Influence of Ground Motion Characteristics on the Seismic Performance of Scoured Bridge Piers

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INFLUENCE OF GROUND MOTION CHARACTERISTICS ON THE SEISMIC PERFORMANCE OF SCOURED BRIDGE PIERS

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Abstract

This paper investigates the seismic performance of scoured bridge piers, focusing on the combined effect of ground motion characteristics and scouring conditions. Numerical analyses were conducted using a finite element framework based on a caisson-pier model embedded in a layer of coarse-grained material. Three numerical models were developed to simulate different hydraulic scenarios: (i) unscoured (NS), (ii) general scour (GS), and (iii) local scour (LS). A set of seven spectrum-compatible recorded inputs were employed, varying in ground motion parameters such as Peak Ground Acceleration, Cumulative Absolute Velocity, and Arias Intensity. Seismic demand is considered in terms of instantaneous measures, i.e., maximum acceleration at the deck, and cumulative measures, i.e., normalized residual horizontal deck displacement and foundation settlement. The results of the study indicate that the maximum acceleration at the deck correlates with the spectral acceleration at the pier fundamental period, increasing and being always larger in NS scenarios, followed by GS and LS scenarios, respectively. Dynamic analyses also show that the seismic amplification occurring in the range of vibration periods of the pier is strongly influenced by scouring conditions, with the GS scenario responsible for the largest base isolation effect. Such beneficial effect is however counterbalanced by the trends observed for the residual displacements. The results of the analyses show indeed that energy-based parameters, such as Arias Intensity and Cumulative Absolute Velocity, are well correlated with the residual displacements, but significantly differ according to the scour scenario, with horizontal displacement being more relevant in the LS scenario and the settlement accumulation in the GS scenario.

Keywords: Foundation Scour, Bridge Piers, Caissons, Soil-Structure Interaction.

1 INTRODUCTION

Numerical analyses, including simplified lumped-parameter models [e.g., 1] and finite element models [e.g., 2], have shown that foundation scour significantly alters the seismic response of bridge piers, with effects depending on scour morphology and extent [2, 3]. In this sense, experimental studies further highlighted the distinct behaviors of general and local scour [e.g., 4, 5]. General scour, characterized by a uniform lowering of the riverbed, reduces both sidewall and base resistance. In contrast, local scour – identified as localized erosion occurring around the foundation – primarily affects sidewall resistance, with scour asymmetry playing a critical role.

Pseudo-static pushover analyses can provide an initial approximation of the effects of scouring on the seismic capacity of bridge piers [e.g., 2]. However, such analyses neglect the nonlinear dynamic behavior of the soil-structure interaction (SSI) system, which manifests through strain accumulation during shaking, particularly at the caisson–soil interface, where nonlinearities, separation, and gapping critically influence the response [e.g., 6]. In dynamic conditions, input motions characterized by different ground motion parameters may induce significantly different effects on SSI systems [7]. In the past, parametric dynamic analyses have been carried out using different ground motions (GMs), primarily focusing on the effects of the structure (e.g., pier height and stiffness and deck mass) and caisson parameters on the dynamic response of the pier [e.g., 6, 8]. However, no systematic analyses are currently available about the influence of GM characteristics on the performance of bridge piers subjected to scouring.

This study focuses on this field by investigating the dynamic response of a single-degree-of-freedom (SDOF) bridge pier founded on a cylindrical caisson foundation embedded on a layer of coarse-grained material. To this end, advanced numerical analyses were performed adopting a set of input motions characterized by different intensity parameters. The results are analyzed in the light of both accumulated permanent displacements of the pier and seismic amplification at the superstructure.

2 NUMERICAL MODEL

The numerical model is based on a case study presented by Foti et al. [9] (Figure 1a). This consists of a soil-caisson-pier system. 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. This approach is valid for studying the bridge pier's response when seismic shaking occurs transversely to the bridge axis. Three numerical models were developed to consider different hydraulic scenarios, namely: *(i) No Scoured (NS) model* (Figure 1b), *(ii) General Scour (GS) model* (Figure 1c), *and (iii) Local Scour (LS) model* (Figure 1d). The first was defined according to the original geometry of the case study (Figure 1a), the second by removing 4 m of the embedment soil, and the latter according to the local scour shape determined by Ciancimino et al. [5] through scaled hydraulic *1g* physical testing.

The compliant soil, characterized by relative density D_R = 45%, is modeled under fully drained conditions using a Pressure-Dependent elastic plastic Multi-surface Yielding model (PDMY, [10]). The structural model comprises the caisson foundation and the pier, with the caisson modeled as a rigid body, the pier as an elastic beam-column element and the deck as a lumped mass. For more details about the model, refer to Molina et al. [11].

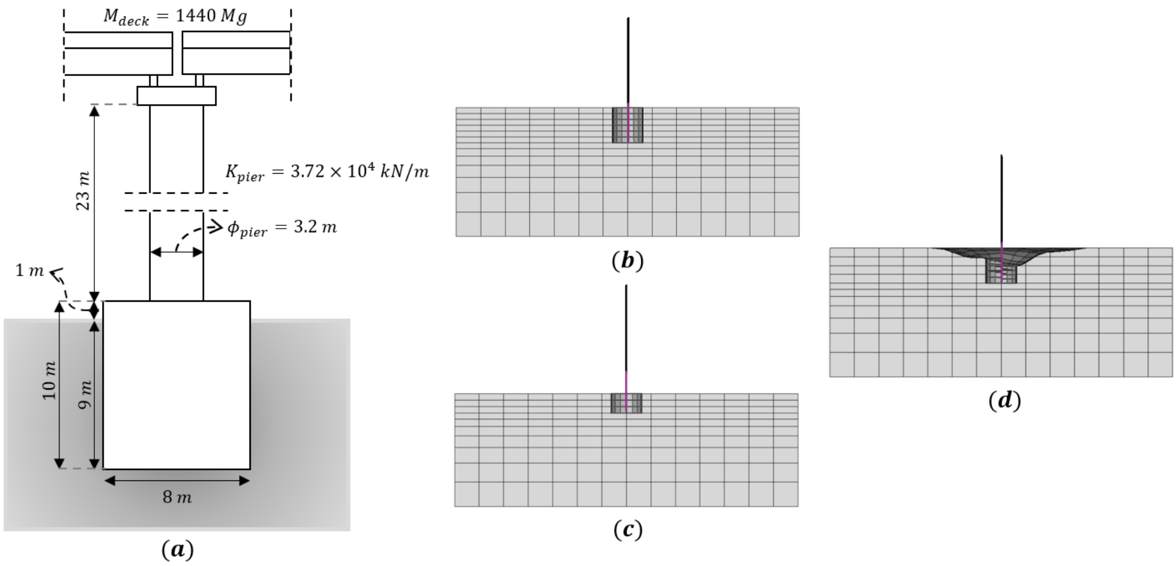

Figure 1: (a) scheme of the pier-foundation system under investigation; (b-d) transversal sections of the numerical models: (b) NS model, (c) GS model, and (d) LS model

$T_{0,pier\text{-}fixed\text{-}base}$	1.27 s
$T_{0,pier\text{-}NS}$	1.41 s
$T_{0,pier\text{-}LS}$	1.47 s
$T_{0,pier\text{-}GS}$	1.56 s
$T_{0,soil\text{-}deposit\text{-}NS}$	0.49 s
$T_{0,soil\text{-}deposit\text{-}GS}$	0.44 s

Table 1: Fundamental Periods (T_0) of the systems

Preliminary analyses were carried out to study the lateral pushover and the free vibration response of the structure [11]. The results have shown the effects of scouring in decreasing both the lateral capacity and the fundamental period of the pier (Table 1). Moreover, it has been shown that the local scour morphology implies an asymmetrical mechanical response, 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 and local scour shape morphology.

A set of seven reference GM records (Table 2), varying in parameters (e.g., Peak Ground Acceleration, *PGA*, and Arias Intensity, *AI*), were employed in the analyses. The records are spectrum-compatible with a medium-seismic hazard level site in Italy (Urbino, with 475-year return period *PGA = 0.17g*) in compliance with NTC18 prescriptions [12] (Figure 2a), as reported by Aimar et al. [13]. This approach allows for assessing the effects of GM characteristics on the system response for a reference seismic hazard level.

However, in engineering practice, seismic actions are commonly considered at the ground surface, representing free-field (FF) conditions, rather than at the bedrock level. Ground Motion at FF is strictly linked to foundation input motion (FIM) [e.g., 14, 15, 16], the latter being influenced by SSI phenomena [16]. For this reason, the results are presented in terms of GM parameters at FF, therefore accounting for site amplification effects. Figure 2b compares the average FF ground motion (FF-GM) response spectra with the average reference GM spectra, highlighting spectral amplification at the fundamental period of the soil deposit ($T_{0\text{-}FF}$), and within the range of fundamental periods of the pier (hatched area, $T_{0\text{-}pier\text{-}range}$, encompassing those for each scour scenario, i.e., $T_{0,pier\text{-}NS}$, $T_{0,pier\text{-}LS}$ and $T_{0,pier\text{-}GS}$, respectively).

Event name	Date	Network-Station	Component	Database	Scaling factor
South Iceland	17/06/2000	SM-Minni-Nupur	X	ESD	1.28
Central Italy	26/10/2016	IT-CLO	EW	ITACA	1.23
Iwate, Japan	13/06/2008	KNET-IWT010	NS	PEER NGA- West2	0.7
Parkfield-02, CA	28/09/2004	CGS-Parkfield-Turkey Flat #1 (0M)	270°	PEER NGA- West2	0.85
Northridge-01	17/01/1994	CGS-Vasquez Rocks Park	0°	PEER NGA- West2	1.05
Cosenza	25/10/2012	IT-MRM	EW	ITACA	1.2
North Western Balkan Peninsula	15/04/1979	CR-ULA	NS	ESM	0.85

Table 2: List of ground motions used in the analysis (from Aimar et al. [13])

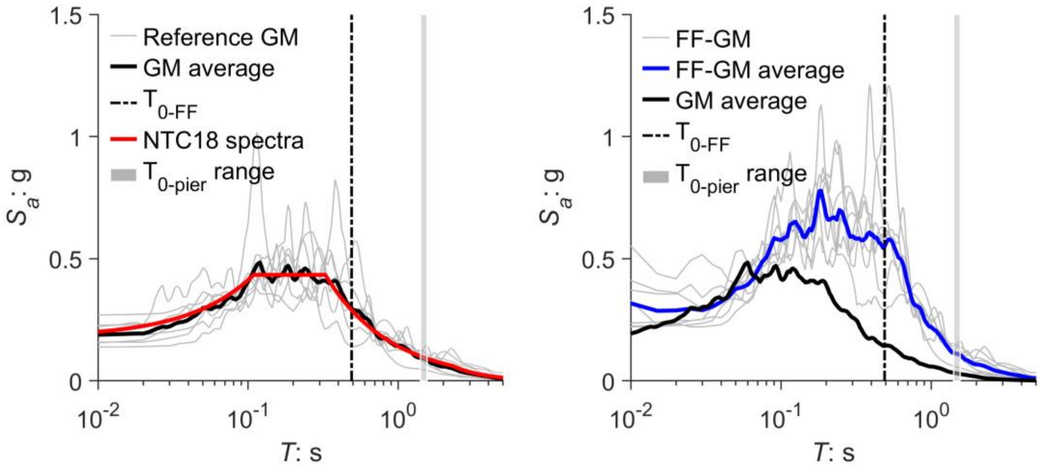

Figure 2: (a) average reference ground motion (GM) response spectrum in compliance with NTC18 prescriptions, (b) average Free-Field (FF) ground motion response spectrum

3 RESULTS

The response of the soil-caisson-pier system was described through three seismic demand measures, i.e., $a_{max,\ deck}$, $\delta_{H,\ deck}/H_{pier}$ and $\delta_{V,\ found}/D_{found}$, focusing on both the superstructure and the foundation response. Table 3 provides a detailed description of these quantities, together with the GM parameters considered in this study (i.e., PGA_{FF}, Sa_{FF} (T_{NS}), AI_{FF} and CAV_{FF}).

Ground Motion Parameters

Notation	Description	Type
PGA_{FF}	Peak Ground Acceleration at Free-Field	Peak (or instantaneous)
Sa_{FF} (T_{NS})	Free-Field Spectral acceleration at $T = T_{0,pier\text{-}NS}$	Peak Period-Based
AI_{FF}	Arias Intensity at Free-Field [17]	Energy-Based (or cumulative)
CAV_{FF}	Cumulative Absolute Velocity at Free-Field [18]	Energy-Based (or cumulative)

Seismic Demand Measures

Notation	Description	Type
$a_{max,\ deck}$	Max. acceleration at the deck	Peak (or instantaneous)
$\delta_{H,\ deck}/H_{pier}$	Normalized residual horizontal deck displacement: $\delta_{H,\ deck}$: residual horizontal deck displ.; H_{pier}: pier height	cumulative
$\delta_{V,\ found}/D_{found}$	Normalized residual foundation settlement: $\delta_{V,\ found}$: residual found. settlement; D_{found}: found. diameter	cumulative

Table 3: Definition of Ground Motion Parameters and Seismic Demand Measures used in the study

Figure 3 shows the comparison between seismic demand measures and GM parameters. Two distinct trends emerge: (*i*) correlation between the peak period-based GM parameter, Sa_{FF} (T_{NS}), with the peak seismic demand measure, $a_{max,\ deck}$; (*ii*) a clear trend between energy-based GM parameters, AI_{FF} and CAV_{FF}, with cumulative seismic demand measures, $\delta_{H,\ deck}/H_{pier}$ and $\delta_{V,\ found}/D_{found}$. Conversely, no clear correlation can be observed between PGA_{FF}, AI_{FF} and CAV_{FF} with $a_{max,\ deck}$. This indicates that peak and energy-based GM parameters may not be well-suited for predicting peak deck acceleration. Similarly, PGA_{FF} and Sa_{FF} (T_{NS}) do not exhibit a correlation with $\delta_{H,\ deck}/H_{pier}$ and $\delta_{V,\ found}/D_{found}$.

In comparing different hydraulic scenarios, higher $a_{max,\ deck}$ values are consistently observed under NS conditions (Figure 3). The disparity between NS and scoured scenarios widens as Sa_{FF} (T_{NS}) increases. Foundation scour induces a base isolation effect that intensifies with Sa_{FF} (T_{NS}), due to soil nonlinearity, limiting the transmitted seismic forces to the system [6]. However, the distinct behavior of GS and LS scenarios, in terms of $a_{max,\ deck}$ and Sa_{FF} (T_{NS}), is not clear. This may depend on the adopted seismic demand measure, especially in terms of associated vibration period, which is a controlling factor of the SSI system [19].

Regarding $\delta_{H,\ deck}/H_{pier}$ and $\delta_{V,\ found}/D_{found}$, both measures increase with the energy-based parameters (AI_{FF} and CAV_{FF}). However, the responses of GS and LS scenarios are significantly different. For $\delta_{H,\ deck}/H_{pier}$, LS scenarios exhibit larger values compared to the GS scenario. The influence of scour morphology is evident when analyzing LS[+] and LS[-] conditions where $\delta_{H,\ deck}/H_{pier}$ can be larger in one scenario than the other for the same input motion, according to the direction of shaking.

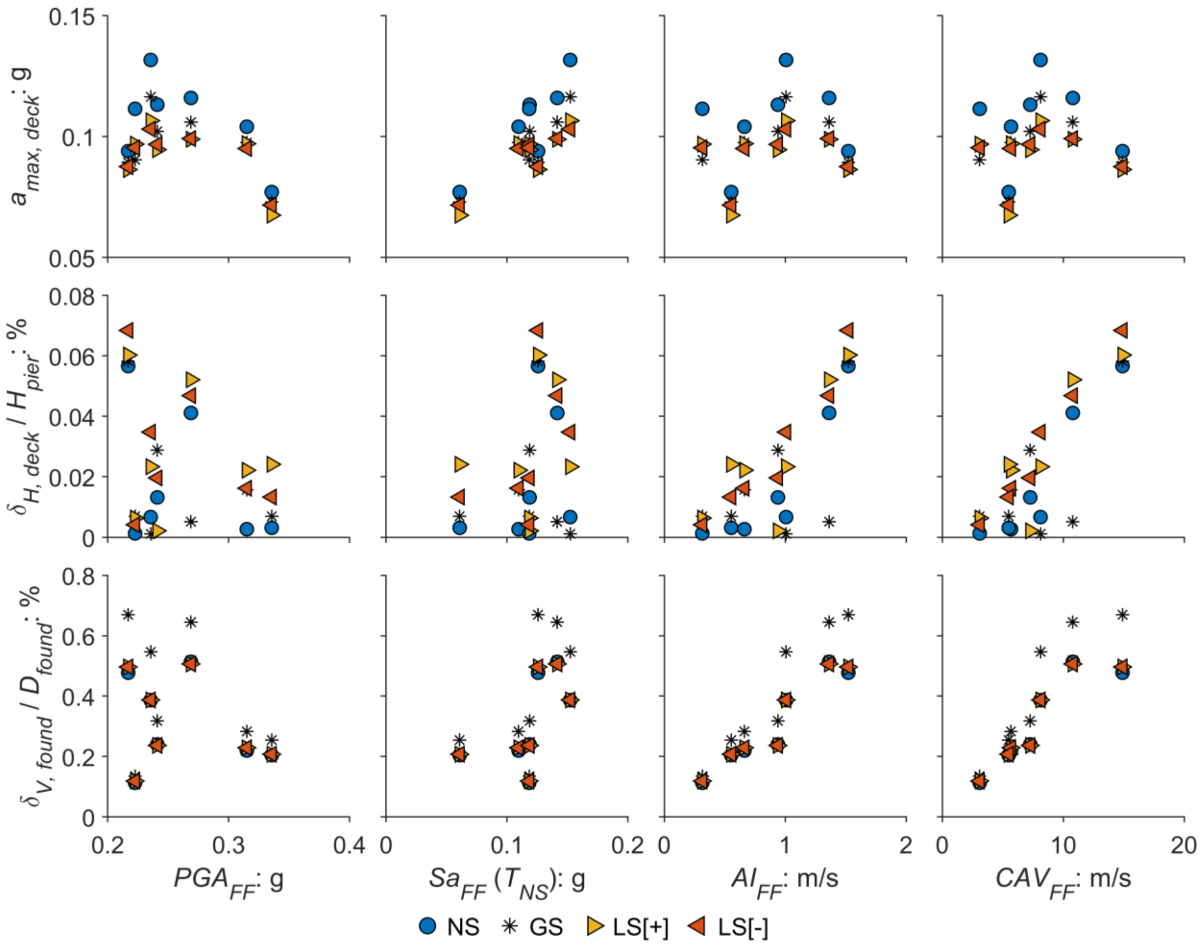

Figure 3: Peak ($a_{max,\ deck}$) and cumulative ($\delta_{H,\ deck}/H_{pier}$ and $\delta_{V,\ found}/D_{found}$) seismic demand measures vs peak (PGA_{FF}), period-based (Sa_{FF} (T_{NS})) and cumulative (AI_{FF} and CAV_{FF}) free-field ground motion parameters

Conversely, in the case of $\delta_{V, found}/D_{found}$, the foundation subjected to GS shows larger values, with a difference from NS conditions that increases with AI_{FF} and CAV_{FF}. Similar behavior has been observed in under-designed and over-designed caisson-foundations. The lower seismic action transmitted to the structure in the under-designed cases leads to a reduction in horizontal residual displacement and an increase in residual foundation settlement [e.g., 6, 20].

For better interpreting the seismic demand in terms of accelerations experienced at the deck, it is important to consider that $a_{max\text{-}deck}$ occurs only for a brief instant (i.e., instantaneous measure) and it is therefore associated with an infinitely rigid pier. An integral spectral amplification parameter (SA, eq. 1) can instead be more appropriate to highlight SSI amplification phenomena occurring at the pier. This is defined as the ratio between the integral response spectra at the deck Sa_{deck} (T) and at the FF motion Sa_{FF} (T), over the period range between T_1 = 1.00 s and T_2 = 1.70 s. This range encompasses $T_{0,pier\text{-}NS}$, $T_{0,pier\text{-}GS}$ and $T_{0,pier\text{-}LS}$, including possible period elongation due to nonlinearities.

$$SA = \frac{\int_{T_1}^{T_2} Sa_{deck}(T)dT}{\int_{T_1}^{T_2} Sa_{FF}(T)dT} \tag{1}$$

Figure 4 presents SA as a function of Sa_{FF} (T_{NS}), revealing that the GS scenario exhibits lower SA values compared to the LS scenarios. This means that concerning the scour scenarios, LS imposes higher spectral acceleration during the shaking. This distinct behavior remains for all simulations and appears to be independent of GM characteristics. Indeed, the average LS[+] and LS[-] are the same, which implies no important influence of shaking direction in the spectral amplification. These results contrast with $a_{max, deck}$, which can sometimes be higher in the GS scenario. The lower SA values in the GS scenario suggest that larger seismic isolation effects are systematically observed under general scour conditions.

4 CONCLUSIONS

In this paper, a series of dynamic analyses is presented to investigate the interplay between ground motion (GM) characteristics and seismic response of a bridge pier subjected to scouring. The main results can be summarized as follows:

(i) In the scoured scenarios, $a_{max, deck}$ values are generally lower than in the NS scenario. This difference increases with Sa_{FF} (T_{NS}) due to the base isolation effect enhanced by soil nonlinearity.

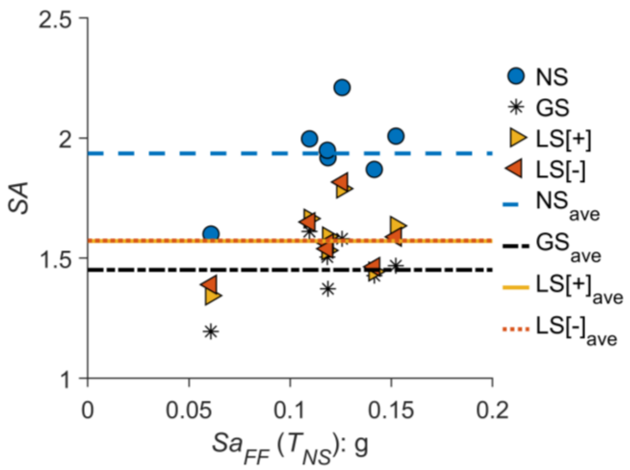

Figure 4: Spectral amplification (SA) vs Sa_{FF} (T_{NS})

(ii) To better highlight the influence of scouring on base isolation effects, reference can be made to the integral spectral amplification parameter (*SA*). The observed trends for *SA* show that the largest energy dissipation due to SSI phenomena occurs for the GS scenario, followed by the LS condition, and finally by the NS model.

(iii) The energy-based GM parameters AI_{FF} and CAV_{FF} showed a good correlation with cumulative seismic demand measures $\delta_{H,\,deck}/H_{pier}$ and $\delta_{V,\,found}/D_{found}$.

(iv) Compared to GS conditions, the increase in $\delta_{H,\,deck}/H_{pier}$ with AI_{FF} and CAV_{FF} in the LS scenario seems to be more relevant. This is probably due to the asymmetric geometry of the scour hole resulting in a preferred side for accumulation of displacements.

(v) $\delta_{V,\,found}/D_{found}$ increases dramatically due to GS, showing a clear discrepancy with the LS and NS scenarios with increasing AI_{FF} and CAV_{FF}. Such results suggest a strong influence of the GS conditions on the progressive accumulation of settlement during shaking, in agreement with experimental and numerical results showing a large detrimental effect of general scour on the bearing capacity mechanism occurring below the foundation.

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REFERENCES

[1] Klinga, J.V. and A. Alipour, Assessment of structural integrity of bridges under extreme scour conditions. Engineering Structures, 2015. **82**: p. 55-71.

[2] Ciancimino, A., et al., Numerical modelling of the effects of foundation scour on the response of a bridge pier. Acta Geotechnica, 2022. **17**(9): p. 3697-3717.

[3] Chortis, G., et al., Influence of scour depth and type on p–y curves for monopiles in sand under monotonic lateral loading in a geotechnical centrifuge. Ocean Engineering, 2020. **197**: p. 106838.

[4] Qi, W.G., et al., Scour effects on p–y curves for shallowly embedded piles in sand. Géotechnique, 2016. **66**(8): p. 648-660.

[5] Ciancimino, A., et al., Experimental assessment of the performance of a bridge pier subjected to flood-induced foundation scour. Géotechnique, 2021. **72**(11): p. 998-1015.

[6] Zafeirakos, A. and N. Gerolymos, *On the seismic response of under-designed caisson foundations.* Bulletin of Earthquake Engineering, 2013. **11**(5): p. 1337-1372.

[7] Ghayoomi, M. and S. Dashti, Effect of Ground Motion Characteristics on Seismic Soil-Foundation-Structure Interaction. Earthquake Spectra, 2015. **31**(3): p. 1789-1812.

[8] Gaudio, D. and S. Rampello, On the assessment of seismic performance of bridge piers on caisson foundations subjected to strong ground motions. Earthquake Engineering & Structural Dynamics, 2020. **50**: p. 1429 - 1450.

[9] Foti, S., et al. Influence of scour of foundations on the seismic performance of bridges. in SECED. 2023. Cambridge.

[10] Yang, Z., A. Elgamal, and E. Parra, *Computational Model for Cyclic Mobility and Associated Shear Deformation.* Journal of Geotechnical and Geoenvironmental Engineering, 2003. **129**(12): p. 1119-1127.

[11] Molina Manrique, M., et al., On The Dynamic Response of Bridge Piers Subjected to Foundation Scour, in XIII INCONTRO ANNUALE DEI GIOVANI INGEGNERI GEOTECNICI. 2024: Turin. p. 77-80.

[12] MINISTERO DELLE INFRAESTRUTTURE E DEI TRASPORTI., *Aggiornamento delle «Norme tecniche per le costruzioni».*, in *CAPITOLO 3. AZIONI SULLE COSTRUZIONI*. 2018, IL MINISTRO DELLE INFRASTRUTTURE E DEI TRASPORTI Rome.

[13] Aimar, M., A. Ciancimino, and S. Foti, *An assessment of the NTC18 stratigraphic seismic amplification factors.* Rivista Italiana di Geotecnica, 2020(1): p. 5-21.

[14] Sotiriadis, D., et al., Improved correlation between foundation and free-field ground motions through strong motion recordings and kinematic soil–structure interaction analyses. Earthquake Engineering & Structural Dynamics, 2022. **51**(4): p. 725-743.

[15] Sotiriadis, D., et al., Analytical expressions relating free-field and foundation ground motions in buildings with basement, considering soil-structure interaction. Engineering Structures, 2020. **216**: p. 110757.

[16] Stewart, J.P., Variations between Foundation-Level and Free-Field Earthquake Ground Motions. Earthquake Spectra, 2000. **16**(2): p. 511-532.

[17] Stafford, P.J., J.B. Berrill, and J.R. Pettinga, *New predictive equations for Arias intensity from crustal earthquakes in New Zealand.* Journal of Seismology, 2009. **13**(1): p. 31-52.

[18] Wu, M.-H., W.J. P., and P.-E. and Chiang, *Cumulative absolute velocity (CAV) seismic hazard assessment for Taiwan.* Journal of Earthquake Engineering, 2022. **26**(7): p. 3440-3460.

[19] Gazetas, G. and M. Apostolou. Nonlinear Soil-Structure Interaction: Foundation Uplifting and Soil Yielding. 2004.

[20] Zafeirakos, A., N. Gerolymos, and V. Drosos, *Incremental dynamic analysis of caisson–pier interaction.* Soil Dynamics and Earthquake Engineering, 2013. **48**: p. 71-88.