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SEISMIC BEHAVIOR OF A VIADUCT AFFECTED BY FOUNDATION SCOUR: A NUMERICAL STUDY

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Abstract

Foundation scour is one of the major causes of failure for bridges over waterways. Its detection is challenging, and limited financial resources often delay necessary repairs and retrofitting. Thus, scoured bridges remain more exposed to future extreme events, such as earthquakes, to which they may be more vulnerable due to the weakened support conditions. Therefore, predicting the behavior under the combined presence of scour and seismic events accounting for soil-structure interaction becomes necessary to understand the long-term performance of a road bridge. This paper presents the results of a numerical study carried out on a continuous deck viaduct located in northwestern Italy. The viaduct is a seismically isolated multi-span steel-concrete composite deck, supported on short piers. The foundation system for each pier is a mat on large-diameter piles. Some piers are subject to lateral scour, due to the erosive action of a river flowing parallel to the viaduct. A finite element model was developed using ABAQUS to investigate the influence of foundation scour on the dynamic response of the viaduct under seismic motions. This study compares the results of variants of the numerical model: one representative of the original configuration, i.e. without scour, and two corresponding to alternative scour scenarios. The superstructure and the seismic isolators were modeled through elastic elements and viscoelastic springs, respectively. Instead, the soil-pile interaction was introduced through the beam-on-nonlinear-Winkler foundation method. Foundation scour induces a significant increase in the peak horizontal displacements at the scoured piers, up to 15-20%. A significant change in both the amplitude and the frequency content of the deck displacements is also observed. These preliminary results contribute to a deeper understanding of the response of structural systems under the combined presence of pre-existing foundation scour and seismic loading, which is crucial for an adequate assessment of bridge vulnerability in seismically active regions.

Keywords: soil-structure interaction, scour, earthquake engineering, nonlinear numerical analysis, multi-risk analysis.

1 INTRODUCTION

Multi-hazard analysis of civil infrastructures requires a holistic view of the numerous potential threats posed by the surrounding environment. That is, these analyses must be comprehensive in dealing with multi-hazard scenarios, where the infrastructure vulnerability increases due to compounded geotechnical, hydraulic, and structural effects. In particular, the possibility of the joint occurrence of combined natural hazards should be adequately assessed.

Foundation scour is one of the main potential threats for bridges over waterways, especially in the long term if erosion is not mitigated with restoration works. Indeed, soil loss due to erosion reduces the stiffness and bearing capacity of foundation systems, significantly increasing vulnerability to strong seismic motions (e.g., [1, 2]). On the other hand, most of the literature research is based on rather simplified assumptions of the hydraulic scenario, typically with uniform lowering of the riverbed and/or assuming equal scouring levels at all piers for multi-span bridges.

This paper investigates the seismic response of the Inverso Pinasca Bridge, a viaduct located in northwestern Italy. The viaduct is affected by significant lateral erosion at some piers, induced by a river flowing parallel to the viaduct itself [3]. The numerical study compares the response of the original (i.e., unscoured) configuration with the one obtained including foundation scour. Scour is introduced at specific locations, with the shape of the scour hole matching the geometry obtained from in situ inspections, thus ensuring accurate modeling of the hydraulic scenario.

2 CASE STUDY

The Inverso Pinasca Bridge (Figure 1) was constructed between 2004 and 2005 as part of significant infrastructure improvements on the SP 023 road connecting Turin with the Chisone Valley. The viaduct extends along the southern bank and crosses the river upstream from the Inverso Pinasca village. The entire structure spans 1849.90 m, featuring four continuous decks divided by expansion joints, supported by 45 piers to which it is connected through seismic isolators. The deck width is 14.6 m, accommodating one lane in each direction. The superstructure is supported by deep foundations comprising pile caps with eight large piles each, having a diameter of 1.5 m and varying in depth from 14 m at pier P01 (southern abutment) up to 33 m at pier P24. The viaduct is constructed on sands, with a clayey layer embedded.

From a hydrogeological perspective, the entire infrastructure is identified as a high flood-risk area. Frequent flooding events since construction, notably in 2010 and 2016, have caused the Chisone River to shift towards its orographic right side, undermining bridge foundations between piers P08 and P11. This shift has exposed pile foundations, causing substantial scour depths reaching ~4 m at piers P09 and P10, measured from the pier cap's bottom. The scouring is asymmetrical due to a scarp near the bridge's longitudinal axis, partially exposing foundations.

Therefore, this study focuses on the southernmost 12 spans of the viaduct from pier P01 to pier P12. Indeed, the presence of a structural joint at the 12th pier allows for considering only this part. Each span measures 40 m, for a total length of 480 m along the deck main axis (which includes straight and curved sections).

Figure 1: left, view of the Inverso Pinasca Bridge during construction (2004; Image courtesy of Seteco Ingegneria s.r.l.). Right view of current scouring conditions at pier P09 as of June 2023.

3 NUMERICAL MODEL

The numerical model is a finite element model developed using the ABAQUS software [4]. The deck was modeled as a girder, with the longitudinal and transverse beams schematized as 1D elastic Euler-Bernoulli beam elements, whereas 2D planar linear quadratic elements were used for the concrete slab. Bridge piers were reproduced using a set of clamped elastic beam elements, while the foundation mat was modeled using 2D plate elements. Instead, 1D Euler Bernoulli Beam elements were used for piles. All the structural components were assumed to behave elastically, with cross-section and material parameters consistent with the nominal values obtained from the final design report. Seismic isolators were modeled as simple supports (rigid links) in the vertical direction and through two uncoupled equivalent linear viscoelastic springs in the horizontal plane, with equivalent secant stiffness and damping ratio estimated from the geometry and material properties of the elastomer.

The soil-pile interaction was introduced through nonlinear hysteretic springs, based on the beam-on-nonlinear-Winkler foundation method. Specifically, a series combination of linear and non-linear springs was applied along the length of each pile, through the approach proposed by Boulanger et al. [5]. The linear springs account for the soil elastic response, including radiation damping, whereas soil nonlinearities are schematized through an elastoplastic spring. This was calibrated to match the *p-y* curves (i.e., unit load transfer curves representing the soil resistance under static loading) calculated through the Matlock [6] relationship and API [7] recommendations for cohesive and granular materials, respectively. Also, a gap element was included to model the partial detachment between the soil and the pile that may occur in fine-grained soils, when large displacements are involved. Pile group effects were accounted for through the scheme proposed by Fayyazi et al. [8]. For simplicity, no vertical springs were included and the base was clamped since the study focused on the horizontal response of the system.

Three numerical models were developed to consider different hydraulic scenarios. One model schematizes the original configuration of the viaduct, at the end of the construction (label “S00-00”). Then, the “S08-10” model includes the effect of lateral erosion at piers from P08 to P10 (Figure 2a), consistent with the findings from in situ inspections (Figure 1). Scour is modeled by removing soil-pile interface springs in their exposed portion, according to the geometry derived from in situ visual inspections. Also, the remaining springs are updated to account for the modified confinement, which affects the *p-y* curves. Finally, the “S04-06” model assumes lateral erosion to occur at piers from P04 to P06 (Figure 2a). This alternative scenario aims to investigate the impact of alternative hydraulic scenarios on the dynamic response.

Simulations involved two input motions (Figure 2b-c). On the one hand, an artificial ground motion was generated and calibrated to match the 700-year return period elastic response spectrum, corresponding to the life safety limit state condition, consistent with the importance class of the viaduct [9]. Then, a second analysis was performed using a real acceleration time history, recorded at Lake Hughes (California) during the Northridge Earthquake (1994) and scaled to the expected PGA of the site.

Each acceleration time history was converted into displacement time histories to be applied at the free end of the soil-pile springs, through a 1D linear viscoelastic deconvolution using the STRATA software [10]. The linear model was chosen because including soil nonlinearities (e.g., through an equivalent linear approach) led to unrealistically large displacement values, in this case. This is a typical drawback of deconvolution analyses, which tend to fail in the presence of strong surface motions and with soft soils (e.g., [11]). To maximize effects, it was assumed that the motion was acting along the transverse direction of the viaduct in correspondence of pier P09, i.e., the most scoured pier (Figure 2a).

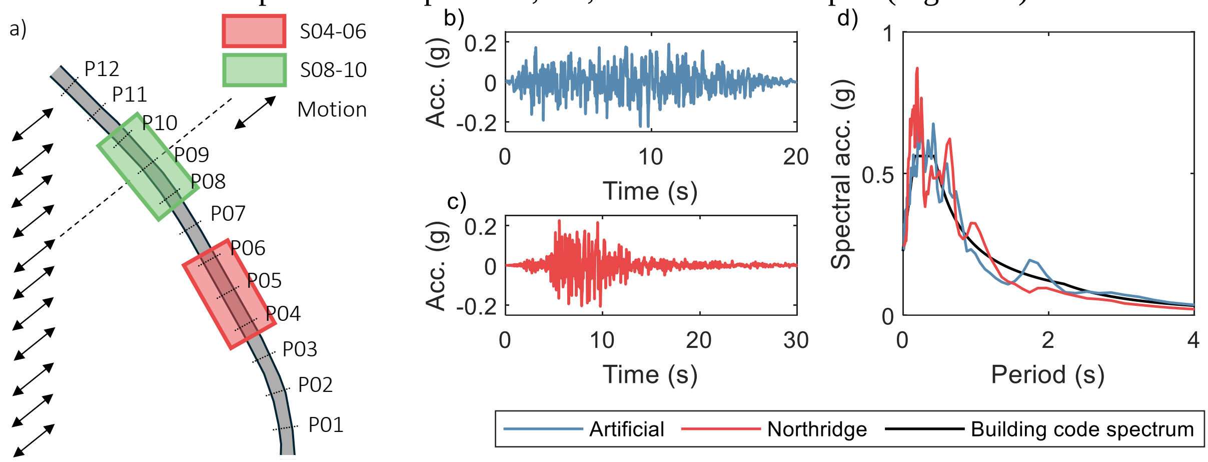

Figure 2: a) Sketch of the considered scour scenarios, with the direction of the input motions highlighted; b-c) Applied input motions, in terms of acceleration time histories for the (b) artificial and the (c) Northridge motion and (d) response spectra (compared with the building code spectrum).

4 RESULTS

The influence of foundation scour was investigated by comparing the peak horizontal displacements at the pier cap for each pier, along the longitudinal and the transverse directions, for the different scouring scenarios. Note that the comparison did not consider the residual displacements, which are negligible in this case. To better understand the combined effect of scouring and seismic motions, Figure 3 represents the peak transverse displacements for each pier, both in absolute value and normalized by the corresponding value for the S00-00 (i.e., unscoured) scenario. In general, peak transverse displacements increase with scouring, up to 25% for the most heavily scoured piers in the S08-10 scenario. This variation can increase the demand on the superstructure due to the high sensitivity of the continuous deck to differential displacement at the supports. It may also be critical to the performance of seismic isolators, with an increased risk of exceeding their deformation capacity. This increases the likelihood of their failure, resulting in loss of support of the deck.

Then, the frequency response of the deck was investigated by calculating the cross-spectrum between the displacements of the piers and the ones calculated at each midspan of the deck. This provides a preliminary insight into the influence of scouring on the frequency response of the superstructure. For brevity, only results for the Northridge motion are presented, although results for the artificial motion are rather similar. For instance, Figure 4 shows the cross spectra for the vertical and the transverse displacements, for the span between P09 and P10. In both cases, the cross-spectrum exhibits a predominant peak at a frequency of around 0.3 Hz, which corresponds to the natural frequency of the seismic isolators. However, when zooming at a higher frequency, the presence of scour induces a shift of the second peak of both the vertical and the transverse response towards a lower frequency. This is consistent with the reduction of the overall stiffness of the structure due to scouring. Note that this shift is much less evident for the "S04-06" scenario, because of both the distance of the considered span from the scoured piers and the reduced change in the overall response due to the motion directionality.

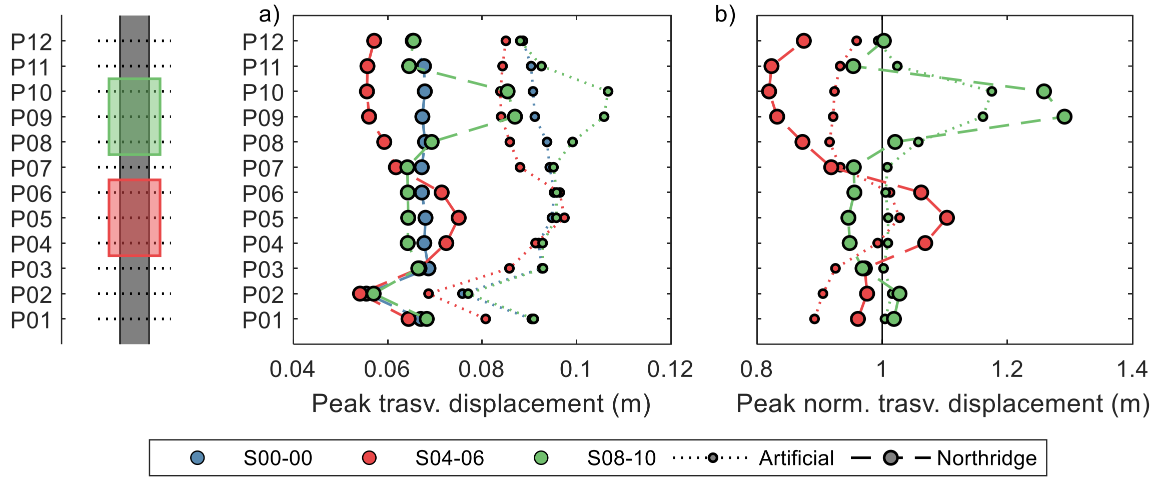

Figure 3. Peak horizontal displacements at the pier caps, in the transverse direction: (a) absolute values and (b) displacements normalized with respect to the ones computed in the unscoured scenario.

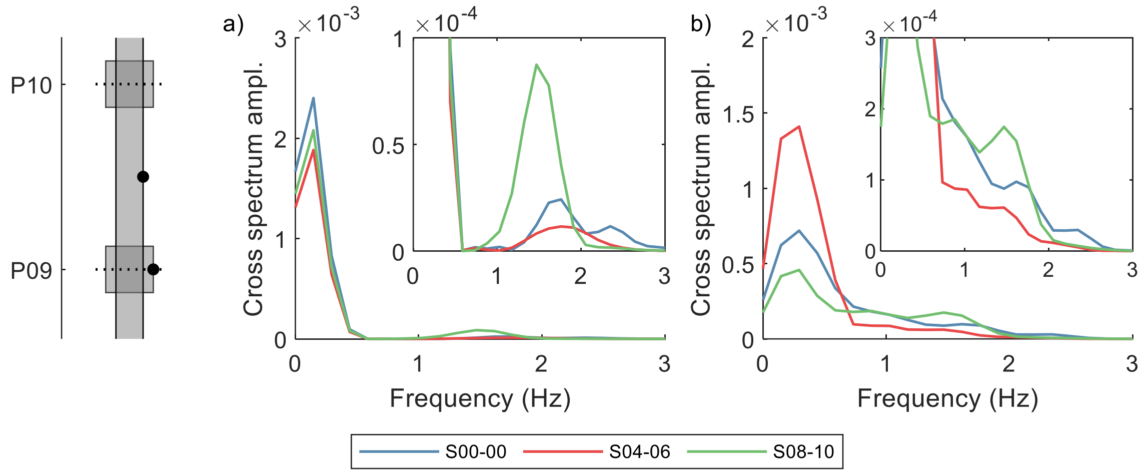

Figure 4. Amplitude of cross-spectra between the displacements at the midspan (between P09 and P10) and those at the pier cap of P09, for the vertical component (a) and the transverse component (b). The panels inside each subplot are a zoomed view for the response at higher frequencies.

5 CONCLUSIONS

- Foundation scour reduces foundation stiffness and bearing capacity, thus altering the bridge dynamic response. This can be particularly hazardous during earthquakes, as the structure is designed to withstand seismic loads under the assumption of full lateral ground support.
- This numerical study explored the impact of lateral erosion on part of the piers of a multi-span real viaduct, under two different seismic motions.

- Foundation scour induces an increase of up to 25% of peak horizontal displacement at piers, and it modifies the frequency response of the superstructure.
- These findings highlight the importance of joint structural and geotechnical evaluations of the structural dynamic response under strong motions and seismic loads, via predictive numerical FE simulations and experimental data analysis.
- Future studies will exploit experimental data from in situ dynamic measurements to calibrate the FE model, and nonlinearities in the structural elements will be incorporated into the model.

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