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TOWARDS A UNIFIED SEISMIC- FLOOD- HAZARD MODEL FOR RISK ASSESSMENT OF ROADWAY NETWORKS IN GREECE

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Abstract

Roadway networks, playing a vital role in the economic prosperity of modern societies. Recent hazardous events in Greece, for instance, the 2021 Thessaly earthquake and floods and the heavy 2019 rainfall in Crete, have demonstrated the vulnerability of roadway networks to natural hazards, resulting in severe physical damage and important economic and societal losses. Severe damage on bridges and tunnels of roadway networks is commonly related to the effects of multiple hazards that may act independently during their life. However, the literature on risk assessment of the above elements is commonly focused on the effects of one hazard, disregarding the potential interaction effects of diverse hazards in a multi-hazard environment. In this context, there is an increasing need for reasonable and effective evaluation of the multi-hazard risk of transportation infrastructure. Research project INFRARES aspires to bridge this gap by gaining further insight into the risk assessment of bridges and tunnels of transportation networks in Greece, when subjected to separated and subsequent hazards, with particular emphasis being placed on seismic and flood hazards. The present paper briefly presents a unified methodology to homogenize the single seismic and flood hazard scenarios and develop appropriate single- and multi-hazard maps for Greece to be used in risk assessment of roadway networks. Seismic hazard data, referring to rock site conditions, developed within the SHARE research project (www.share-eu.org), is initially selected and is properly amplified to account for site effects, by employing a simplified $V_{S,30}$ model originating from morphology and topography data of each region in Greece. The seismic hazard is estimated for a return period of 475 years. Flood hazard zones are derived for whole Greece using newly developed data from the Joint Research Center of the European Commission (https://data.jrc.ec.europa.eu/dataset) for the 100-years return period scenario. Using the above input, both single hazard and multiple hazard models are developed and provided in terms of maps in GIS format. The model developed within this study is expected to be a valuable contribution towards the generation of a uniform multiple hazard model for the risk assessment of critical elements of transportation infrastructure in a multi-hazard environment.

Keywords: Natural hazards, earthquakes, floods, multi-hazard risk assessment.

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1 INTRODUCTION

The reliability of roadway networks and their components, exposed to multiple natural hazards, is on the frontline of engineering research during the last three decades since potential damage on their critical components (e.g., bridges and tunnels) is strongly related to important direct and indirect economic losses. In this context, enhancing the resilience of roadway networks is key for a safety and an economic viewpoint. Disaster resilience is defined by the National Academies as "*the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events*," while "*enhanced resilience allows better anticipation of disasters and better planning to reduce disaster losses – rather than waiting for an event to occur and paying for it afterward*" [1]. To achieve such enhanced resilience, civil infrastructure systems must not only survive natural disasters, but also recover to functional levels within acceptable time and cost limits.

The spatial extent of most civil infrastructure systems, including roadway networks, and the disparity of their elements make them susceptible to a wide range of natural hazards. Bridges and tunnels are considered to be the most critical components of urban and interurban transportation systems, and as such should ensure mobility and intercity connection after extreme hazard events. Bridge damage may cause significant disruption to a transportation system, resulting in severe substantial direct and indirect losses; for instance, the Loma Prieta 1989 earthquake resulted in more than 40 deaths due to bridge damage and $1.8 billion monetary direct losses due to damage to the transportation infrastructure [2]. Flood due to heavy rainfall may result in substantial losses, as well; for example, in 2007, heave rainfall in the UK affected the road network with estimated cost £60 million (The Parliamentary Office of Science and Technology, Post Note Number 362, October 2010). Extreme weather conditions, associated with recorded climate changes, e.g., floods and extreme temperatures, are expected to worsen the performance of many bridges in the near future [3]. Damage on bridges due to extreme weather conditions in Greece (e.g., reported damage due to heavy rainfall in Trikala in 2016 and in Crete in2019) is more frequently recorded during the last years. Bridge damage related to flood, scouring and ground failures may result in collapse and traffic disruption. Although to a lesser extent, natural hazards may result in damage on tunnels as well. For instance, a large number of mountain tunnels suffered significant damage during the 1999 Chi-Chi earthquake in Taiwan, as well as during the 2008 Wenchuan earthquake in China [4].

During the last 30 years, several methods have been developed for the assessment of performance and vulnerability of bridges [5] and tunnels [4, 6] against seismic and flood hazard [7]. Recognizing the significant effects of multiple hazards, as well as of climate change, on the vulnerability of civil infrastructure, the research interest has been recently shifted upon the derivation of multi-hazard fragility curves [8]. However, the lack of knowledge in this field remains significant, when referring to transportation infrastructure, including roadway networks.

Regardless of the examined system or element at risk, one of the most critical steps of any multi-risk assessment methodology is the appropriate definition of multiple hazard scenarios under which the examined system or element may be subjected throughout its life.

Based on the above considerations, the main objective of the present paper is to present briefly a framework for the development of combined seismic- flood-hazard scenarios to be used for the risk assessment of critical elements of roadway networks, i.e., bridges and tunnels, referring to whole Greece. The proposed framework helps towards a unified seismic- flood hazard model, which will be used in within the research project INFRARES (https://www.infrares.gr/) that aims at assessing the risk and resilience of bridges and tunnels of roadway networks in Greece against the aforementioned hazards.

2 INFRARES PROJECT

A comprehensive methodology for the risk and resilience assessment of roadway networks in a multi-hazard environment, will be developed in the framework of INFRARES, focusing on bridges and tunnels. To meet the objectives of the project, various methodological frameworks will be used, associated with the following steps enclosed in the definition and assessment of risk: (i) exposure: an inventory of crucial elements of transportation systems, i.e., bridges and tunnels, which may be affected by diverse natural hazards, will be developed accounting for typologies found commonly in Greece. (ii) Multi-Hazard assessment: various scenarios of distinct and multiple natural hazards will be defined, focusing on earthquakes and floods since these hazards are considered more relevant for the risk assessment of the transportation infrastructure in Greece. This step will include also the definition of appropriate measures to describe the intensity of examined hazards. (iii) Vulnerability assessment: the degree of loss on the given element or set of elements at risk, when subjected to a specific natural hazard or to a combination of diverse hazards will be calculated, by employing comprehensive numerical analyses of the selected elements, while accounting thoroughly for the effects of ageing-related degradation phenomena of the elements, as well as of Soil-Structure Interaction (SSI) effects.

A fully parametrized software will accompany the methodology, allowing for its easier application by providing the provided time-dependent, multi-hazard fragility curves for roadway bridges and tunnels. Figure 1 presents a first draft of the general flowchart of the methodology that is being developed in the framework of the INRARES project.

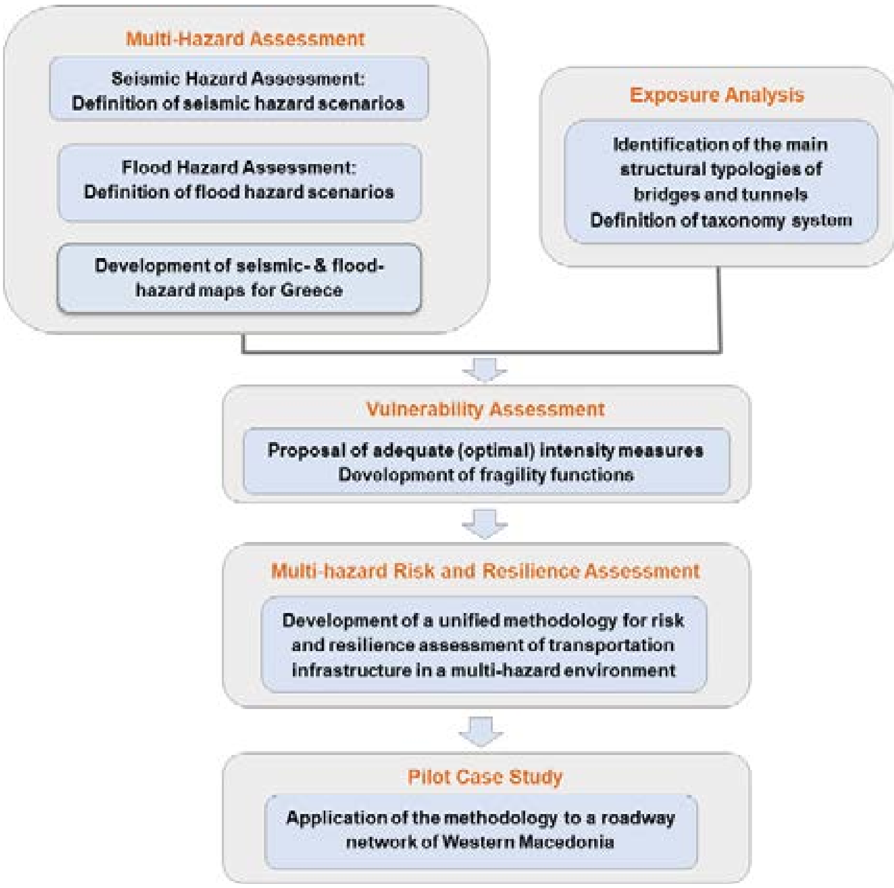

Figure 1: Flowchart of INFRARES project

In particular, INFRARES is expected to contribute on the State of the Art by providing an innovative methodology for the generation of multi-hazard maps, to be used for the definition of relevant scenarios in the framework of multi-hazard risk assessment of transportation or other civil infrastructure. In addition, new, analytical fragility curves and functions will be developed for various typologies of bridges and tunnels, and for distinct and/or combined hazards, considering in the latter case combinations of hazards that are relevant for Greece. Moreover, the damage state definitions within fragility analysis of bridges and tunnels will be case- and hazard-specific, considering different failure modes and damage mechanisms, to fill relevant knowledge gap. Finally, a resilience index will be proposed for bridges and tunnels typologies, as well as for roadway networks, referring to distinct hazards and various hazard combinations. In this context, the index will be appropriately modified so that to be applicable for multi-hazard assessment purposes. The methodology and the software could be used for rapid and rigorous pre- or post-event assessment of infrastructure or for post-event risk management, constituting very useful tools for stakeholders, operators, consultancies and public authorities.

In the following sections, we focus on one of the main steps of the methodology, namely the multi-hazard assessment. More specifically, we present an innovative methodology for the generation of multiple seismic- flood- hazard models in GIS format.

3 MULTIPLE HAZARD SCENARIOS FOR TRANSPORTATION INFRASTRUCTURE IN GREECE

In the framework of the multi-hazard assessment approach adopted herein, diverse natural hazards and combined hazards scenarios are carefully selected, prioritized on the basis of the potential to cause damage on transportation infrastructure and further examined. After a thorough literature review and lessons learned from past hazards events, earthquakes and floods are selected as the most critical natural hazards for the assessment of the transportation infrastructure in Greece. Initially, each natural hazard is studied separately, while in a second phase we examine the combination of the two hazards, proposing a unified framework for multi-hazard scenarios. Both single or multiple hazards scenarios are visualized in the form of maps in GIS format, referring to whole Greece.

The main steps of the herein proposed framework are:

Step 1: Establish a ranking of the different types of natural hazards, considering potential interactions between them.

Step 2: Identify single-hazard models.

Step 3: Identify multi-hazard models, covering all potential intensities and relevant hazard interactions.

Step 4: Generate single- and multiple- hazard scenarios and relevant maps in GIS format for the assessment of transportation infrastructure in Greece.

For the sake of presentation of the framework, in the present paper, we consider for the seismic hazard the standard design/assessment seismic scenario with a return period equal to Tm_s=475 years. For the flood hazard, we examine a design/assessment flood hazard scenario with a return period equal to Tm_f=100 years.

3.1 Single hazard maps

In the present work, a unified methodology is employed to homogenize the single seismic and flood hazard scenarios. These single-hazard scenarios are displayed in the form of GIS maps and can be used for the risk assessment of any examined element. Moreover, they may be used to and develop appropriate maps for multi-hazard scenarios as discussed in section 3.2.

Seismic hazard data for rock site conditions, developed within the EU-funded research project SHARE (https://www.share-eu.org), is initially selected. This data is subsequently properly amplified to account for site effects, by employing a simplified $V_{s,30}$ model, originating from morphology and topography data of the examined region. In the present study, the seismic hazard is estimated for a return period of 475 years.

More specifically, the seismic hazard estimates were extracted from the global seismic hazard map produced by Pagani et al. [89]. The hazard is expressed in terms of the Peak Ground Acceleration (PGA, as a fraction of g) for a probability of exceedance of 10% in 50 years (equivalent to a 475-year return period) on rock (average shear-wave velocity down to 30 m - V_{s30} = 760 m/s). A detailed description of how the global seismic hazard model was developed may be found in Pagani et al. [9]. The seismic hazard analysis is performed using the OpenQuake engine [10], an open-source seismic hazard and risk calculation software developed, maintained and distributed by the Global Earthquake Model (GEM) Foundation. Recent studies on the use of the European Seismic Hazard ESHM13 [11] may be found in Riga et al. [12] and Karatzetzou et al. [13].

With reference to the flood hazard, flood hazard zones were derived for one scenario based on 100 years return period. In particular, a newly developed dataset for Europe referring to river flood hazard, was derived from the Join Research Center of the European Commission [14]. The flood hazard zones were based on the combination of river flow data, estimated through the hydrological model LISFLOOD, while the inundation simulations were performed with the 2D hydrodynamic modelling LISFLOOD-FP. Subsequently, the hazard was expressed in terms flood extent zones in different flood frequencies (e.g., T=100 means frequency 1-in-100-years).

Figure 2 portray the resulted single hazard maps for Greece for the examined seismic and flood hazards scenarios, respectively.

3.2 Multi-hazard maps

For the homogenization of the single hazard maps of Greece (i.e., seismic hazard map and flood hazard map, presented in section 3.1), we used a bivariate scaling system. This qualitative approach is often used to depict pairs of variables, whose mathematical combination might not be straightforward or possible, for instance, social vulnerability and natural hazards [15] or seismic and biological hazards [16]. In the herein proposed framework, we define four thresholds to classify each variable into *low, moderate, high* and *very high* hazard. These thresholds are created automatically in Arc-Gis using the quantile method. Then, we create a color matrix comprising all the combinations between the two variables. In this study, we combine the seismic hazard in terms of the PGA for the selected return period (475 years) with the river flood hazard in the terms of the percentage distribution of flood hazard zones, respectively for return period equal to 100 years. Figure 3, presents the resulted multiple-hazard map for Greece, for the examined scenarios.

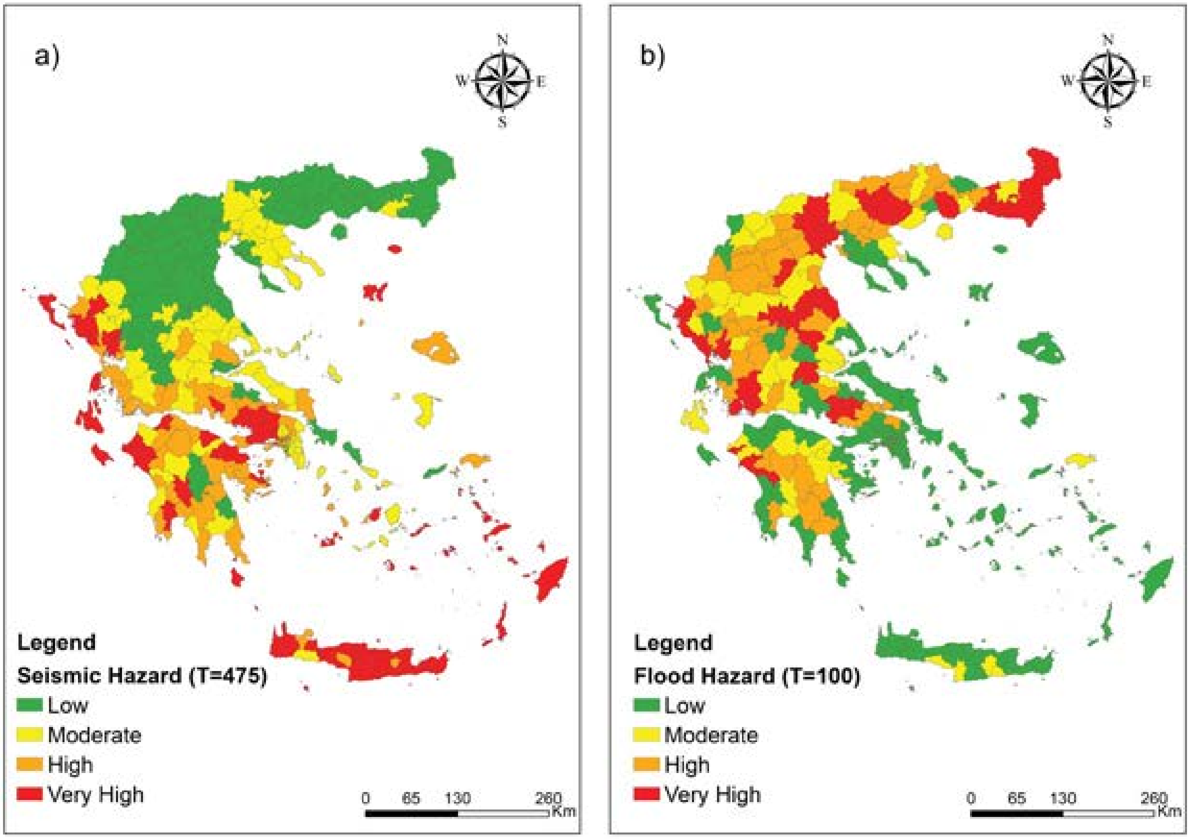

Figure 2: (a) Seismic hazard map for a return period equal to Tm_s=475 years and (b) flood hazard map for a return period equal to Tm_f=100 years for Greece

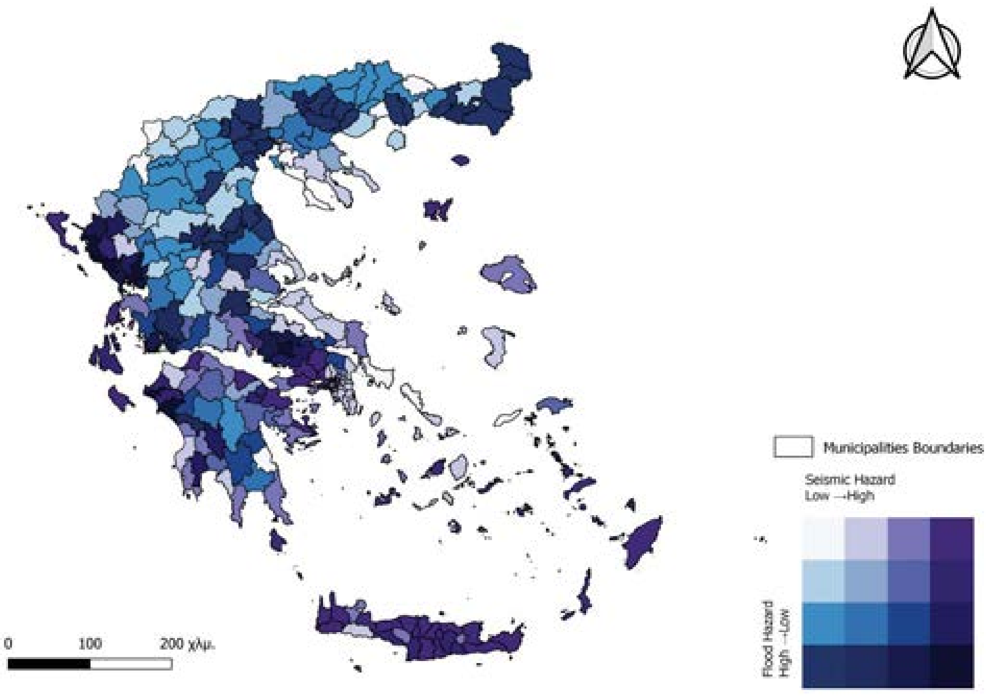

Figure 3: Bivariate map depicting the combination of seismic (Tm_s=475 years) and flood (Tm_f=100 years) hazard for Greece.

4 CONCLUSIONS

The present paper presented a unified framework to homogenize the single seismic and flood hazard scenarios and develop appropriate single- and multi-hazard maps for Greece to be used in an under-development methodology for the risk assessment of critical elements of transportation infrastructure in a multi-hazard environment. The work was developed within the INFRARES research project, which is also briefly presented.

With reference to seismic hazard; seismic hazard data for rock site conditions, developed within the SHARE research project (www.share-eu.org), was initially selected and is properly amplified to account for site effects of various regions in Greece, by employing a simplified $V_{s,30}$ model originating from morphology and topography data. The seismic hazard was estimated for whole Greece and for a 475-years return period scenario and plotted in a relevant map in GIS format.

Regarding flood hazard; flood hazard zones were derived for Greece from a newly developed database of the Joint Research Center of the European Commission [14] for one scenario based on 100 years return period. The resulted flood hazard was estimated for whole Greece and plotted in a relevant map in GIS format.

A bivariate scaling system was used for the homogenization of single-hazard maps referring to the above hazards. For the development of the multi-hazard map, four thresholds were automatically created in Arc-Gis to classify each hazard into *low, moderate, high* and *very high* level. A color matrix was then created comprising all the combinations between the two variables-hazards, leading to the creation of the multi-hazard map for whole Greece.

The framework presented within this study is expected to be a valuable contribution towards the generation of a uniform multiple hazard model for the risk and resilience assessment of roadway networks.

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