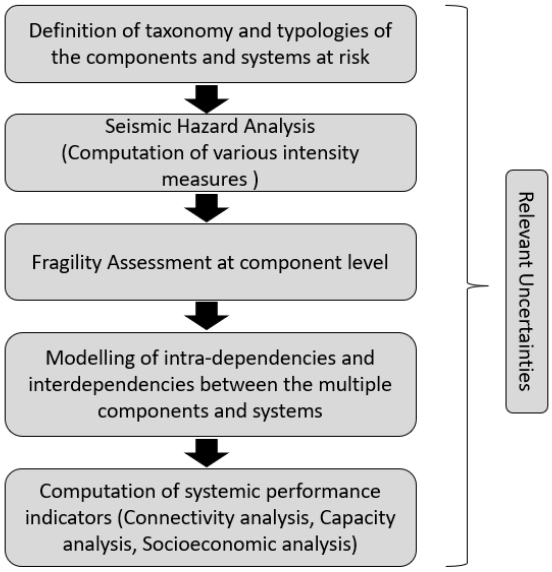

Figure 1: Methodological framework of SYNER-G project.

The elements at risk, namely inhabited areas, utility and transportation systems and critical infrastructures, represented as region-like, network-like or point-like systems, are classified in specific typologies based on appropriate taxonomy schemes. The results of the seismic hazard analysis are combined with the appropriate fragility models to obtain the fragility and vulnerability assessment firstly at the component level. Then, after processing the modelling of the intra- and interdependencies, the results of the analysis are expressed in terms of performance indicators that measure the overall impact to the system. The tool developed during the project is called OOFIMS (Object-Oriented Framework for Infrastructure Modelling and Simulation). It is developed in MATLAB and is based on the object-oriented paradigm (Franchin, 2014). Within SYNER-G, the proposed methodology was applied to the city of Thessaloniki, the Brigittenau district in Vienna, the gas distribution system of L'Aquila, the road network of Calabria and the electric power network of Sicily (Pitilakis et al., 2014b).

4. Prospect of SYNER-G

In order to ensure the extensive utilization of the powerful concept of the SYNER-G methodology and to further familiarize the larger community with the systemic approach, which is of utmost importance at present, it has been decided to adapt it in a way that allows a simple and user-friendly usage coherent in current practices. In this respect, the integration of SYNER-G to the OpenQuake platform, referred to in the following as SYNER-G+, could be a rational solution.

OpenQuake platform, developed by the GEM Foundation, is a hub for integrated seismic risk assessment and is being used widely around the globe. It provides an open-access, dynamic and interactive environment and is constantly developing. It includes scenario-based, classical probabilistic and event-based probabilistic (suitable for spatially distributed system) hazard and risk analysis, including a large dataset and libraries to comprehend its usage globally (Pagani et al., 2014; Silva et al., 2014). For example, it already offers a large set of GMPE models (which is one of the limitations of the present OOFIMS tool developed in SYNER-G) that can be used for the systemic approach. The combination in SYNER-G+ of the capabilities of this powerful platform with the systemic methodology developed within SYNER-G is expected to result in a wide use of themethodology by the engineering community, as well as greater visibility, power and finally usefulness in practice. Eventually, this would help to establish the systemic approach and assist in a better communication between different stakeholders.

At present, the OpenQuake tool already allows seismic hazard analysis with a large set of GMPE models, vulnerability and damage analysis of point-like components or region-like components which is the prerequisite for a systemic approach. OpenQuake directly includes a large set of taxonomy and fragility models only for buildings, therefore it would be necessary to incorporate models for the components (both nodes-like and edge-like) of the other critical infrastructures. Moreover, for the introduction of the systemic approach in the OpenQuake platform, the following capabilities will need to be incorporated in the platform: vulnerability and damage analysis of line-like components like pipelines or cables, connectivity analysis through the network-based approach of the system, computation of systemic performance indicators. The incorporation through SYNER-G+ of the SYNER-G concept to OpenQuake would not only allow to establish a powerful systemic approach, but it would also further enhance the capabilities of OpenQuake, which is presently focused on buildings. The integration of the SYNER-G methodology in a widely accepted, well-calibrated, user-friendly and open-source tool like OpenQuake would certainly facilitate a better understanding of complexities due to interaction among critical infrastructure operations, and enable well-informed decision-making and efficient disaster risk management by infrastructure owners and operators, insurance companies, consulting agencies and local authorities. It would help to evaluate the overall impact of interdependencies on the performance at city/region scale, and assist in identifying the critical components or system as a whole for disaster mitigation. One can scrutinize in a backward direction each factor or component or method involved for identifying the topological insufficiency, functional vulnerability or do some sensitivity analysis to study its overall effect and come up with better mitigation plans or recovery models.

OpenQuake is based on the PYTHON programming language and is available in public repository. PYTHON itself, being open-source, offers vast libraries support assisting to the wider application not limiting the usage to only core programmers. As a further research work in this direction, in SYNER-G+ abstraction of the concept and methodology is coded in PYTHON using various available libraries that are coherent to the development of the OpenQuake platform. For example, for the connectivity analysis of the water supply system (WSS) interdependent to electric power network (EPN), the two networks are formed with a set of nodes and edges. The damageability of each node-like vulnerable components of the interconnected systems is checked from the the hazard computation directly provided from OpenQuake. The capability of estimating vulnerability and damageability of the edge-like components directly from OpenQuake should be introduced. For instance, for pipelines, which have a varying topology due to their line-like structure, the assessment of damage may not be straightforward, since the respective fragility curves correlate repair rate with PGV and PGD, from which eventually the probability of damage is computed using Poisson distribution. Subsequently, the various conditional statement are introduced to model the interdependencies between various components of the systems and the functionality/operability of the components added to its own vulnerability should be updated. Ultimately, after knowing the state of each component, connectivity analysis of a system, in this example the WSS network, is performed using an algorithm based on graph theory to distinguish the isolated demand nodes from the sources and to compute the water connectivity loss. Similarly, other critical infrastructures shall be introduced accordingly based on a systemic approach.

5. Application

In the frame of this work, an application of the under development SYNER-G+ is presented. More specifically, the impact to the water supply system of Thessaloniki of the interdependent electric power network has been studied for a specific seismic scenario case. This analysis allows proper planning and prioritization of the mitigation actions before and after the earthquake, concerning in particular the vulnerability of transmission substations of electric power network and its effect on the connectivity loss of water supply system. At this stage, there is an ongoing process of implementing, and checking through application examples, as the one presented herein, the various new modules of the SYNER-G+ approach in OpenQuake.

A simplified model of the water supply system (WSS) of Thessaloniki, considering only the main lines, is shown in Figure 2, consisting of pumping stations, storage tanks, pipelines and demand nodes. Interdependencies with electric power network (EPN) is taken into account considering the functionality of transmission substations to ensure electricity supply to pumping stations. The EPN substations are also shown in Figure 2. For the seismic hazard analysis, the scenario of the Mw 6.5 1978 Thessaloniki earthquake was applied using the OpenQuake engine. The event was simulated as an earthquake rupture using the fault rupture model by Roumelioti et al. (2007). For strong ground motion modelling, we used the GMPE model for active shallow crustal regions by Akkar & Bommer (2010). The local soil conditions are available for Thessaloniki from its microzonation study (Anastasiadis et al., 2001).

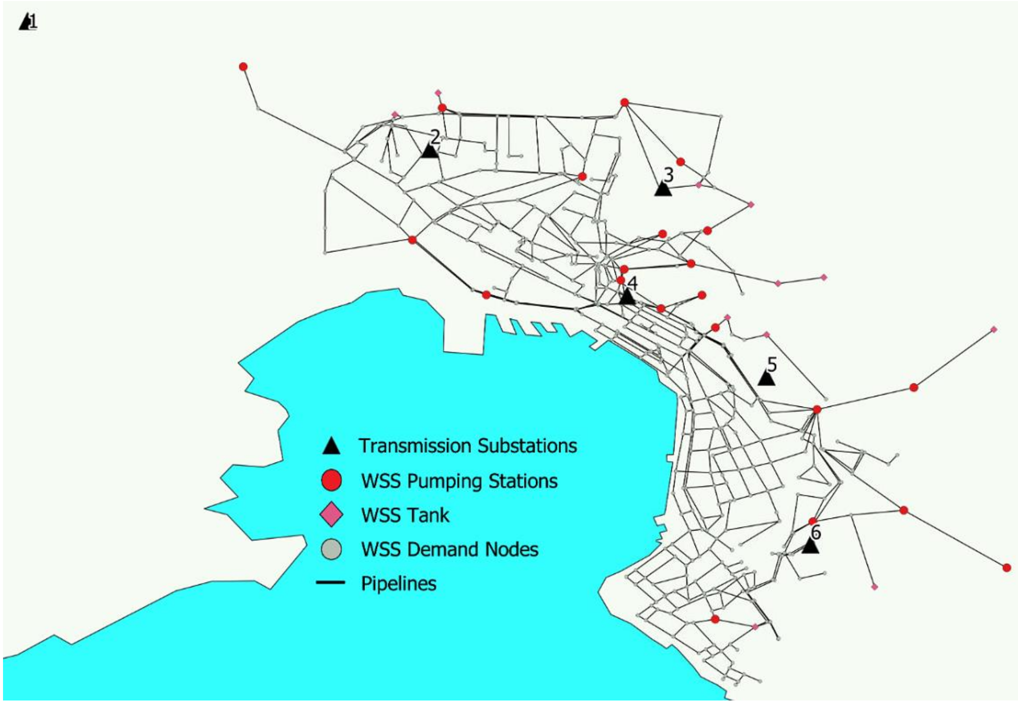

Figure 2: Water supply system and transmission substations of electric power network of Thessaloniki

The calculated spatial variability of the appropriate intensity measures, namely PGA and PGV, have been then used to perform the vulnerability and damage analysis for each vulnerable component, i.e. transmission substations of EPN and pumping stations and pipelines from WSS with the help of appropriate fragility curves. Three types of substations are identified, i.e., as closed type, opened type and the mixed type and the fragility model is employed from SRMLIFE (2007). For simplicity, all the pumping stations are considered to be anchored components in low rise R/C buildings with a high-level seismic design using adequate fragility curves employed from SRMLIFE (2007). For the pipelines, the fragility model is employed from ALA (2001).

After obtaining the damage state of each component, the next step is to model interdependencies and perform the connectivity analysis. Here, the interdependency considered refers to the linkage between electric transmission substations of EPN and pumping stations of WSS. It means that the functionality/operability of the pumping stations is not only dependent on its own vulnerability/damageability but also on the functionality and damages of the particular substation through which it gets an electric supply. The overall impact to the WSS is measured with an appropriate performance indicator, which in this case is the water connectivity loss (WCL). WCL gives the ratio of isolated demand nodes before and after the earthquake event. Box plot showing the value of WCL with and without interdependencies is shown in Figure 3. From this figure, it can be seen that the mean value of the water connectivity loss is increased from 0.048 to 0.082. Therefore, the effect of interdependencies is important and should be taken into consideration while analyzing the performance of WSS.

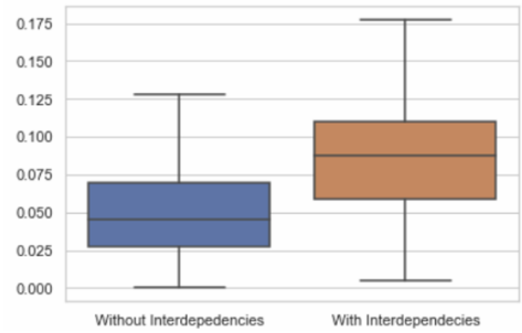

Figure 3: Box plot of water connectivity loss with and without interdependencies

Assuming that the resources are limited both in terms of budget and manpower, the authorities may need to prioritize the mitigation strategies in the preparedness periods and the recovery phase. So, after knowing the overall impact to the WSS considering its own vulnerability, intra-dependencies between its components and the EPN, it is now necessary to identify the critical component for efficient mitigation and recovery planning. In this example, it has been decided to analyze only the 6 main transmission substations shown in Figure 2.

The functionality of transmission substations themselves and the connectivity of those substations to pumping stations and eventually to demand nodes are the two factors that should be analyzed to check their effect on the performance of WSS. The functionality of the transmission substations is again dependent on its own vulnerability and the connectivity with other components of EPN. However, as transmission substations are the only components of EPN considered to be vulnerable, connectivity with other components of EPN is out of the scope in this study. Figure 4 shows the probability of the damage state of each transmission substation obtained from the OpenQuake engine according to the numbering given in Figure 2. From this figure, we can observe that substation number 6 is the one most prone to damage due to its own vulnerability (without considering any interdependency). Secondly, the effect of each transmission substation to the pumping stations eventually impacting the demand nodes was checked in terms of network topology or connectivity. This was done by evaluating the effect of the non-functionality of each transmission substation assuming that the rest of the components of the whole system are not vulnerable in terms of water connectivity loss. This would help to see the effect of each particular transmission substation alone on the whole system applying network topology. Results of the effect of the non-functionality of each substation are shown in Figure 5. From this figure, we can observe that substation number 6, followed by 4 and 5, are the substations with higher interdependence with the WSS, impacting the overall connectivity loss. Transmission substation number 6, which is of closed type, is the most vulnerable in itself and also, produces the highest impact to the water connectivity loss. Regarding transmission substations 1-5, we can see that the probabilities of damage for all of them are comparable (Figure 4); however, substations 4 and 5 affect more the WCL followed by 2 and 3. The results of this analysis, performed with the OpenQuake platform after integration of the SYNER-G methodology, allow us to identify the priority for the mitigation measures, allocation of redundant power supply and the actions in the recovery process, with respect to the impact on the water supply system.

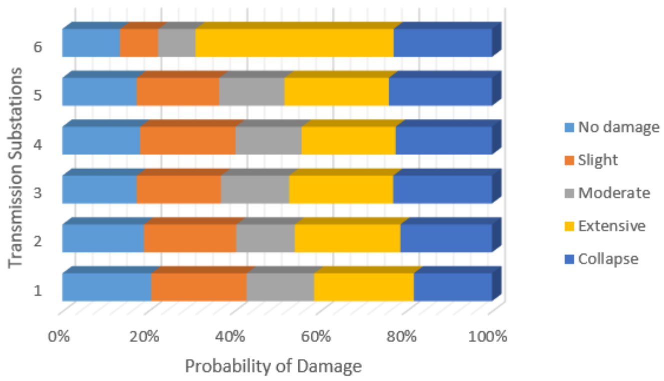

Figure 4: Probability of damage of each transmission substation

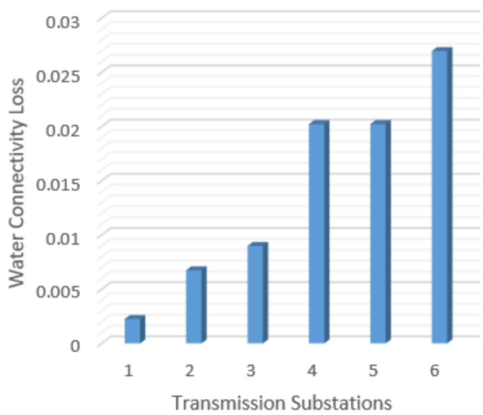

Figure 5: Effect to water connectivity loss due to failure of each transmission substation

6. Conclusions

In this paper, we shortly described the importance of a systemic approach while modelling the seismic risk assessment of interconnected critical infrastructures and utility systems. For that the SYNER-G approach has been used, which, while is a robust approach in itself, still has limited usage at present in the disaster risk reduction field. Therefore, it has been decided to incorporate the components and conceptual tools developed in SYNER-G in a powerful, globally used, user-friendly tool like OpenQuake to allow extensive usage by many stakeholders' communities. The abstraction of the methodologies and framework of the SYNER-G is in process to be incorporated in the OpenQuake platform, which is expected to boost the platform towards seismic risk assessment of critical infrastructures including networks and eventually the systemic approach.

To demonstrate the capabilities of the prospecting SYNER-G+, i.e. the integration of SYNER-G approach in OpenQuake, we selected to show here an application of the effects of the interdependencies between the water supply system and the electric power network. The results highlight the way the impact of the interdependencies between interacting systems may be evaluated through this promising incorporation of the systemic approach in an existing powerful hazard and risk assessment tool like OpenQuake.

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