ON THE DYNAMIC RESPONSE OF BRIDGE PIERS SUBJECTED TO FOUNDATION SCOUR

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ABSTRACT. Caisson foundations play a pivotal role in supporting long-span bridges. However, their performance is susceptible to the effects of scouring, which is exacerbated by the increasing frequency and intensity of flood events associated with climate change. Therefore, to ensure the structural integrity of caisson-supported bridge piers during seismic events, it is critical to investigate the complex interactions between scour, the soil-caisson-pier system, and seismic forces. This paper presents a series of dynamic analyses carried out on a specific case study including three scouring scenarios: unscoured, general scour, and local scour. The simulations are analyzed in terms of spectral accelerations, cumulative displacements and permanent shear strains to shed light on the different effects of local and general scour. The results show larger cumulative displacements in scoured cases, compromising the serviceability of the structure, but lower accelerations at the deck, reducing the structural seismic demand.

1. INTRODUCTION

The hydraulic processes responsible for foundation scour during flood events are nowadays well understood (Chiew 1992). However, the effects on the mechanical performance of scoured foundations have not yet been fully investigated. In the state of practice, this assessment is commonly performed through numerical analyses (Wang et al. 2014), including simplified lumped-parameter models (e.g., Klinga & Alipour 2015) and finite element models (e.g., Ciancimino et al. 2022a). All of them confirm the detrimental impact that scouring can have on the seismic response of the structure, depending on its morphology and magnitude (Chortis et al. 2020). Experimental studies conducted by Qi et al. (2016) and Ciancimino et al. (2022b) have shown that the effects of general and local scour are notably different. General scour, characterized by the uniform lowering of the riverbed level, is recognized to affect both sidewall and base resistance mechanisms (Ciancimino et al. 2022a). Instead, local scour effects strongly depend on the morphology and the asymmetry of the scour hole, primarily affecting sidewall resistance.

This study evaluates how foundation scour affects the seismic behavior of a bridge pier supported by a caisson foundation, using a specific case study. It examines the impact of general and local scour on the system's performance through dynamic simulations conducted with the OpenSees finite element framework. The study explores how different support conditions at the base affect the spectral acceleration and displacement of the pier-caisson-soil system during seismic events.

2. NUMERICAL MODEL

The caisson-pier system is composed of reinforced concrete cylindrical sections (Figure 1a). The pier supports a multi-span isostatic bridge assumed as simply supported. In this way, the kinematic interaction between the deck and the pier is not considered and only the pier with the mass of the deck is modeled instead of the whole bridge. The foundation is embedded in gravel. The bridge model was firstly presented in (Foti et al. 2023) and it is shown in Figure 1a. Three numerical models were developed to consider different hydraulic scenarios, namely: *(i)* No Scoured (NS) model, *(ii)* General Scour (GS) model, and *(iii)* Local Scour (LS) model (Figure 1). The first was defined according to the original geometry of the case study (Figure 1a), the second by taking out four meters of the embedment soil, and the latter according to the local scour shape determined by Ciancimino et al. (2022b) through scaled hydraulic 1***g*** physical testing.

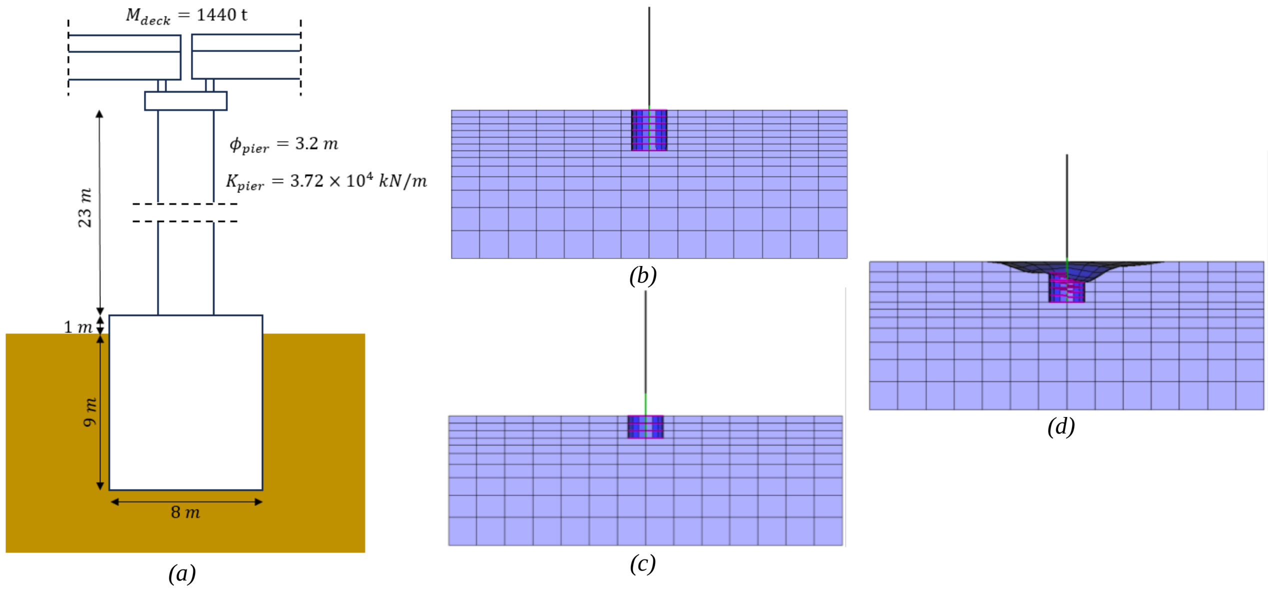

Figure 1. (a) Scheme of the pier-foundation system under investigation; (b-d) Transversal sections of the numerical models: (b) NS model, (c) GS model, and (d) LS model.

The soil mechanical behavior is modeled under fully drained conditions with a Pressure-Dependent elastic-plastic Multi-surface Yielding model (PDMY) to account for the non-linear behavior during cyclic loading and the depth-dependent change in stiffness, typical in coarse-grained soils (Yang et al. 2003). The constitutive parameters are defined according to the calibration process performed by Gorini (2017) on Messina Gravels, based on a wide range of experimental data (e.g., Crova et al. 1993, Fioravante et al. 2012). This soil is characterized by medium relative density $D_R = 45\%$, void ratio $e_0 = 0.35$, Poisson ratio $\nu = 0.2$, unit weight $\gamma = 22.0\ kN/m^3$ and hydraulic conductivity (k) in the order of $10^{-4}\ m/s$.

The structural model is composed by the caisson foundation and the pier. The first was modeled by using rigid-link beam-type elements to consider the caisson as infinitely rigid, and the latter by using Elastic-Beam-Column-Elements (Mazzoni 2006) with flexural elastic stiffness $K_{pier} = 3.72 \cdot 10^4\ kN/m$. To simplify the model, the mass of the caisson, of the pier, and of the deck were defined as lumped masses applied into the element centroid. The soil-structure interface was modeled using a rigid-link procedure (Gorini 2017).

The input motion employed (Northridge, 1994) was applied at the base of the model as a force history using base dashpots following the Joyner and Chen (1975) approach. This ensures symmetric proportional dynamic loading and impedance (Lysmer 1978). Scaling factors from 1 to 6 were applied to the input motion amplitude to assess system response to strong ground motions along with soil non-linearity effects.

In addition to the numerical simulations here presented, preliminary analyses were carried out to study the lateral pushover and the free vibration response of the structure (Molina 2023). The results have shown the effects of scouring in decreasing both the lateral capacity and the fundamental frequency of the pier. Moreover, it has been shown that the local scour morphology implies an asymmetrical mechanical response of the system, leading to larger lateral capacity when the structure is loaded towards the upstream (less scoured) direction. As a consequence, the LS model was divided into LS[+] and LS[-] to analyze the combined effect of the motion direction application and the local scour shape morphology.

3. RESULTS

Figure 2 presents the results for the Northridge earthquake (unscaled) in terms of time histories of caisson rotation (Figure 2a) and lateral deck displacement (Figure 2b). It is quite evident the effect of scouring in increasing both the peak and the residual values. However, this effect depends on the motion direction in the local scour case. If the direction of the maximum seismic forces is either in the direction of greater or lesser scouring, higher or lower displacements will result due to the asymmetric mechanical response of the local scour hole. Nevertheless, this asymmetry effect of local scour is practically negligible in terms of dynamic settlement (Figure 2c). Conversely, the accumulated settlement is notably higher in the general scour case, showing that this type of scour is more likely to affect the base-resistant mechanism.

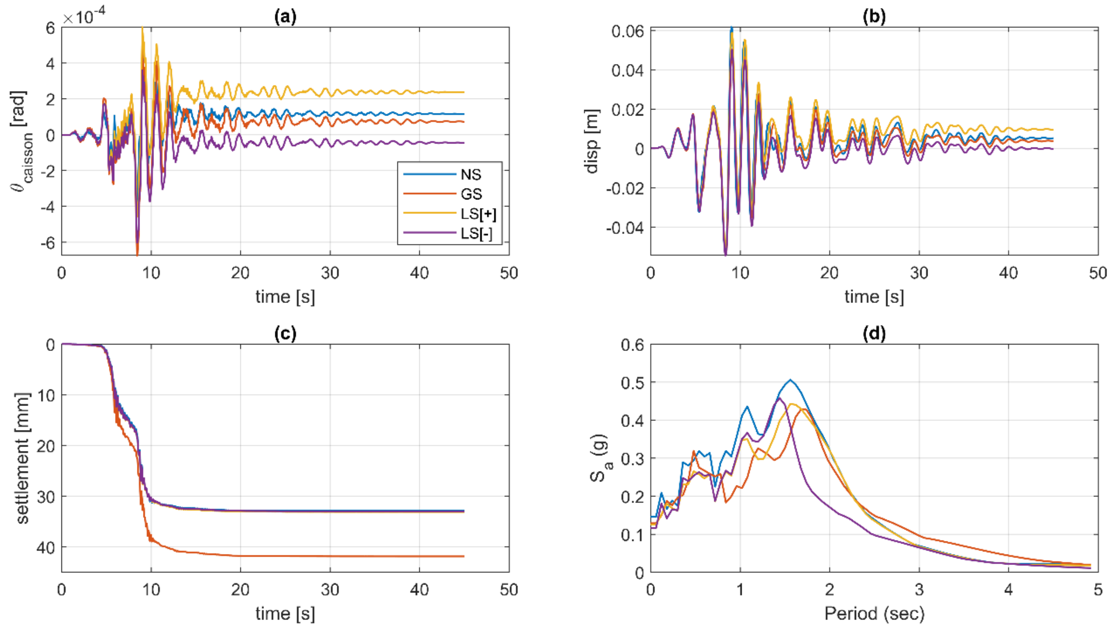

Figure 2. Results of dynamic analyses with the Northridge ground motion: (a) caisson rotation, (b) deck lateral displacement, (c) settlement time-histories, and (d) deck spectral acceleration.

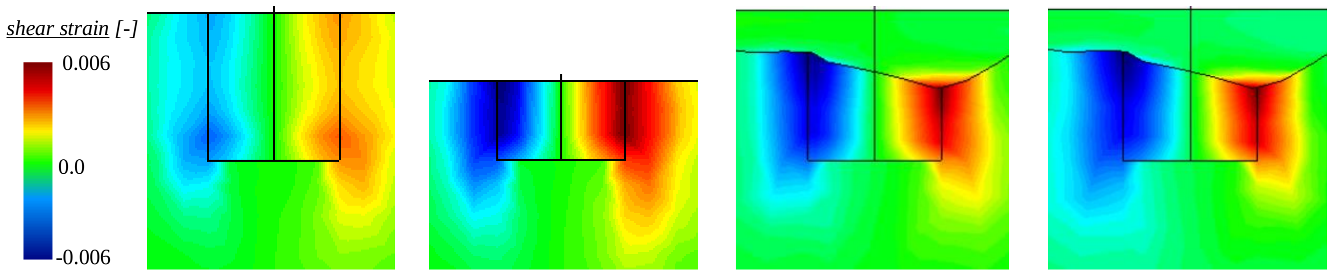

Figure 3. Residual soil shear strains, (a) NS scenario, (b) GS scenario, (c) LS[+] scenario and (d) LS[-] scenario

As for the spectral acceleration at the deck (Figure 2d), it can be observed a seismic isolation effect in both scoured cases, which is stronger in the general scour scenario. This can be attributed to the enhancement of soil-structure interaction effects due to scour itself, together with soil non-linearities. As the soil-foundation stiffness decreases, the amount of energy dissipated tends to increase, reducing in turn the seismic action acting on the structure (Anastasopoulos et al. 2012). The relevance of soil nonlinearities can be visualized by looking at the residual shear strains, that are larger in the scoured scenarios (Figure 3). Specifically, the GS scenario shows both a larger portion of compliant soil affected by residual strains and higher values of residual shear strains (Figure 3b), compared with the NS scenario (Figure 3a). Therefore, a higher influence of the soil non-linearity is expected in this case. On the other hand, the LS scenarios (Figure 3c-d) show high residual strains, which are significantly larger in the direction towards the structure is loaded.

The mentioned base seismic isolation effect increases when an increasing scaling factor is applied to the amplitude of the input motion. Indeed, a more significant reduction in the maximum deck acceleration is observed for the scoured scenarios for stronger ground motions (Figure 4a). However, this is counterbalanced by larger rotations of the caissons, especially for the general scour scenario (Figure 4b).

4. CONCLUSIONS

The impact of general and local scour on maximum and accumulated caisson rotation and deck displacement differs significantly. General scour primarily affects the vertical response, leading to greater dynamic settlement accumulation during shaking. Conversely, local scour mainly influences the lateral response, which can either worsen or improve depending on the shaking direction. The asymmetry of the local scour hole shape significantly affects seismic performance. Hence, precise modeling of the hydraulic scenario is crucial for predicting the mechanical consequences of scour under seismic conditions.

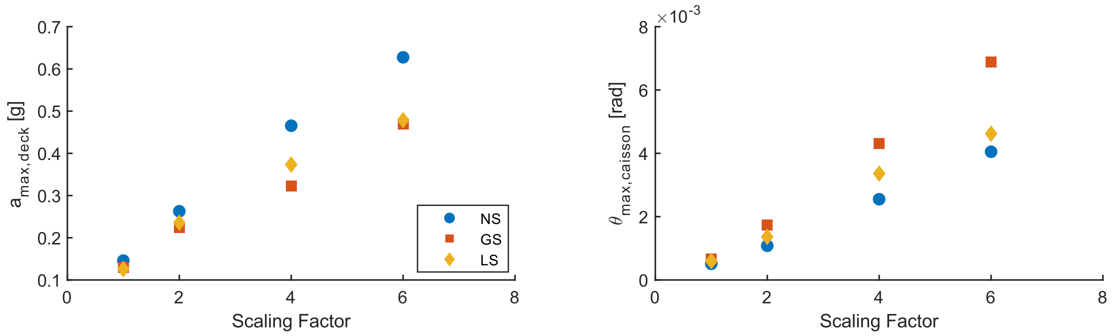

Figure 4. Results of dynamic analyses with the Northridge ground motion, with scaled amplitude. (a) Maximum deck acceleration $a_{max,deck}$ vs Scaling Factor and (b) Maximum caisson rotation $\theta_{max,caisson}$ vs Scaling Factor

On the one hand, scour notably alters the horizontal stiffness of the soil-caisson-pier system. On the other, it may increase the amount of energy dissipated by the soil-foundation system inducing a seismic isolation effect. This suggests a paradox between compromised serviceability in scoured scenarios and reduced structural seismic demand due to the combined effect of scouring itself and soil non-linearity.

5. ACKNOWLEDGMENTS

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