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Multi-hazard fragility assessment of bridges: Methodology and case study application

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ABSTRACT

Reliability of road systems and their critical components exposed to multiple natural hazards is on the frontline of engineering research during the last three decades since potential damage of infrastructure is strongly related to important direct and indirect economic losses. In this context, the research project INFRARES (www.infrares.gr) aims at delivering a comprehensive methodology towards a more efficient risk and resilience assessment of roadway networks in Greece subjected to various natural hazards. In this context, an analytical framework for the fragility assessment of bridges subjected to independent and/or multiple subsequent natural hazards, is proposed herein and applied to a case study bridge. The proposed methodology includes the estimation of seismic and flood fragility and the development of multihazard fragility curves. The proposed approach considers multiple structural components for the development of fragility curves, which are generated based on case-specific estimation of limit state thresholds accounting for multiple failure modes and SSI effects. A probabilistic framework is introduced to account for the uncertainties in the demand and capacity in case of single hazards, which is then extended for multiple -separate and/or subsequent- hazards, highlighting the effect of cumulative damage on the fragility assessment. The proposed methodology is applied to a case study bridge in Greece, considering multiple hazards, separate in time (i.e. two subsequent flood events). The results in terms of flood fragility curves are discussed with a view to evaluate the effect of damage accumulation in multiple hazard analysis; the probability of damage was found to drastically increase for all limit states considered.

Keywords: seismic hazard, flood hazard, multiple-hazards, fragility curves, bridges, components

INTRODUCTION

The spatial extent of most critical infrastructure systems and the disparity of their components make them exposed to a wide range of natural hazards. Bridges are the most critical components of urban and interurban transport systems, and as such they should ensure seamless mobility after of the occurrence of a natural disaster. Bridges are in direct interaction with the environment and are exposed to climate risks, including earthquake and extreme weather events, the frequency and severity of which has been significantly increased and will continue being aggravated due to climate change. Floods, for instance, have been recognised as one

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of the main causes of bridge collapse. Unlike earthquakes, flood events tend to occur more frequently and with higher intensities in high rainfall areas; hence, flood-induced bridge damage and collapse account for a significant portion of disasters in many countries (Lee et al., 2016).

Severe damage due to extreme weather events (e.g., floods) has been observed recently in urban and interurban road networks in Greece. Two representative examples are shown in Figure 1, i.e., the failure of a bridge at Kalamata, Trikala, in 2016, due to flood loading resulting in deck unseating (right) and the failure of a river bridge at Serres in 2021, due to flood induced hydraulic loading and accumulated debris (left). It should be also underlined that recently, in September 2020, flooding in Karditsa resulted in failure of bridges and overpasses, while flood events were recorded in Larisa on March 23, 2021, subsequent to the 6.3Mw earthquake event of the 3rd of March 2021 leading to damage on bridges of local networks.

Figure 1. *(Left): Bridge failure due to flood and accumulated debris (Serres, Greece). (Right): Bridge failure due to flood, causing deck unseating (Kalampaka, Trikala, Greece)*

In line with the above, and accounting for the fact that potential bridge damage is related to important direct and indirect economic losses, various research studies have focused on the vulnerability assessment of bridges against natural hazards, proposing relevant fragility curves. Recognizing the effect of climate change and multiple hazards on the vulnerability of bridges, the research interest has lately been shifted upon the derivation of not only single-, but multi-hazard fragility curves, as well. Several methodologies have been recently developed for the vulnerability assessment of bridges in a multiple-hazard environment; however, most of these studies do not account for all critical components of bridges, all potential failure modes and uncertainties for the estimation of capacity, demand and, finally, fragility, rendering the results dependent on the assumptions made and the level of accuracy of the analysis approach.

Regarding single hazards, numerous methodologies have been developed for the assessment of the *seismic* performance and vulnerability of bridges (Stefanidou & Kappos 2017; Tsionis & Fardis 2012, Nielson & Des Roches2007) etc). Most methodologies in the literature are analytical and are differentiated on the basis of definitions of the *Limit State (LS)* threshold values considered in capacity estimation, the type of analysis employed for the seismic demand estimation, the treatment of uncertainties, the selection of the appropriate intensity measures (*IMs*) and the probabilistic model used for the fragility analysis (probabilistic seismic demand model, response surface models, and others) (Stefanidou & Kappos, 2021).

A limited number of methodologies are available in the literature for the *assessment* of bridges against flood hazard (Kim et al., 2017; Hung & Yau 2017; Ahamed et al. 2020). The methodologies are differentiated based on the definition of critical components (i.e., the consideration of multiple components, of the piers, the foundation, etc), the *LS* thresholds proposed, the modelling assumptions for demand estimation (i.e., used of 2D or 3D numerical models, accounting for or neglecting soil-structure interaction phenomena) and the uncertainty consideration and treatment. Nonlinear static analysis cosidering water pressure and the impact of accumulated debris is mainly used for the demand estimation. Rarely nonlinear dynamic fluid structure interaction (FSI) analysis is employed. Fragility curves are derived considering different *IMs*, with and without scour effects.

Fragility assessment is important for prioritization of retrofitting, guidance and optimal retrofit strategy selection, therefore, multiple hazards at the lifetime of the bridge should be accounted for (Argyroudis & Mitoulis, 2021). It should be outlined that fragility analysis for multiple natural hazards is also essential for newly constructed bridges, since such an analysis may contribute towards highlighting the most vulnerable components of the examined bridges, hence, optimizing the maintenance and potential retrofit costs. The methodologies available in the literature for multiple hazard assessment of bridges are referring to either multiple -separated in time- events or combined (triggered), subsequent and simultaneous events (Ghel & D'Ayala, 2015). Most methodologies consider earthquake and flood hazards, and the cases that a flood event is followed by an earthquake event, providing seismic fragility curves for different scour depths. An indicative list of available methodologies for multiple-hazard analysis of bridges is presented in Table, mentioning the different hazards and the critical components considered in each case for the fragility assessment.

Table 1. *Methodologies for single and multiple-hazard analysis of bridges.*

References	**Multiple-hazard fragility curves**		**Critical component(s)**
	Earthquake	**Floods (scour)**	
Stefanidou & Kappos (2017)	✓		All
Tsionis & Fardis (2012)	✓		All
Nielson & Des Roches (2007)	✓		All
Ghosh & Padgett (2010)	✓		All
Kim et al. (2017)		✓	Piers – deck unseating
Hung & Yau (2017)		✓	Piers & foundation
Ahamed et al. (2020)		✓	Piers & foundation
Alipour et al. (2013)	✓	✓	Piers
Gehl & D'Ayala (2015)	✓	✓	All
Yilmaz et al. (2016)	✓	✓	All
He et al. (2020)	✓	✓	Piers - Piles
Argyroudis & Mitoulis (2021)	✓	✓	All (deck, piers, bearings, abutments, foundation)
Wang et al. (2014)	✓	✓	Piers - foundations
Dong et al. (2013)	✓	✓	Piers
Chandrashekaran & Banerjee (2014)	✓	✓	Piers

In line with the above, the research program INFRARES aspires to deliver a comprehensive methodology towards a more efficient risk and resilience assessment of transportation infrastructure in Greece subjected to various natural hazards. The main target of INFRARES is to develop a holistic methodology including distinct steps that could be followed in case of single natural hazards (separated in time) or combined hazards for fragility assessment of bridges in a multiple-hazard environment, regardless the interaction scenario (triggered phenomena, unrelated hazards in time, or simultaneous hazard events) and the hazard sequence (flood followed by an earthquake and vice versa, successive flood or earthquake events). This paper focuses on the vulnerability assessment of bridges against natural hazards, proposing a relevant methodology. The methodology addresses all critical issues related to the reliability of results and conclusions, i.e., the consideration of all critical components, their inelastic performance and different failure modes for capacity and demand estimation, the uncertainty treatment, and the probabilistic framework for the derivation of fragility curves and/or surfaces.

METHODOLOGY

A comprehensive and holistic methodology is proposed for the fragility assessment of bridges in a multiple hazard environment, as described in detail in Figure 4. Initially, the distinct steps for the single-hazard fragility assessment are described for the cases of seismic hazard and flood hazard. The two approaches (i.e., for seismic and flood fragility estimation) require the estimation of the capacity of critical components of the examined bridge, the definition of demand and the definition of relevant uncertainties to calculate component- and, eventually, system-fragility curves.

Methodological approach for seismic fragility analysis

For the estimation of seismic fragility curves, the basic principles of the methodology proposed in Stefanidou & Kappos (2017) are adopted. The capacity of all critical components of the examined bridge is initially defined along with the limit state (LS) thresholds for all considered *LS*. In particular, for bearings and abutments, the threshold values proposed in Stefanidou & Kappos (2017) are adopted, whereas, for bridge piers the relevant values are estimated on the basis of inelastic pushover analysis results and the capacity (pushover) curve of the pier subsystem. The threshold values considered, are initially defined at local (cross-section) level (Table 2) and subsequently matched to global engineering demand parameters (*EDPs*) via inelastic pushover analysis of the fully inelastic component model. It should be outlined that the herein proposed methodology considers the foundation as critical component and thus accounts for soil-structure-interaction (SSI) effect, to derive more representative and accurate, case-specific threshold values results. The consideration of SSI is also related to the need for a homogenized methodology for seismic and flood capacity assessment, with the latter being strongly related to damage at foundation level. Regarding the estimation of seismic demand at component control points, seismic ground motions are selected for pre-defined criteria (i.e., magnitude and epicentral distance range) and inelastic time-history analysis of the fully inelastic model is performed for the studied bridge sample to estimate the seismic demand at component control points, as well as relevant uncertainties. Critical parameters (i.e. material and foundation soil properties, bearing properties, gap size) are considered as varying for the estimation of the bridge sample, applying the Latin Hypercube Sampling (LHS) method. The earthquake ground motion is also introduced as a variable in LHS (mixed integer LHS), for compatibility issues to the relevant methodology for flood fragility. Based on the capacity and demand values estimated for every component and all the bridges of the sample analyzed, the seismic fragility is estimated at component level, by applying Equation 1, where P(D) is the conditional probability that the component will be damaged to damage state "i" 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 β_{tot} denotes the logarithmic standard deviation.

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

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, Zhang & Huo 2009):

$$\max_{i=1}^{n}[\mathrm{P}(\mathrm{F}_i)] \leq P(F_{system}) \leq 1 - \prod_{i=1}^{\pi}[1 - P(F_i)] \tag{2}$$

The lower bound corresponds to completely correlated components, while the upper bound assumes no correlation between components. Bridge fragility lies within these two bounds and the exact value is dependent on the correlation of the component response. Both upper and lower bound bridge-specific fragility curves for all limit states are calculated herein.

Table 2. *Component: Piers - Limit state thresholds (in terms of local EDP) (for details see Stefanidou & Kappos, 2017)*

Limit State (LS)	Threshold values of curvature (φ)	Quantitative Performance Description
LS 1 Minor-Slight damage	**φ1**: φ_y	Quasi-elastic behaviour – Cracks barely visible.
LS 2 Moderate damage	**φ2**: min (φ: $\varepsilon_c > 0.004$, φ: $\varepsilon_s \geq 0.015$)	Spalling of the cover concrete; strength may continue to increase – Crack width 1-2mm.
LS 3 Major-Extensive damage	**φ3**: min (φ: $\varepsilon_c \leq 0.004 + 1.4 \cdot \rho_w \cdot \frac{f_{yw}}{f_{cc}}$, φ: $\varepsilon_s \geq 0.06$)	First hoop fracture, buckling of longitudinal reinforcement, initiation of crushing of concrete core – Crack width >2mm.
LS 4 Failure-Collapse	**φ4**: min (φ: $M < 0.90 \cdot M_{\max}$, φ: $\varepsilon_s \geq 0.075$)	Loss of load-carrying capacity - Collapse

Methodological approach for flood fragility analysis

The basic steps of the methodology proposed for flood fragility analysis are similar to the relevant for seismic fragility analysis described above. The two issues that should be discussed further is the capacity and demand estimation of critical components. As already stated, the pier-pile foundation system is considered as critical component (as described in Stefanidou & Kappos, 2019) and inelastic pushover analysis of the fully inelastic system with plastic hinges at pier and pile element top & bottom is performed (Figure 2), additionally, considering nonlinear (trilinear) p-y springs (Matloc et al.,1970) to account for SSI. The structural damage on piers and piles is monitored during pushover analysis and the global *EDP* (displacement) values are recorded at component control point (pier top) when the relevant local (in φ terms) value is exceeded. Therefore, the thresholds for all the *LS* considered are explicitly defined and calculated. It is noted that damage is recorded and expressed at the pier-pile system, considering series connection between components (i.e., the component that reaches the relevant *LS* first is the one that defines the *LS* (Figure 2). In case that scour depth is considered (Arneson et al., 2012), the soil springs along the scour length are deactivated to perform pushover analysis.

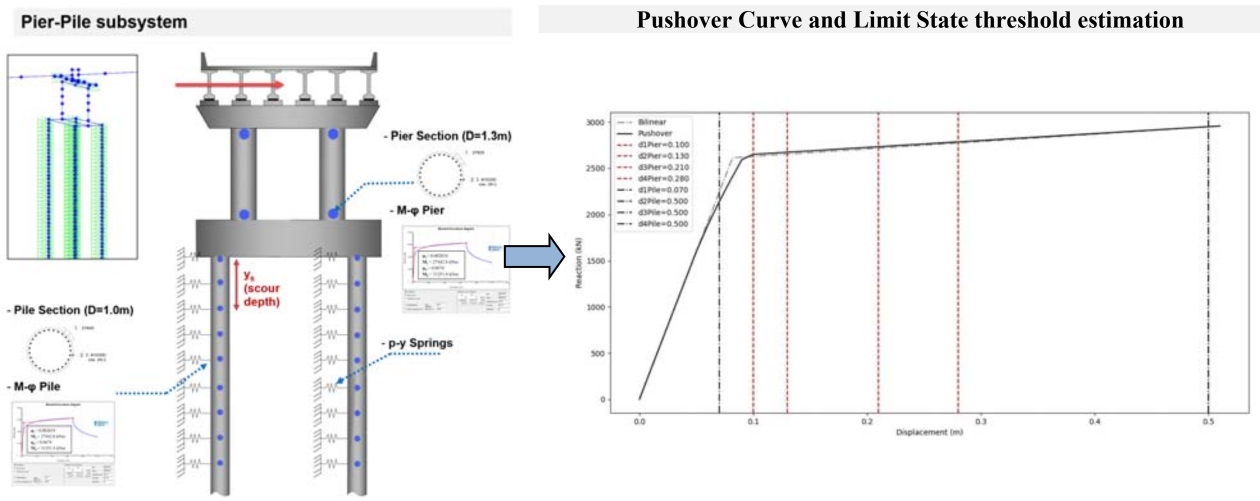

Figure 2. *Numerical simulation of pier-piles subsystem employed in pushover analyses to determine capacity curves and thresholds of relevant Limit States of the subsystem*

With reference to the estimation of demand, the equivalent hydrostatic force due to flood is estimated according to EN 1991-1-6 (CEN, 2005) and applied to the pier columns (Figure 3). Water discharge (Q) is selected as the most appropriate *IM*, with different Q values (ranging from 500 to 5500 m/sec^3) being applied to the bridge system and the demand at component control point being estimated for all the bridge samples studied. The discharge is used as variable in LHS and the bridge sample is analysed for multiple discharge values to obtain both demand and relevant uncertainties. Based on the capacity and demand values estimated for every component and all the bridges of the sample analysed, the seismic fragility is assessed at component level, applying Equation 1 and at bridge system level considering a series connection between subsystems.

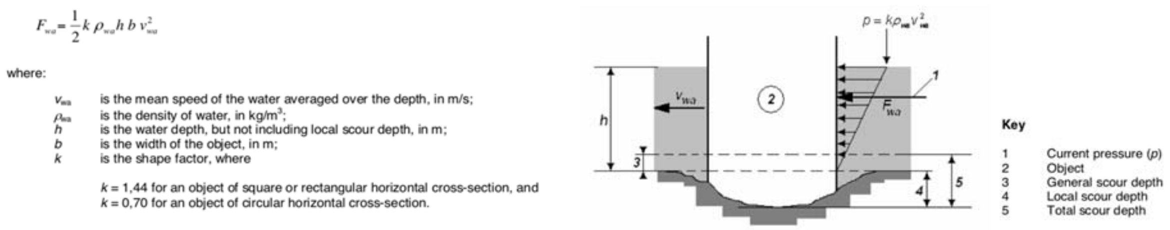

Figure 3. *Flood hydrostatic pressure according to Eurocode 1 (EN 1991-1-6, CEN 2005)*

Methodological approach for multiple seismic-flood fragility analysis

For the fragility assessment of bridges against multiple natural hazards, i.e., seismic and flood hazards, a combination of the methodologies presented above for single events is initially performed. Several scenarios of uncorrelated and different (separated in time) hazard events are developed for the derivation of bridge system fragility curves. It should be outlined that the events are applied subsequently and, therefore, cumulative damage is considered. All the above are depicted in the flowchart of Figure 4.

The main novelties of the proposed holistic methodology for the bridge system fragility estimation in a multi-hazard environment, are summarized below:

- Limit states are defined in a quantitative manner based on the capacity curves derived from pushover analyses, considering a fully inelastic pier-pile system and accounting for both pier and pile structural components damage.
- Potential damage on piles (and relevant damage states) are considered in the definitions of both the demand and capacity, with an assumption of a series connection to the pier for the estimation of the pier systems' capacity and demand.
- The proposed methodology is applicable regardless the sequence and the correlation of the events in time (earthquake & flood, flood & flood, flood & earthquake etc.)
- A reference model is considered within the proposed framework for analysis (subsequent events) accounting for subsequent events and cumulative damage and its effects on capacity and demand.

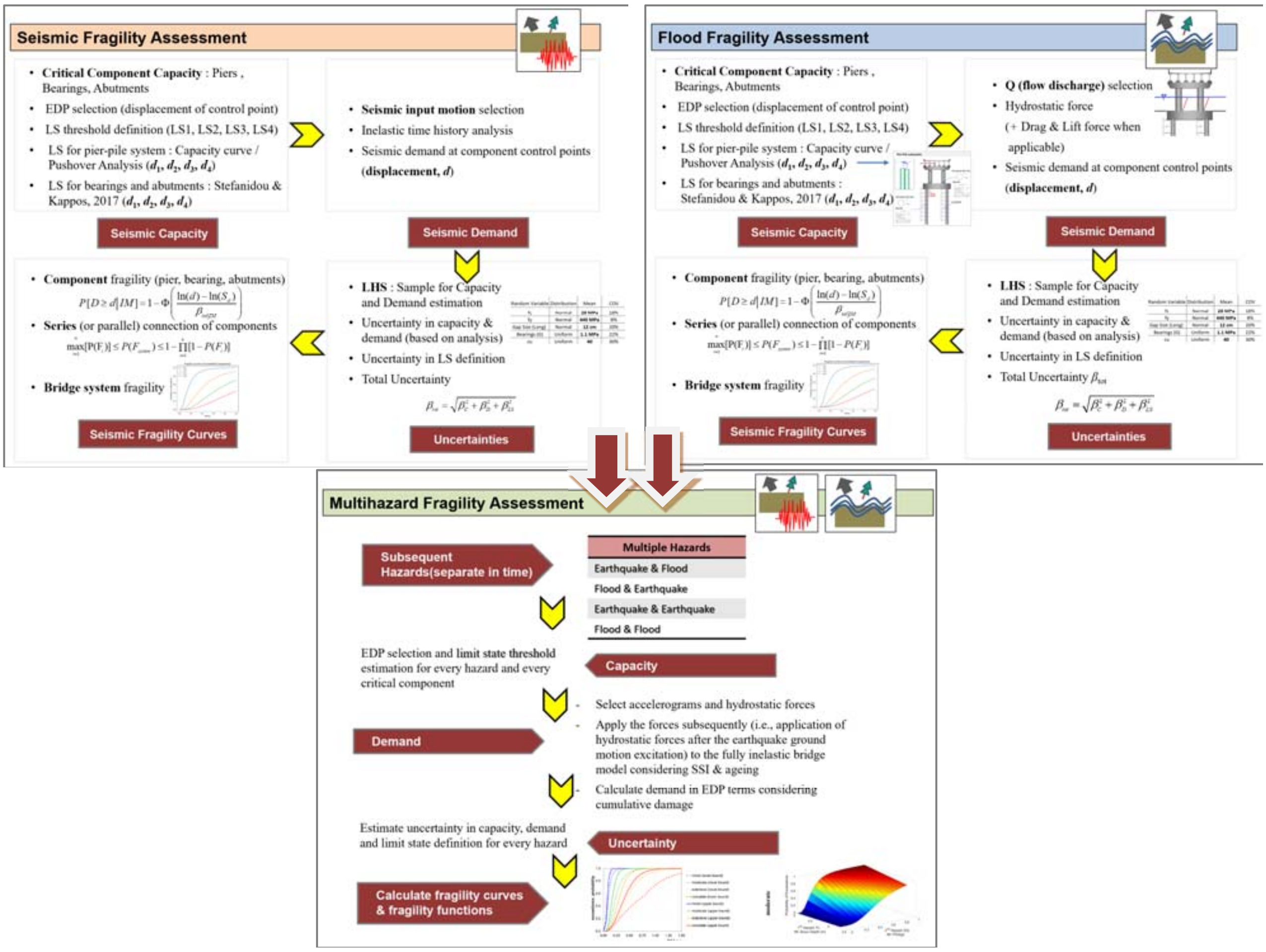

Figure 4. *Proposed methodology for seismic, flood and multi-hazard fragility assessment of bridges*

CASE STUDY APPLICATION

The methodological approach proposed above is applied to a case study bridge, examining a specific hazard scenario, i.e., two subsequent flood events. The selected bridge studied is the Vardarovasi river bridge at the Thessaloniki-Giannitsa National Road Greece that 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) by means of pile foundations, comprised of four reinforced concrete piles (length, l =33m, diameter d =1.0m) (Figure 5). Flood fragility curves are estimated for two cases: (a) a flood event and (b) two subsequent flood events. The first event is considered to result in scour of both foundations, leading to a scour depth equal to 3m.

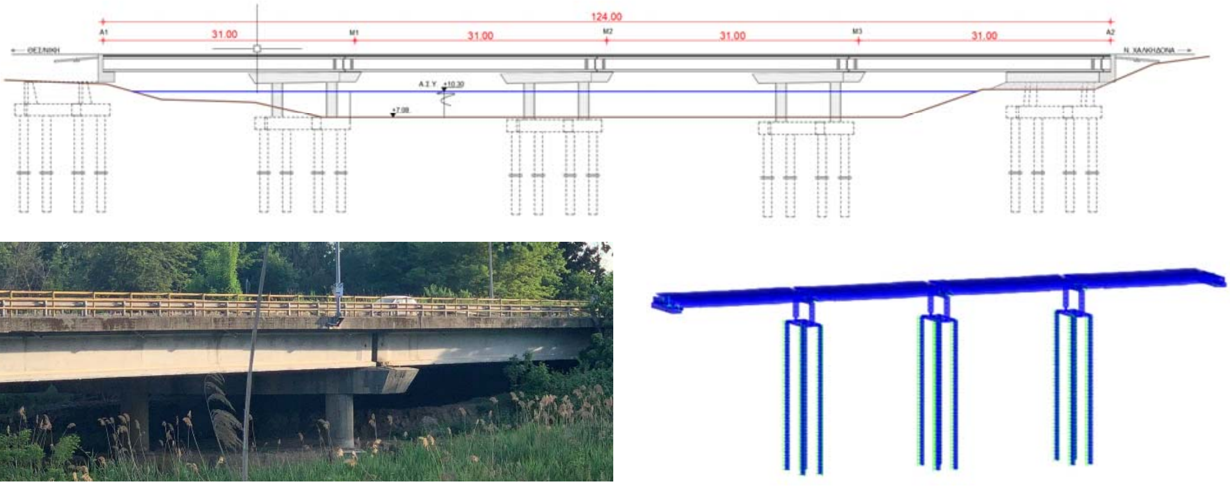

Figure 5. *Drawings and 3D Model of Vardarovasi bridge.*

For the case of single hazard (flood event), the pier system capacity is initially defined without consideration of scour (see also Figure 2). Both pier and pile structural failures are considered for the definition of limit state thresholds in terms of displacement of the control point. For the case where no scour is considered (Figure 6), the bridge piers define the systems' capacity thresholds, whereas for the case when a 3m scour is considered (Figure 7), piles are the most critical component, defining the systems' capacity.

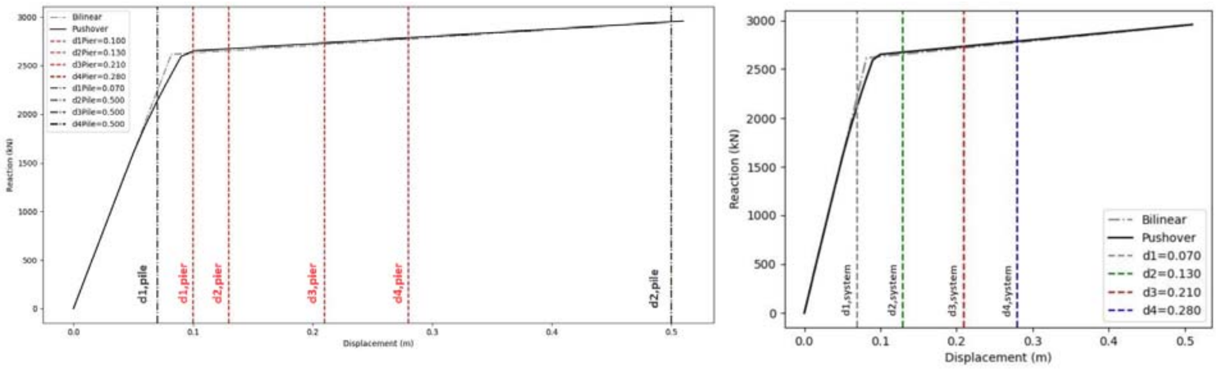

Figure 6. *Capacity curve and limit state definition in terms of global EDPs (displacement at component control point) for the case of pier-pile foundation system* ***without*** *scour.*

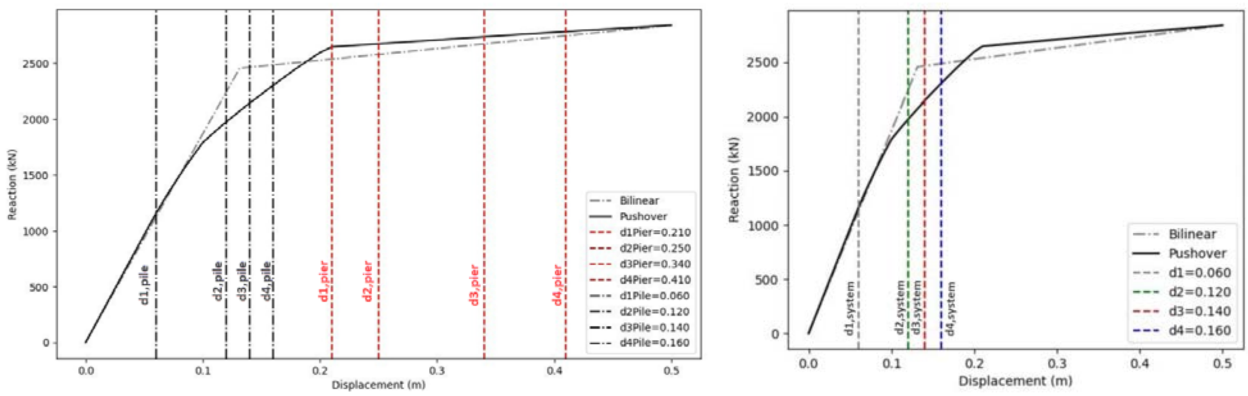

Figure 7. *Capacity curve and limit state definition in terms of global EDPs (displacement at component control point) for the case of pier-pile foundation system* ***with*** *3m scour.*

The methodology proposed herein for flood fragility assessment is applied to the examined river bridge for the case that no scour is considered (Figure 8-left), as well as for the case when a 3m scour is considered (Figure

8-right). The upper and lower bounds of system fragility are also provided in Figure 8. Evidently, the probability of damage is higher for the case of subsequent (separate in time) flood events, when the first one causes scour at both bridge piers.

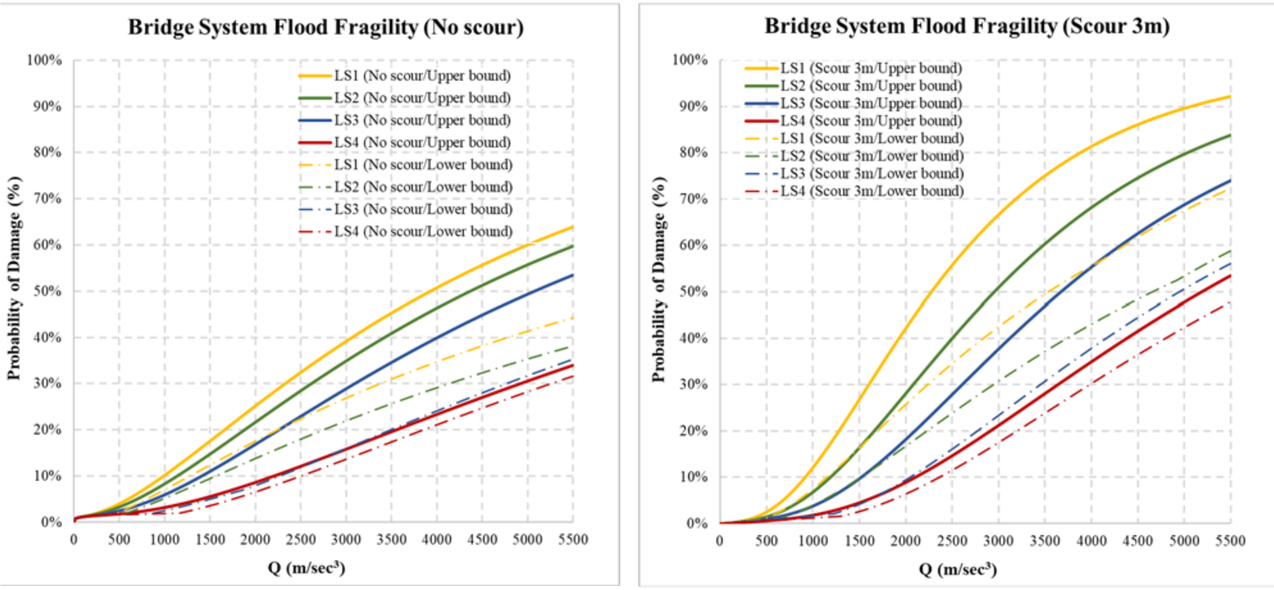

Figure 8. *Fragility curves for the assessment of examined bridge against flood hazard, considering the no scour scenario (left), and the scenario of scour with depth 3m(right)*

CONCLUSIONS

The paper presented the main aspects of a methodology for the fragility assessment of bridges against natural hazards, developed as part of a methodology for the risk and resilience assessment of transport infrastructure in the frame of the research project INFRARES (www.infrares.gr). The main highlights of this work are:

- The comparisons of the capacity curves of the examined bridge computed accounting for or neglecting scour phenomena, highlighted the important effect of scour on the capacity curve of bridge piers. Indeed, such phenomena result in strength and stiffness reduction of the bridge pier - pile foundation system, additionally affecting the LS thresholds values for fragility assessment.
- Consideration of subsequent flood events with the first one causing foundation scour, results in an increase of seismic fragility for all limit states considered.
- During the evaluation of the effect of scour depth on the flood fragility of bridges, the critical component of the pier-pile foundation system should be considered. Series connection between piers and piles is considered for fragility estimation relating the system damage to the damage of the most vulnerable component.
- The effect of scour on the flood fragility of bridges is expected to be more crucial, when bridge foundation is the most vulnerable (not adequately designed) component of the system.

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