FRAGILITY ANALYSIS OF BRIDGES IN A MULTIPLE HAZARD ENVIRONMENT

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ABSTRACT

Since road and rail networks are exposed to multiple hazards, the impact of the latter on the reliability assessment of structural components (such as bridges) should be accounted for in the frame of fragility analysis and resilience assessment. The aim of this paper is to propose and apply a structure-specific methodology for fragility analysis of bridges for the combined events of earthquake and scour, advancing the state-of-the art regarding the limit state threshold definition, dully tailored to account for all pier and pile foundation properties that affect component capacity and, hence, fragility. The most critical component, namely bridge piers, is considered and limit state thresholds are explicitly derived based on the pertinent pushover curves considering both the pile foundation alone and the pier-foundation system. Local damage in both piers and pile foundation is accounted for in the analytical estimation of limit state thresholds. Fragility curves for the combined effects of scour and earthquake are provided, accounting for varying pier and soil properties via related uncertainties and different scour depths (1.5m and 2.0m), while the results are discussed from the perspective of road network resilience in a multihazard environment.

Keywords: bridges, multiple hazard, fragility curves, scour, earthquake

1. INTRODUCTION

Road bridges are important projects as the state financial investment for their construction is high, while bridge failures are related to significant direct and indirect social and economic losses. Bridges are in direct interaction with the environment and are exposed to multiple hazards and climate risks, including extreme weather events, the frequency and severity of which has been significantly increased and will continue being aggravated due to climate change. Serious damage due to extreme weather events (e.g., flood) has been observed at the Greek urban and interurban road network recently Greece. Two characteristic examples are presented in Fig.1, the failure of a bridge at Kalamata, Trikala in 2016, due to flood loading resulting in deck unseating (left) and the failure of a newly constructed bridge at Rodopi, Iasmos, possibly due to foundation and abutment failure (rotation). Very recently, in September 2020, flooding in Karditsa resulted in failure of bridges and overpasses.

Figure 1: Bridge failure due to flood, causing deck unseating at Trikala, Kalampaka. Bridge failure due to foundation failure (rotation) at Iasmos, Rodopi.

Several methodologies are available in literature for the estimation of bridge fragility in a multiple hazard environment, however, many of them do not account for all critical components or failure modes for the estimation of seismic capacity, demand and, finally, seismic fragility, rendering the results dependent on the assumptions made and the level of accuracy. Fragility analysis results are important for retrofit prioritization, guidance and optimal retrofit strategy selection, therefore multiple hazards at the lifetime of the bridge should be accounted for. It should be outlined that fragility analysis for multiple hazards is essential for newly constructed bridges as well, highlighting the most vulnerable components and optimizing the maintenance and retrofit costs. To this end, a methodology for the derivation of bridge-specific fragility curves is proposed and applied herein, accounting for different failure modes (both at substructure and foundation). A pile foundation bridge is analysed and fragility curves are derived accounting for scour at bridge piers. Bridge capacity is calculated accounting for foundation damage as well and the effect of scour on seismic fragility is evaluated.

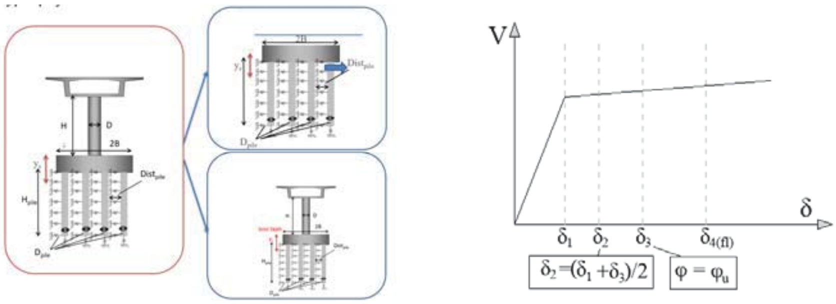
2. FRAGILITY OF BRIDGES IN A MULTIPLE HAZARD ENVIRONMENT

2.1. Available methodologies in literature

The available methodologies for the estimation of bridge fragility curves are classified into empirical (based on expert judgment or actual damage), analytical (based on analysis results) and hybrid (a combination of the above). In the last 30 years the development of analytical methodologies has occupied several research groups that cover both existing and reinforced bridges. Regarding the exposure of bridges in a multiple hazard environment, it is noted that several methodologies are proposed in the last decade for the vulnerability estimation of bridges not only against earthquake but for other natural disasters as well, having a high probability to happen during the lifetime of the structure (multi-hazard framework). Most of the proposed methods account for the vulnerability estimation in case of combined action of earthquake and flood, while some of them take into account the interaction with the environment (corrosion, etc). It is worth noting that only one methodology assesses the overall vulnerability for all of the above [1] while most of them take into account bridge piers as a critical component, ignoring the effect of other components on the systems' vulnerability.

Specifically, Wang et al., [2] showed that the scour depth plays an important role in seismic response as it renders the foundation of the structure weaker and more flexible increasing the eigenperiod. They showed that the probability of failure, in general, increases with the scour depth, while Ganesh Prasad & Banerjee, [3] found that this increase is non-linear and a significant depth of the undercut to 3m. Yilmaz et al., [4], report that the bridge component that is most influenced by scour is the piers and in particular the first and last failure level, along with the bearings in the longitudinal direction, while the abutments remain practically unaffected. Similarly, Gehl & D'Ayala, [5] found that that the influence of the scour depth is greater for large limit states (related to loss of bearing capacity or collapse), and Wang et al., [6] that in the case of scour the most critical and vulnerable component is bridge piers.

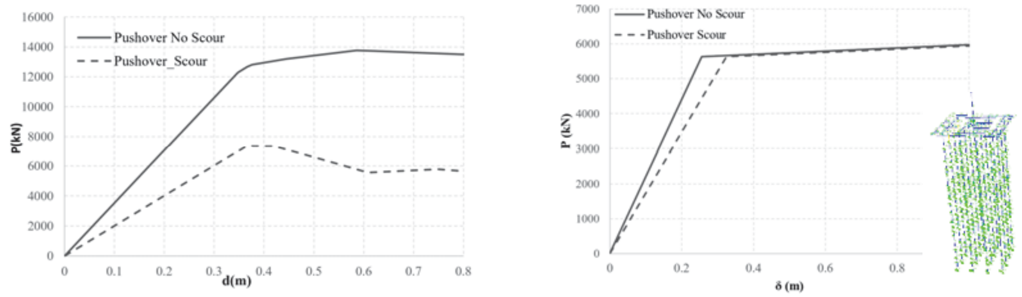
Very recently, Stefanidou and Kappos [7] proposed a component-based methodology for the estimation of bridge-specific fragility curves accounting for all critical components and various failure modes. The methodology is extended to account for foundation damage, defining limit state thresholds initially for the pile foundation and subsequently for the pier – pile foundation system, accounting for series connection between components (Fig.2(a)). It should be noted that limit states of the pile foundation are expressed in displacement terms, based on inelastic analysis results and the pushover curve, as depicted in Fig.2(b).



(a) **(b)**

Figure 2. (**a**) Analysis of bridge pier system for the capacity estimation; analysis of the pile foundation and the total (pier and pile foundation) system (**b**) Limit state threshold definition based on the capacity curve of the bridge pier system

A pier-pile foundation system is analysed herein and fragility curves with and without scour consideration are provided. The two subsystems of the pier system are analysed, namely the pile foundation with dimensions 12.0x12.0(m), 4x4 piles having 25m length and 1.0m diameter and the cylindrical pier having D=2.0 diameter and longitudinal reinforcement ratio equal to 1%. Pile springs are calculated considering soil type D, while scour depth equal to 2.0m is considered. The capacity curves of the pile-foundation and the pier-pile foundation system are presented in Figure 2 (a & b) and are differentiated when scour is accounted for. The decrease in strength is expected, since the inelastic deformation in piles occurs earlier, while the structure, in case of scour, is more flexible. Furthermore, the decrease in stiffness is obvious, owning to the removal of soil springs and the increase of free pile height.



(a) **(b)**

Figure 3: Capacity curve of pile foundation (a) and pile-foundation system (b) with and without scour

Fragility curves of the pier- pile foundation system are calculated and depicted in Figure 4, highlighting that seismic fragility is increased due to scour for all limit states. It should be outlined that the critical system component is the pier, yielding before the pile foundation.

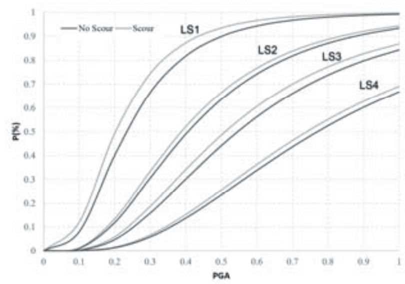


Figure 4: Fragility curves of bridge pier for all limit states, with and without scour consideration

3. CONCLUSIONS

The most improtant findings are summarised below:

- The effect of scour on the seismic capacity of bridge piers is essential, resulting in strength and stiffness reduction of the pile foundation and the system pier - pile foundation.
- 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 seismic fragility of bridges the critical component of the pier- pile foundation system should be considered. In case that the bridge pier yields before the yielding of the system of the pile foundation, the forces transferred to the foundation are approximately constant and foundation damage may occur at a next stage. The possibility for an adequately designed pile foundation to fail should be examined, highlighting the possibility to consist a more vulnerable, compared to bridge piers, component.
- The effect of scour on the seismic fragility of bridges is expected to be more crucial, in case that bridge foundation is the most vulnerable component of the system.

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