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Assessment of Systemic Seismic Vulnerability and Risk in Urban Infrastructure and Utility Systems: A Review

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Abstract**—** Seismic vulnerability and risk assessment of infrastructure and utility systems are critical for adequately preventing or mitigating negative outcomes, implementing resilience management techniques, and recovering quickly after a severe earthquake. Having numerous interacting and interconnected infrastructures becomes even more necessary in a complex metropolitan context. Earthquake threats do not just harm one asset; their impact is significantly bigger due to the inter- and intra-dependence of multiple infrastructure, utility systems, and lifelines. As a result, we urgently require effective techniques for quantifying and assessing the systemic vulnerability and risk of urban infrastructure and utility systems. This is a difficult problem that is attracting increased attention from the scholarly community, industry, and government. The purpose of this study is to explore the various modelling methodologies and tools for seismic risk assessments of linked systems, including their benefits and limits. It focuses on the European-funded SYNER-G project, which addresses interdependencies, provides a holistic approach, and implements a complete framework based on the Object-Oriented Modelling paradigm. The SYNER-G framework's capabilities are demonstrated through a selected application involving the seismic risk analysis of linked infrastructure and utility systems in Thessaloniki, Greece. Among other things, the paper discusses hazard modelling issues of the two common approaches, the probabilistic and the scenario-based procedure, and illustrates the impact of mitigation strategies in a specific example, based on their effect on the performance of interconnected systems and overall loss reduction. The incorporation of interdependencies into risk analysis and resilience strategies allows for a better understanding of critical infrastructure operation and allows for well-informed proactive and reactive decision making as well as efficient disaster risk management by infrastructure owners and operators, insurance companies, consulting firms, and local governments.

Keywords**—SYNER-G, Seismic vulnerability, risk assessment, utility systems**

I. INTRODUCTION

Earthquakes have been one of the world's most devastating natural disasters, wreaking havoc on people's lives and economies. It is critical to create a more secure and robust constructed environment in order to deal with the effects of the earthquake. Evidence from previous earthquakes illustrates the fragility of infrastructure assets and has helped to the creation of seismic risk models for various components of the built environment. One of the essential components to be investigated for earthquake risk assessment and mitigation is vulnerability analysis of various structures. However, although most existing vulnerability models focus on specific structures or system components, the impact of an earthquake is not limited to a single structure. It should be investigated from a comprehensive perspective, integrating all of the components of a complex system, such as a metropolitan environment, with inter and intradependencies between them. Previous seismic disasters, such as the 2012 Christchurch earthquake and the 1995 Kobe earthquake, among many others, demonstrate that the rising effect is considerable due to the interdependence of essential infrastructures. As a result, a systemic vulnerability and risk assessment of the infrastructure is critical to a comprehensive strategy. The major issue of the systemic approach and the main emphasis of this study is considering intradependencies among components of the same system as well as interdependencies between different systems. Addressing the issue, the SYNER-G project established a comprehensive method through an integrated effort among a few.

The parts that follow provide an overview of available approaches for modelling critical infrastructure interdependencies, as well as a brief discussion of the SYNER-G methodology and its application to seismically vulnerable infrastructure in Thessaloniki, Greece. The programme incorporates crucial component identification, which is necessary for decision-makers to prioritise expenditure in order to limit risk.

The paper's main topic is the water supply system, which is often made to last for a very long time and should be able to withstand a variety of risks during the course of its existence.

In addition to its inherent vulnerability, it is important to consider how the water supply system interacts with other infrastructures, such as the electric power network, as power outages might result in significant losses in the water supply system. In order to analyse the possible effects of mitigating measures to increase the resilience of the water system, an example of improving the performance of the power supply system is employed.

II. MODELLING OF CRITICAL INFRASTRUCTURES' (CIs) INTERDEPENDENCIES

Infrastructure, according to PCCIP is "a network of autonomous, largely privately owned, man-made systems and processes that work cooperatively and synergistically to produce and distribute a continuous flow of essential goods and services." Critical among them are those whose destruction might have a crippling effect on economic and personal security. In the past, CIs frequently went unnoticed until unanticipated failures occurred. Due to interdependencies, CIs' effectiveness is less apparent in a stable environment, but their influence is significantly greater when an extraordinary event has just occurred. Due to their inability to be contained within the confines of a single infrastructure, external hazards like natural catastrophes might considerably enhance the losses brought on by interdependencies. Understanding and evaluating current vulnerabilities and interdependencies of assets and networks is crucial for reducing losses in any critical infrastructures owing to all types of catastrophes. Additionally, it should be mentioned that the current environment, which includes urbanization, climate change, and a rise in demand for CI services, makes infrastructure failure much more detrimental. Rinaldi et al. make one of the most notable attempts to convey the idea that critical infrastructures (CIs) do not behave in isolation but rather are strongly linked to one another. This describes dependencies in terms of four categories: logical (dependencies other than the others mentioned), geographic (effect of local environment on multiple infrastructures due to geographic proximity), cyber (information flow among different infrastructure systems), and physical (state of one infrastructure affects the material output of another). The systemic approach, along with the benefits and drawbacks of simulating CI interdependencies using simulation methodologies in the context of natural disasters, is outlined in Table 1.

Table 1: Methods for modelling critical infrastructure interdependencies

Methods	Description	Advantages	Limitations
Empirical methods	"-Analysis is carried out in accordance with past occurrences and professional opinion"	Based on real-time data, it may represent physical, geographic, logical, and cyber interdependencies and has a relatively low processing cost. It can also provide a good form of validation in addition to other sorts of analysis.	-Possibility of being biased due to unstandardized techniques of data collection -Reliance of the previous record to the new disaster
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
Agent based modelling	Bottom-up approach, which is Based on the idea that complexity arises through the interaction of several individual agents with their environment in accordance with a set of rules.	Gives a clear visual and graphical depiction of the behaviour and has the ability to handle unknown component properties. Can depict physical, logical, geographic, and cyber interdependencies; Support time-stepped simulation;	"-Calibrations is frequently difficult due to the limited availability of information on CIs," according to the statement "-Computational cost is relatively high -Complicated to simulate for macro-level analysis."
System dynamics	"-Top-down approach, with the aid of a stock and flow diagram illustrating the flow of information and a casual-loop	meso to macro level simulation versus agent-Based approach Models	Component level dynamics analysis is not possible. The semi-quantitative technique

	diagram showing influence among variables."	interdependences dynamic behaviour, capturing cause and effect, and it is capable of representing physical, logical, and cyber-interdependencies.	heavily relies on the subject matter expert. A large quantity of data is needed for calibration.

Input-output models, Petri nets, Bayesian network-based models, high-level architecture, or artificial neural network techniques are some more techniques for describing interdependencies. Each strategy has a purpose, and the combination of different approaches may produce a more accurate depiction and comprehension of the system performance.

The hybrid modelling approach, such as object-oriented modelling (OOM), used in SYNERG, can include additional techniques, giving the modelling flexibility for maintenance and extension in accordance with future requirements. The interaction and link between systems and components are constructed from the primary functional unit and are categorized as classes and objects in the OOM paradigm. OOM is one of the reliable simulation technologies since it can be centrally controlled and, unlike agent-based modelling, objects only respond to commands. This approach has a strong track record of absorbing the complexity and scale of the system of systems. The OOM paradigm's guiding principles of inheritance and composition enable the model to be very abstract and decompose hierarchically.

It is also important to note that the systemic approach for the complex network of infrastructures has not been addressed in the majority of recent large-scale efforts developing loss models at an urban and global scale, including HAZUS, CAPRA, GEM, RISK-UE, LESSLOSS, IFRARISK, MAEviz, OPENRISK, and RISKSCAPE, to name a few. The SYNER-G project is one of the major achievements made in the area of systemic vulnerability.

III. THE SYNER-G METHODOLOGY

One may think of infrastructure as a complicated system of systems. This indicates that the collection of parts, which are themselves systems, are ordered hierarchically and have a very wide variety of actual states. Three fundamental models—the hazard model, the component's physical vulnerability model, and the system (functional and socio-economic) model—make up the SYNER-G technique, which was developed to handle this issue thoroughly. Pitilakis et al. provide information on the approach in detail. But in a nutshell, the project offers an all-encompassing methodology and comprehensive framework that includes: (i) a thorough taxonomy of infrastructure systems and components, such as 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) component fragility assessment; and (iv) modelling. SYNER-G is made up of populated regions, transportation and utility networks, and vital infrastructure. Accordingly, different systems are shown as region-like, network-like, and point-like systems. By using vulnerability, connectivity, capacity, and fault tree assessments, these systems are assessed. The results of these assessments are summarized in terms of representative performance indicators (PI), which assess how well the system and the seismically vulnerable components are performing.

The study from SYNER-G aids in identifying the important parts or system as a whole to be enhanced for the disaster mitigation measures in addition to providing the overall impact of interdependencies on the performance of the city/region. Through comparison to the final metrics that are crucial for strategic catastrophe planning, one may determine the topological inadequacy, functional vulnerability, or the most sensitive component. One of the findings of this study is this realization and the effect of the mitigating techniques.

IV. UTILITY SYSTEMS' SYSTEMIC VULNERABILITY

Hazard modelling, choosing fragility functions, taking into account interdependencies, and evaluating the water supply system's performance using performance indicators are all aspects of the SYNER-G method. These are briefly outlined here.

a) Hazard

For the purpose of performing a probabilistic seismic risk analysis, a sample of ground movements for a single deterministic scenario and a collection of stochastically produced events are generated using the "Shakefields" approach. The steps involved in putting this procedure into practise are (i) creating a source event with a specified magnitude and geometry (point, rupture surface), (ii) attenuating the median ground motion field using the appropriate ground motion prediction equation (GMPE), (iii) creating a standard Gaussian field to represent the spatial correlation structure of the necessary intensity measure (IM),

(iv) creating ground motion values for various IM, and (v) scaling the ground motion factor.

b) Fragility Functions

For the purpose of performing a probabilistic seismic risk analysis, a sample of ground movements for a single deterministic scenario and a collection of stochastically produced events are generated using the "Shakefields" approach. The steps involved in putting this procedure into practise are (i) creating a source event with a specified magnitude and geometry (point, rupture surface), (ii) attenuating the median ground motion field using the appropriate ground motion prediction equation (GMPE), (iii) creating a standard Gaussian field to represent the spatial correlation structure of the necessary intensity measure (IM), (iv) creating ground motion values for various IM, and (v) scaling the ground motion factor. In the context of this paper, pumping stations, pipelines, and demand nodes have been modelled; pipelines have been taken into consideration as a component that is vulnerable to direct damage due to ground shaking, and pumping stations have been taken into consideration as a component that is vulnerable to power failure while taking into account the interdependencies with electric power substations. Peak ground velocity and permanent ground displacement have been chosen as the IM for pipelines in this study based on research from the literature. In order to describe the number of anticipated repairs per unit length of the pipes for a specific seismic intensity, damage is typically represented in terms of repair rate. The fragility functions established by ALA (2001) for subterranean pipelines are used in this study because they provide a reasonably accurate estimation of the vulnerability. Equations (1) and (2) provide the repair rate RR (in km) as a function of PGV (in cm/sec) and PGD.

$$RR = K_1 \text{ X } 0.002416 PGV \text{.......... (1)}$$

$$RR = K_2 \text{ X } 2.5829 PGD^{0.319} \text{...... (2)}$$

where K_1, K_2 are the values that may be used to modify them based on the kind of material, connection type, soil type, and pipe diameter.

The interaction with the electric transmission substations is taken into account in the framework of this article and will be discussed in the following sections. According to the findings of a previous project, the vulnerability of the electric power transmission substations has been assessed in terms of peak ground acceleration (PGA) to verify the damageability of substations. According to voltage level, EPN substation systems are divided into closed-type (sub-components completely contained in the building of a separate vulnerability) and open-type. Circuit breakers, power switches, transformers, and buildings (in the case of closed-type) are just a few examples of the various sub-components whose damage functions are probabilistically combined to evaluate the substation system's fragility curves in terms of the fault tree/Boolean method.

Focusing on the resilience of the structure at the component level, which is likely to be more vital given the severity of the hazard at the site and the degree of connection of its condition to the overall performance, is crucial for reducing the effect of earthquakes. By appropriately reinforcing the components, mitigation measures can be used, which would be reflected on updated fragility curves throughout the study. Since the interdependencies between WSS and the EPN system are the focus of this study, attention is placed on examining how improving the EPN substations would affect WSS's overall performance.

c) Systemic Vulnerability

WSS primarily interacts with the building stock (BDG), the health care system (HCS), and the electric power network (EPN). Physical damage to EPN results in the pumping station's inability to function, demonstrating the physical interdependence of WSS and EPN. WSS and BDG are physically interdependent since a shortage of water supply causes a population to be relocated and increases the need for housing. Again, there is a physical connection between WSS and HCS since, over time, a hospital's lack of water supply makes it more difficult to respond to emergencies. This study solely takes into account the interaction with EPN, or substations. It is crucial to assess the condition of the electric power substations since pumping stations need an electric supply to function. Damage to the substations will immediately impact the operation of the related pumping stations, and ultimately the entire system would be unable to provide water to its end consumers. As a result, a simulation is used to understand how certain EPN transmission substations are connected to WSS pumping stations. Following analysis, the most important elements must be examined in order to determine the level of interdependencies and susceptibility before choosing additional mitigation tactics.

For the connectivity analysis, many performance indicators (PI) (such as damage ratio, service ratio, connectivity loss, redundancy ratio, and reachability) are applied to assess the connection between the supply and demand nodes. The flow analysis determines if the system can supply enough water to the user or can fulfil the demands at the demand node. It is typically calculated using the average head or flow rate between before and after the earthquake at each node.

Water connection loss (WCL) is used as a single performance measure in this study and is provided by,

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

Where, N_i^s and N_o, respectively, represent the number of linked nodes under seismic and non-earthquake situations.

Understanding the overall functioning of the system following the earthquake is made easier by the computation of metrics like WCL and other analysis from SYNER-G. We may assess the extent of the effect of other systems like EPN on WSS when allocating the interdependencies to the analysis. This aids in determining the best mitigation solutions, such as retrofitting a particular important component, addressing topological inadequacy, or boosting redundancies in the event of catastrophic occurrences.

VI. CONCLUSIONS

The article briefly addresses the various interdependency modelling techniques in the context of physical infrastructures exposed to natural disasters. In particular, the conclusions and contributions of this study are as follows.

- The many ways for calculating interdependencies that are now in use each have their own relevance, and combining different approaches may improve how the performance of the system is represented and understood. SYNER-G, which is based on the OOM paradigm and functions as a hybrid modelling methodology, may integrate other techniques, giving the modelling flexibility to be maintained and expanded in response to changing demands.
- The probabilistic model in the systemic method provides a logical overview, capturing the correlation of all the crucial elements to overall performance that would have been missed by the deterministic approach, as in any sort of vulnerability and risk assessment.

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