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RESILIENCE ASSESSMENT OF ROAD BRIDGES IN MULTI-HAZARD ENVIRONMENT

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Abstract

Highway transportation networks play a vital role in today's economic and societal life and affect growth and employment. Hence, their undisrupted functionality and their quick recovery even after extreme natural hazard events are critical. To this end, resilience assessment of transportation networks against natural hazards is needed for decision-making processes in planning maintenance and retrofit actions, as well as for post-event risk management. This study aims to propose a multi-hazard resilience assessment framework for bridges that are the key components of transportation networks. The first step of the framework is the identification of critical hazards (i.e., earthquakes, floods) and the derivation of hazard curves and scenarios based on their probability of occurrence. The second step consists of a fragility assessment process based on computational analysis for single or multi-hazard occurrences given a range of hazard intensities. The third step includes the evaluation of functionality losses based on fragility assessment. In the fourth step, the required restoration time is estimated, and resilience metrics are calculated as dimensionless indicators. The proposed framework is applied to a case study riverine bridge, and comparative results on the single hazard and the multi-hazard resilience metrics are discussed. It has been observed that the effect of the consideration of multi-hazard scenarios is significant on the resilience of bridges.

Keywords: bridges, seismic hazard, flood hazard, resilience

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1 INTRODUCTION

Multi-hazard resilience is a critical aspect of infrastructure design and management, especially in regions that are prone to natural disasters. Infrastructure assets are vulnerable to a variety of hazards, such as earthquakes, floods, hurricanes, landslides, and wildfires, which can cause severe damage, disrupt operations, and lead to economic losses [1]. Therefore, ensuring that infrastructure systems are resilient to multiple hazards is crucial for maintaining the safety, reliability, and functionality of these assets. The concept of multi-hazard resilience goes beyond the traditional approach of designing for a single hazard and considers the interdependencies and cascading effects that can occur when multiple hazards affect an infrastructure system. For example, a flood can cause damage to transportation networks, disrupt power supply, and contaminate water resources, which can in turn lead to further cascading effects. Hence, multi-hazard resilience, requires a holistic approach that considers the complex interactions among hazards, infrastructure assets, and the environment. Infrastructure systems that are resilient to multiple hazards have several benefits. They can withstand the impacts of disasters, minimize downtime, reduce damage and associated losses, and ensure the continuity of essential services. Additionally, multi-hazard resilience can help enhance social, economic, and environmental sustainability by improving the overall performance and efficiency of infrastructure assets.

In this context, it is critical to integrate resilience assessment into decision-making systems to support transportation network stakeholders in their strategic planning against natural hazards. For this reason, it is needed to provide appropriate metrics to quantify the capacity of civil engineering assets to “bounce back” from extreme events.

To facilitate the quantification of resilience considering various aspects, several methodological approaches have been developed. Cimellaro (2016) [2] provides a comprehensive overview of resilience indicators, e.g. indices, scorecards, tools and models, and their role in evaluating the resilience of different systems against natural and man-made hazards. Alipour and Shafei (2016) [3] presented the concept of resilience curves (time-functionality) and their use in quantifying the resilience of infrastructure systems against natural and man-made hazards. Numerous works focus on evaluating resilience against single hazard events. Deco et al (2013) [4] argue that traditional deterministic approaches for assessing seismic resilience are often limited by their reliance on simplified models and assumptions, which can lead to inaccurate predictions. The use of a probabilistic approach, such as the one presented in their paper, offers a more comprehensive and realistic way of modeling the complex uncertainties involved in seismic resilience. Capacci, Biondini, and Titi (2016) [5] also proposed a methodology to assess the seismic resilience of transportation networks. In recent years, the development of multi-hazard resilience strategies has become more popular since there has been a growing recognition that hazards can occur simultaneously or sequentially. Argyroudis et al (2020) [6] proposed a resilience assessment framework for critical infrastructure in a multi-hazard environment, with a specific focus on transport assets, including both quantitative and qualitative measures providing a detailed explanation of the framework, which includes four stages: (1) hazard analysis, (2) system analysis, (3) resilience assessment, and (4) resilience enhancement. The hazard analysis stage involves the identification and characterization of relevant hazards, while the system analysis stage involves the identification and modeling of the critical infrastructure system and its interdependencies. Most methodologies consider earthquake and flood hazards as the most critical ones for transportation assets and especially for bridges.

In line with the above, this study proposes a holistic methodology for the resilience assessment of assets of transport networks, which includes four distinct steps. The methodology may be applied in case of single natural hazards (separated in time) or combined hazards in a multiple-hazard environment, regardless of the interaction scenario and the hazard sequence (flood followed by an earthquake and vice versa, successive flood or earthquake events) and it is presented for the assessment of bridges (as one of the most important assets of transportation networks) The novelty of the methodology lies in the consideration of the effect of cumulative damage of the examined transportation asset caused by subsequent and unrelated natural hazards, on the resilience assessment of the asset. This is done by employing fragility functions that were developed for multi-hazard scenarios. In this paper, the proposed methodology is applied to a reinforced concrete bridge and the results for various hazard scenarios are presented.

2 DESCRIPTION OF THE RESILIENCE ASSESSMENT METHODOLOGY

The methodology consists of four steps that are summarized in Figure 1 and presented below. It is acknowledged that due to the diversity of hazards and their combinations, it would be impractical to describe every possible hazard scenario. However, the proposed framework aims to be comprehensive and representative by including several critical hazard scenarios that cover a wide range of potential events in a multi-hazard environment.

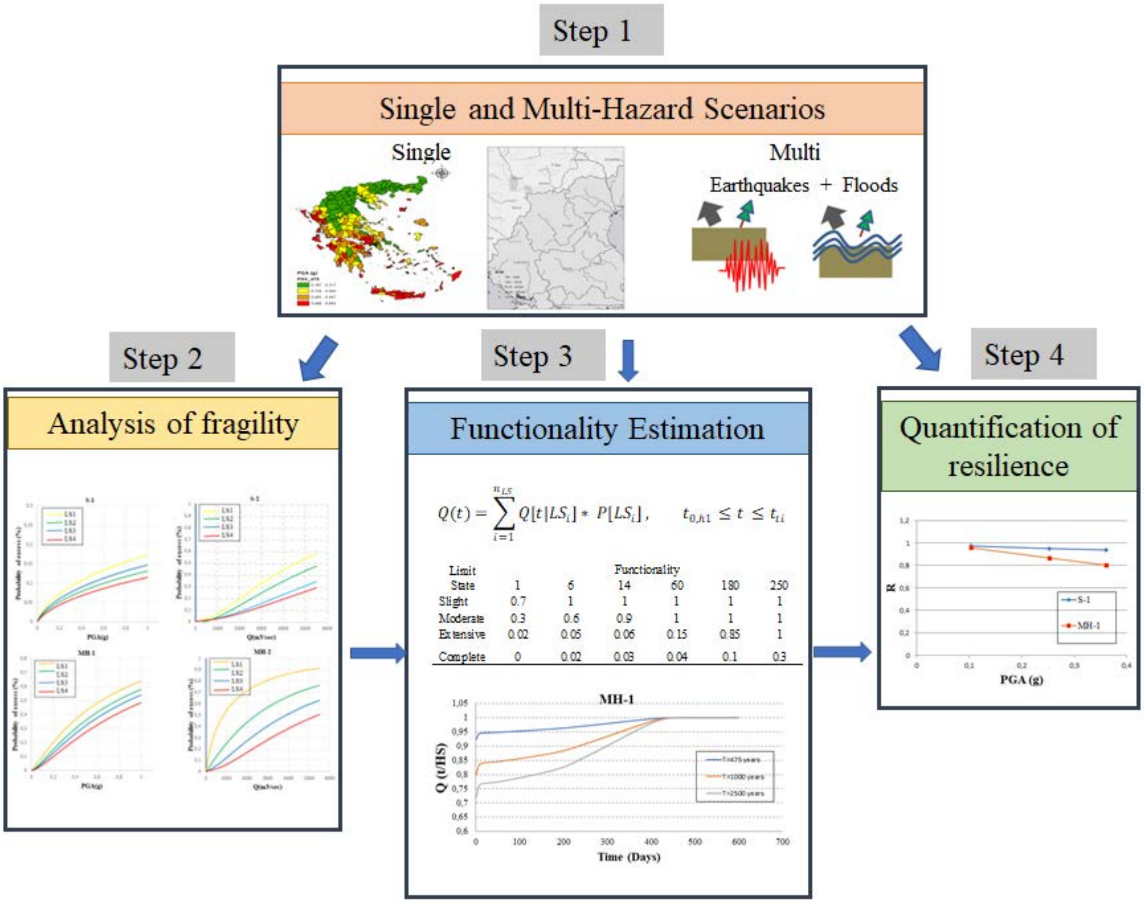


Figure 1: Multi-hazard Resilience Framework for road network components.

First step: Single and Multi-Hazard Scenarios

The purpose of this step is i) to identify the critical natural hazards that may occur at the location of the asset (location of interest) and ii) develop for these natural hazards appropriate single and multiple hazard models that will be taken into consideration in resilience assessment.

In this study, seismic and flood hazards are selected as the most critical natural hazards for the assessment of critical elements (i.e., bridges) of roadway networks in Greece [7].

For each critical hazard, appropriate intensity measures (IM) are defined accounting basically on their computability/availability and to some extent their effectiveness, efficiency, sufficiency and robustness. In seismic events, the Peak Ground Acceleration (PGA) or the Peak Ground Velocity (PGV) at ground surface may be used as adequate intensity measures to associate seismic hazard to structural damage. Accordingly, discharge (Q) can be used as the intensity measure for the assessment against flood hazard. After a literature review performed in the framework of INFRARES, Peak Ground Acceleration (PGA) is selected since this metric is used as intensity measure by the majority of studies proposing fragility functions for the assessment of bridges and tunnels.

In addition to the selection of an appropriate IM for each natural hazard, different scenarios with various return periods of the examined hazards should also be defined. These values could be derived from existing hazard maps, curves, or site-specific hazard analyses. Hazard analysis provides the probability of exceeding a specified level of demand in a given exposure period. Therefore, when hazard scenarios are considered in the analysis the occurrence probability is associated with specific return periods. Herein, each natural hazard is studied either separately or as a combination of the two hazards. In the framework of the multi-hazard assessment approach adopted herein, diverse natural hazards scenarios, as well as combined hazard scenarios are carefully selected and prioritized based on the potential to cause damage on the examined asset(s). It should be outlined that the present methodology accounts only for independent multi-hazard events that occur subsequently in time. The hazard assessment approach used in this study is presented in detail in [7].

Second step: Analysis of fragility

Fragility analysis is based on numerical analysis of a refined finite element model of the structure, conducted either for a single natural hazard or a multi-hazard occurrence for a given range of hazard(s) intensities. The approach employed herein is presented in detail in [8] whereas a short summary is presented in the following. The main core of the methodology is the same, regardless of the hazard considered. The critical components of the examined asset (e.g., bridge) are initially identified, and their capacity and limit state thresholds are estimated. An Engineering Demand Parameter (EDP) is selected for every component and damage is quantified based on the component's capacity curve, estimated on the basis of inelastic pushover analysis. The demand estimation at the component level is related to the hazard considered. Seismic analysis (i.e., dynamic analysis) is performed for selected earthquake ground motions and flood analysis (i.e., static analysis) is performed for selected discharge values, calculating the demand at control points of the selected components of the asset. To quantify the uncertainties in capacity and demand, random variables for the material and modelling properties are considered (distribution, mean and dispersion values) and samples are generated, using the Latin Hypercube Sampling method. Multiple analyses are performed for the estimation of capacity and demand and the derivation of fragility curves according to Equation 1.

$$P[D \geq d|IM] = 1 - \Phi\left(\frac{ln(D)-ln(\theta_i)}{\beta_{tot|IM}}\right) \tag{1}$$

Where $P[.]$ is the conditional probability that the component will be damaged to damage state ith or a more severe damage state as a function of demand parameter, D, Φ denotes the standard normal (Gaussian) cumulative distribution function, θ_i denotes the median value of the probability distribution, and $\beta_{tot|IM}$ denotes the logarithmic standard deviation.

For the derivation of bridge system fragility curves ($P(F_{system})$), fragility of all critical components is considered ($P(\,F_i)$) and Equation 2 is applied (upper and lower bound) [9].

$$^{i=1}_{\;n}max[P(\,F_i)] \leq P(F_{system}) \leq 1 - \prod_{i=1}^{\pi}[1 - P(F_i)] \tag{2}$$

For the fragility assessment against multiple natural hazards, i.e., seismic and flood hazards, the same methodology is performed. Several scenarios of uncorrelated and different (separated in time) hazard events can be developed for the derivation of system fragility functions. It should be outlined that the events are applied subsequently and, therefore, cumulative damage is considered in all examined multi-hazard scenarios

Third step: Functionality Estimation

Functionality is estimated after an extreme event or at different time steps during the retrofit/restoration phase of the structure under study. The evaluation of functionality is based on the fragility assessment and is derived by Equation 3 [10].

$$Q(t|HS) = \sum_{i=1}^{n_{LS}} Q[t|LS_i] * P[LS_i|HS], \qquad t_{0,h1} \leq t \leq t_{ti} \tag{3}$$

Where $Q(t|HS)$ is the functionality level at time t for a selected hazard scenario (HS) (multi/single), n_{LS} is the number of limit states used in fragility analysis, $Q[t|LS_i]$ is the functionality level at time t for the limit state LS_i, $P[LS_i]$ is the probability to be in this limit state as derived from the fragility curves t_{ti} is the time in the restoration process that is investigated, $t_{0,h1}$ is the time that the hazard occurs (single or multi-hazard).

Unfortunately, restoration functions for critical assets of transportation networks (e.g., tunnels and bridges) are rarely available in the literature.

. Due to this lack of data, the FEMA restoration functions [11] are used in the proposed framework. To represent more accurately the local conditions in Greece based a multiplication factor was applied to FEMA values based on expert judgment. In Table 1 the restoration time for bridges is presented. When multi-hazard scenarios are considered, regarding the subsequent events, it is assumed that no restoration has started after the first hazard event (assuming that the events have limited time difference). Therefore, the same restoration times are also applied for the multi-hazard scenarios.

Limit State	Functionality 1	6	14	60	180	250
Slight	0.7	1	1	1	1	1
Moderate	0.3	0.6	0.9	1	1	1
Extensive	0.02	0.05	0.06	0.15	0.85	1
Complete	0	0.02	0.03	0.04	0.1	0.3

Table 1: Restoration functions for Bridges in Greece

Fourth step: Quantification of resilience

In this final step, the results of the fragility assessment, the functionality losses, the estimated duration for repairs and the recovery process to restore functionality are combined to quantify the resilience of the bridge against single or multi-hazard scenarios.

More specifically, the resilience metric R is calculated based on Equation 4 [10].

$$R = \frac{\int_{t_{o,h1}}^{t_{ti}} Q(t)}{t_{ti} - t_{o,h1}} \tag{4}$$

Where R is the resilience index, t_{ti} is the time in the restoration process that is investigated, $t_{0,h1}$ is the time that the hazard occurs (single or multi-hazard) and $Q(t)$ is the functionality level at the time t.

3 CASE STUDY

3.1 Description of the case study bridge

The selected bridge is the Vardarovasi river bridge at the Thessaloniki-Giannitsa National Road Greece which was constructed in 1985. The case study is a typical river bridge with a deck of precast/prestressed beams, simply supported on three multicolumn piers with two cylindrical columns of diameter d =1.3 m each. The piers are founded on soil class C (according to Eurocode 8 [12]) by means of pile foundations, comprised of four reinforced concrete piles (length, l =33m, diameter d =1.0m) (Figure 2). The finite element model of the bridge was developed in Opensees [13]. Further details on the bridge simulation can be found in [8].

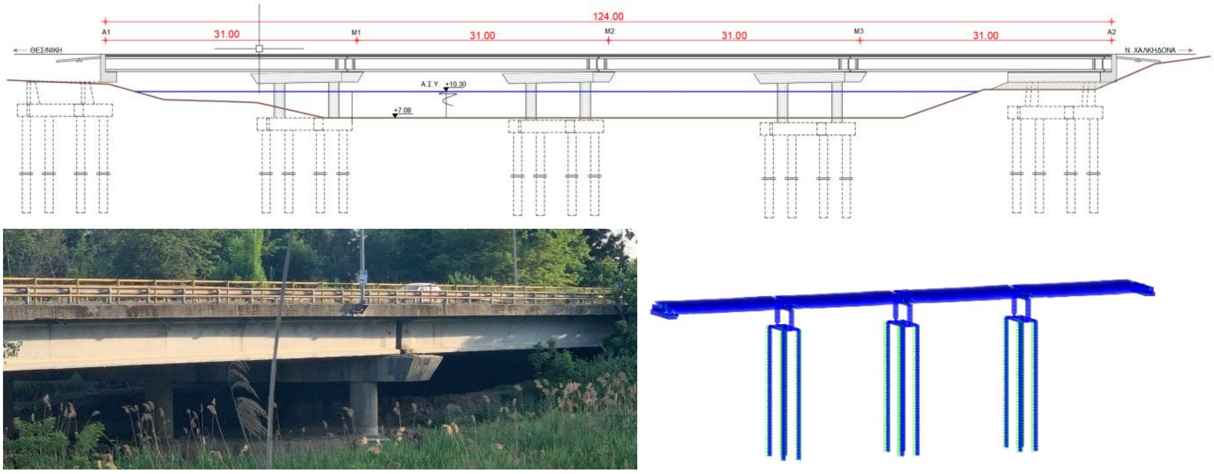


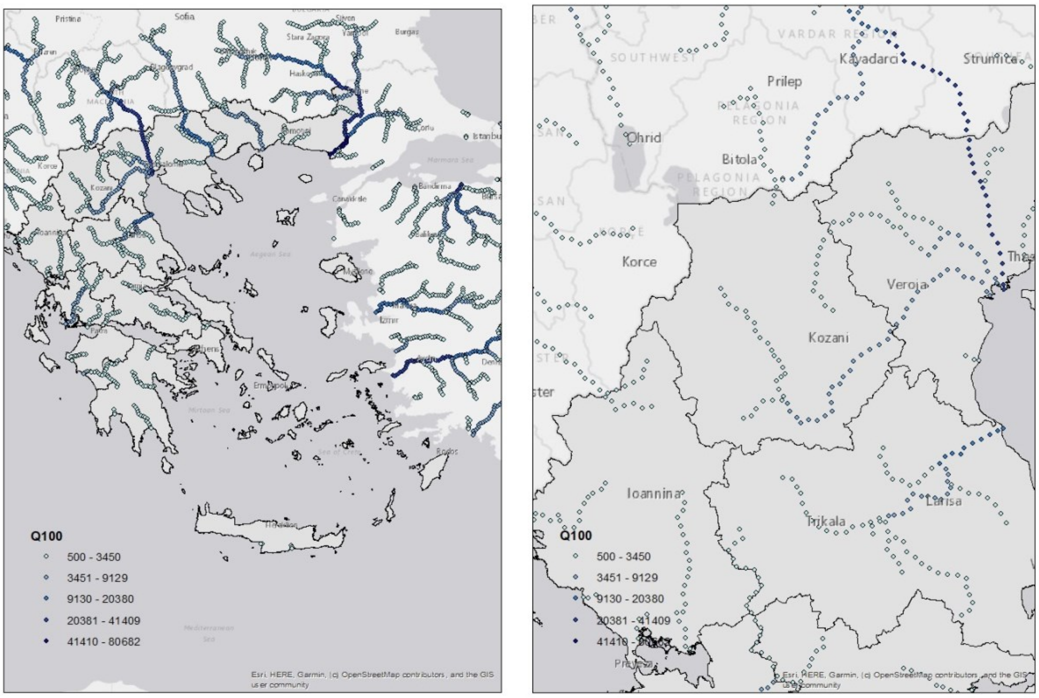
Figure 2: Drawings and 3D Model of the simply supported river bridge with prestressed/precast beam deck and multicolumn piers (Vardarovasi bridge).

3.2 Hazard Analysis

In the frame of the selected case study bridge, specific hazard scenarios are selected [7]. Table 2 depicts the potential hazard scenarios that are considered in a multi-hazard environment. More specifically, S-1 is a single earthquake event, S-2 is a single flood event, MH-1 are two subsequent events that are a flood followed by an earthquake event, MH-2 are two subsequent events that are an earthquake followed by a flood event, MH-3 are two subsequent flood events (i.e. flood event also considering for scour at bridge piers owning to previous flood event (3m scour)) and 4. a flood event also considering for scour at bridge piers owning to previous flood event (3m scour)) and an earthquake event have been considered.

Hazard Scenarios	Event Combination
S-1 (Single)	Earthquake
S-2 (Single)	Flood
MH-1 (Multi)	Flood + Earthquake
MH-2 (Multi)	Earthquake + Flood
MH-3 (Multi)	Flood + Flood

Table 2: Multi-hazard scenarios for earthquakes and floods



(a) (b)

Figure 3: Flooding discharge Q values for T=100 years in a) Greece b) focus area

Regarding earthquake events, three return periods, T= 475 years, T=1000 years and T=2500 years were considered. For flooding events, the discharge values for a 100-year return period was investigated. In Figure 3, single hazard maps for the selected discharge in Greece and the investigated territory are shown.The corresponding values IM values for the selected return periods both for seismic and flooding events are presented in Table 3.

IM	Return Period	Value
PGA	475	0.103 g
PGA	1000	0.252 g
PGA	2500	0.36 g
Q	100	4800 m^3/s

Table 3: IM values and their corresponding return periods

3.3 Fragility Analysis

The fragility curves of the bridge for the selected hazard scenarios were derived following the methodology presented in section 2. The development of the fragility curves is the basis for deriving the resilience metrics.

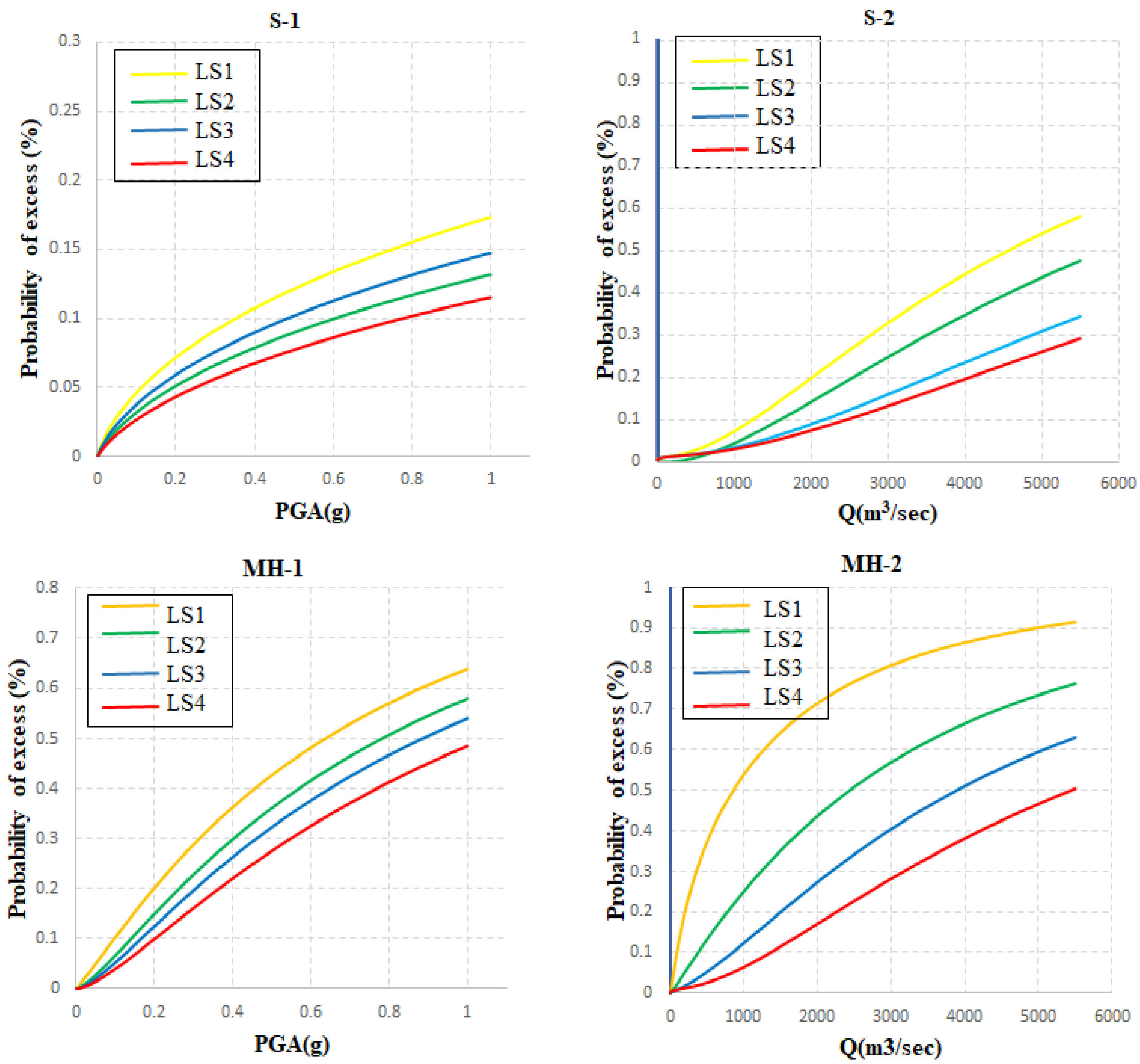


Figure 4: Fragility curves for Vardarovasi Bridge

To account for multi-hazard scenarios it is necessary to use the corresponding fragility curves that account for cumulative damage. Based on the elected multi-hazard scenarios as shown in Table 2, fragility analysis was performed. To assess seismic fragility, the y-direction was used to develop the fragility curves of the bridge system as it is more critical for the case study bridge. The occurrence of a flood prior to another hazard event is simulated as a 3m scour on the bridge foundation. In Figure 4, four of the derived fragility curves are presented, [8].

3.4 Restoration models

Based on the methodology described in section 2, the restoration models are developed as they are critical to perform resilience analysis. Immediately after the event occurrence, the functionality of the bridge is 70% for slight damage, 30% for moderate damage, and 2% for extensive damage and 0% for collapse. As recovery time increases the bridge functionality increases gradually. According to Table 1, the recovery of the bridge functionality is achieved in about 6, 60, and 250 days for slight, moderate and extensive damage, respectively. In Figure 5, the restoration model for a single earthquake event and for a multi-hazard scenario, i.e. a flood event followed by an earthquake is depicted. It is evident that the functionality losses are larger during the recovery process after two subsequent events than after a single seismic event and that the post-event immediate residual functionality Q (t =0 day) of the bridge decreases significantly as the seismic intensity level increases for both single and multi-hazard scenarios.

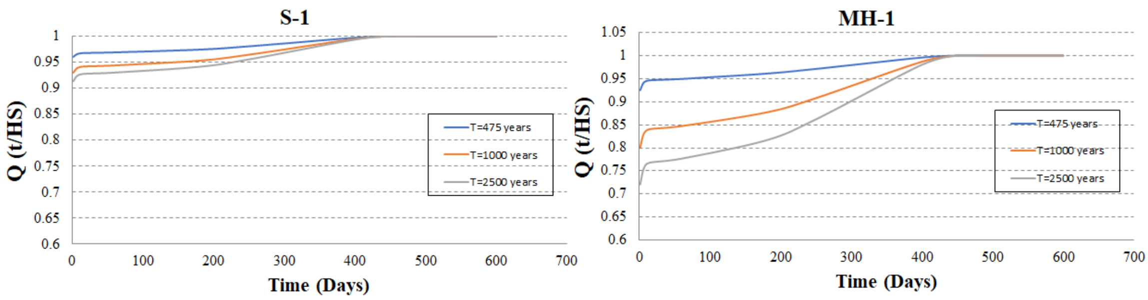


Figure 5: Restoration Models for Vardarovasi Bridge

3.5 Resilience Assessment

Resilience indices for the selected hazard scenarios are produced by utilizing the overarching framework depicted in Figure 1, along with the fragility and restoration models presented in sections 3.3 and 3.4. It is important to mention that the time frame t_{ohi}- t_i in Equations (3)-(4) signifies the timeframe during which the assessment of resilience is conducted. This time frame enables the comparison of R values across different assets and/or various hazard scenarios. Typically, the maximum restoration time of the examined assets is considered to determine t_i. For the purposes of this paper, the resilience index is calculated with t_i representing the recovery time for extensive damage which amounts to 250 days. More specifically, the fragility curves were used in the resilience analysis to determine the probability of occurrence of each damage state for the single and multi-hazard scenarios (see section 3.2). The functionality of the case study bridge was then computed for each damage state using the restoration model presented in Table 1. Figure 6 shows the R metric of the Vardarovasi Bridge for three shaking level intensities in the case of a single earthquake event compared to the corresponding intensities of the MH-1 scenario. It can be observed that the slope of the R trend line is higher for the MH-1 scenario which depicts the negative effect of the occurrence of subsequent events on the resilience of the bridge. In particular, the resilience metric R of the bridge is 20% lower in the MH-1 scenario compared to the S-1 for the PGA equal to 0.36g.

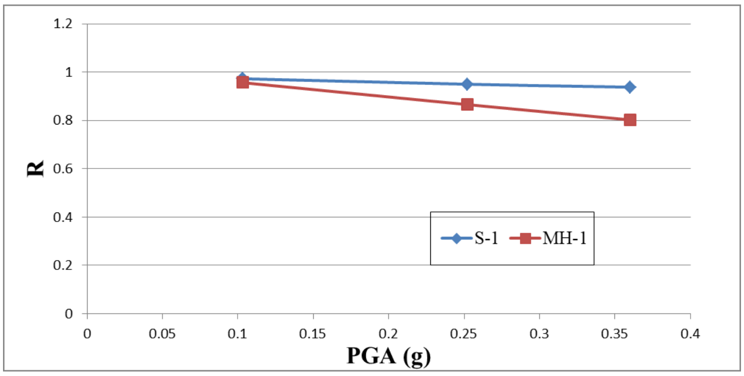


Figure 6: Resilience analysis for earthquake scenarios

In Figure 7, the resilience metrics R for S-2, MH-1 and MH-2 scenarios are presented. These scenarios correspond to T=100 years as the return period of the flood discharge Q for the single and the multi-hazard scenarios, respectively. The R values indicate that the differences on the computed resilience can become more than 50% lower in a multi-hazard environment.

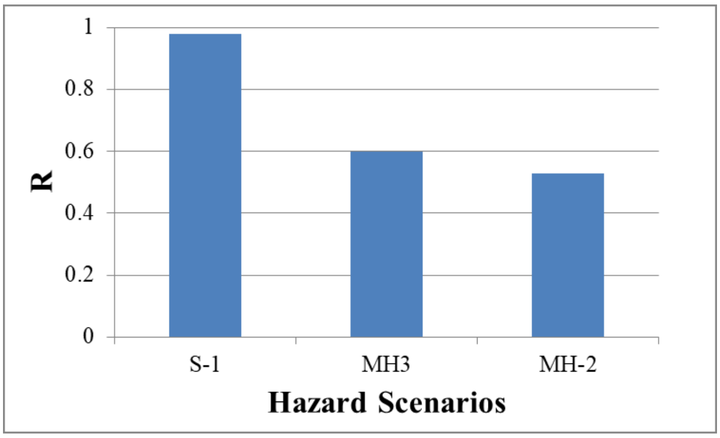


Figure 7: Resilience metric for discharge Q (T100)

4 CONCLUSIONS

The present study proposes a multi-hazard resilience assessment framework for key assets of transportation networks, focusing on bridges. The methodology includes the following steps: i. hazard analysis, ii. fragility assessment based on numerical analysis of the examined structures/assets against single or multi-hazard scenarios and for a range of hazard intensities, iii. evaluation of functionality level and iv. quantification of resilience metrics as dimensionless indicators of resilience. The proposed framework was applied to a riverine bridge. Regarding earthquake events, it has been observed that the post-event immediate residual functionality Q (t =0 day) of the bridge decreases significantly as the seismic intensity level increases. In particular, especially in the multi-hazard scenario the bridge functionality losses are more than 20% higher for the 2500 years return period than for the 475 years return period. Moreover, the bridge functionality losses are larger during the recovery process after two subsequent events than after a single seismic event. The difference between the functionality level values is more evident when the high seismicity level is considered. Regarding flooding scenarios, the computed resilience metrics show that the bridge resilience is significantly lower when multi-hazard scenarios are taken into account than that considering only a single flood event occurrence. More specifically, the R metric becomes more than 50% lower in the case of a flood-flood scenario than that of a single flood event. Hence, the study highlights the significance of estimating resilience of bridges in a multi-hazard environment since the consideration of solely single events underestimates the effect

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