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SEISMIC VERIFICATION OF VIADUCT PIERS ON PILED RAFT FOUNDATIONS IN SOFT SOILS

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Abstract. *European critical infrastructures, including bridges and viaducts, play a vital role in transportation, emergency services, and economic activities; however, they are frequently exposed to seismic hazards. Traditional seismic assessments often employ pseudo-static approaches or consider dynamic analysis neglecting foundation system compliance (the base is assumed to be rigid). In this study, the authors introduce a conceptual model that captures the dynamic response of viaduct piers on piled foundations in soft soils by: (i) idealizing the deck as a concentrated mass, (ii) assuming the involved mass of the pier and the foundation system to be negligible, (iii) modeling the pier behavior with an in parallel spring–dashpot system, (iv) incorporating the translational and rotational displacements of the foundation system; (v) evaluating foundation stiffness by employing the macroelement approach and by considering Piles-Raft-Soil Interaction. The model has been applied to simulate the bridge response under 20 seismic records taken from the Italian database. Results indicate that considering SSI effects very often leads to a decrease in the actions on both the structure and the foundation system. The comparison with an existing elastic-plastic macroelement recently proposed by the authors suggests that for $PGA < 2m/s^2$ the piled raft foundation can be reasonably schematized by means of elastic springs.*

Keywords: Piled foundations, Seismic Soil-Structure-Interaction, Macroelement

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1 INTRODUCTION

Bridges and viaducts are essential for society, ensuring transportation, emergency services, and economic activities. However, they are vulnerable to seismic events, which can cause severe structural damages, disruption of essential services, and, in extreme cases, catastrophic collapses ([1]). Consequently, a comprehensive assessment of the seismic performance of these infrastructures is essential to safeguarding their integrity.

Today, it is critical to assess many viaducts at the end of their intended lifespan, whose foundations were designed more than 50 years ago without considering seismic actions.

In common practice, many simplifying assumptions are made for the verification of both the superstructure and the foundation system (often piled foundations in the case of viaducts on soft soils). The superstructure is typically modeled as rigidly clamped at the base, by disregarding Soil-Structure Interaction (SSI). The forces computed at the rigid base are then used to verify the foundation system. In case of piled raft foundations, the foundation system is simplified and piled raft is reduced to a pile group (Piled-Raft-Soil Interaction (PRSI) is neglected). The assumption of neglecting both SSI and PRSI can lead to non-optimized retrofitting designs in relation to both superstructure and the foundation system. Indeed, recent studies have highlighted the importance of accounting for both SSI ([2], [3], [4]) and PRSI ([5], [6]), on system mechanical response.

In cases of pile raft foundations under undrained conditions and general load combinations, considering the PRSI interaction, [7] (i) observed that the mechanical response is elastic for low load levels (Elastic Nucleus, EN in Figure 1), (ii) proposed geotechnical and geo-structural interaction domains (GEO ID and GEO-STRU ID in Figure 1) and (iii) defined a macroelement model predicting piled raft displacements under pseudostatic combined loads, representative of seismic actions ([8]). Although it provides a more accurate safety assessment than traditional simplified approaches that neglect PRSI, it treats the seismic actions as combined monotonic quasi-static loads and, as a result, does not capture the dynamic response of the system.

In Figure 1 GEO ID, GEO-STRU ID and EN are illustrated in M-H plane for V=25MN (the vertical load acting on the piled raft). GEO ID corresponds to the geotechnical failure of the system obtained by assuming piles to be elastic. GEO-STRU ID corresponds to the structural failure of the most loaded pile. For M-H load combinations lying inside EN and GEO STRU ID, the system response is elastic.

In this work, a conceptual model for the dynamic response of viaduct piers on piled foundations in soft soil is proposed, accounting for both SSI and PRSI: (i) idealizing the deck as a concentrated mass, (ii) assuming the involved mass of the pier and the foundation system to be negligible, (iii) modeling the pier behavior with an in parallel spring–dashpot system, (iv) incorporating the translational and rotational displacements of the foundation system; (v) evaluating foundation stiffness according to the macroelement theory.

The model is used to simulate the response of a representative case study pier of a bridge (Figure 2a) subject to 20 different seismic input records taken from the Italian database (with PGA values ranging from $0.33 m/s^2$ to $6.32 m/s^2$). The predicted forces transmitted from the superstructure to the foundation are then compared with GEO ID, GEO-STRU ID and EN (i) to quantify the benefit of considering SSI and (ii) defining in which case the assumption of elastic foundation is valid.

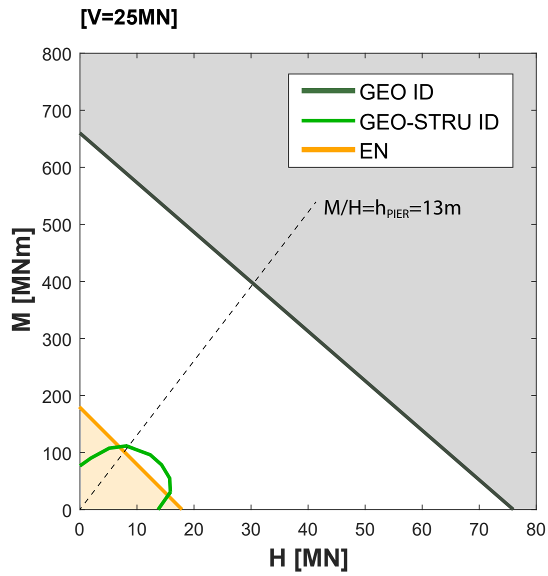

Figure 1: Interaction domains (GEO and GEO-STRU) and elastic nucleus (EN).

2 MODEL

The model is based on the idealization of the deck as a concentrated mass m. The masses of pier, foundation and soil interacting with it are assumed to be negligible, with respect to m. For the sake of simplicity, radiation damping, which results from energy dissipation due to the propagation of waves away from the foundation into the surrounding soil, is neglected.
The total horizontal displacement $x(t)$ of mass m with time t, representing the deck drift, is obtained by adding (i) external seismic input ($u(t)$), (ii) pier displacement due to pier deformability ($y(t)$) and (iii) foundation displacements (horizontal translation $u_f(t)$ and rotation ($\theta_f(t)$)):

$$x(t) = u(t) + y(t) + u_f(t) + \theta_f(t)h_s \tag{1}$$

where h_s is the pier height (Figure 2b).
The vertical displacements are not considered.

The mass inertia force $F_I(t) = m\ddot{x}(t)$ is balanced by the reaction due to pier deformability ($F_S(t)$) that is evaluated by modeling the pier response as an in parallel spring-dashpot system (Figure 2c):

$$F_s(t) = k_s y(t) + c_s \dot{y}(t) \tag{2}$$

where pier elastic stiffness k_s is defined as a function of pier material Young modulus E, inertia moment of pier cross section I and h_s:

$$k_s = 3EI/h_s^3 \tag{3}$$

Structural damping coefficient c_s is defined as follows:

$$c_s = 2m\omega_{n,s}\zeta_s \tag{4}$$

where $\omega_{n,s} = \sqrt{k_s/m}$ is the pier natural frequency and ζ_s is a model parameter (typically assumed in structural analyses equal to 0.05).

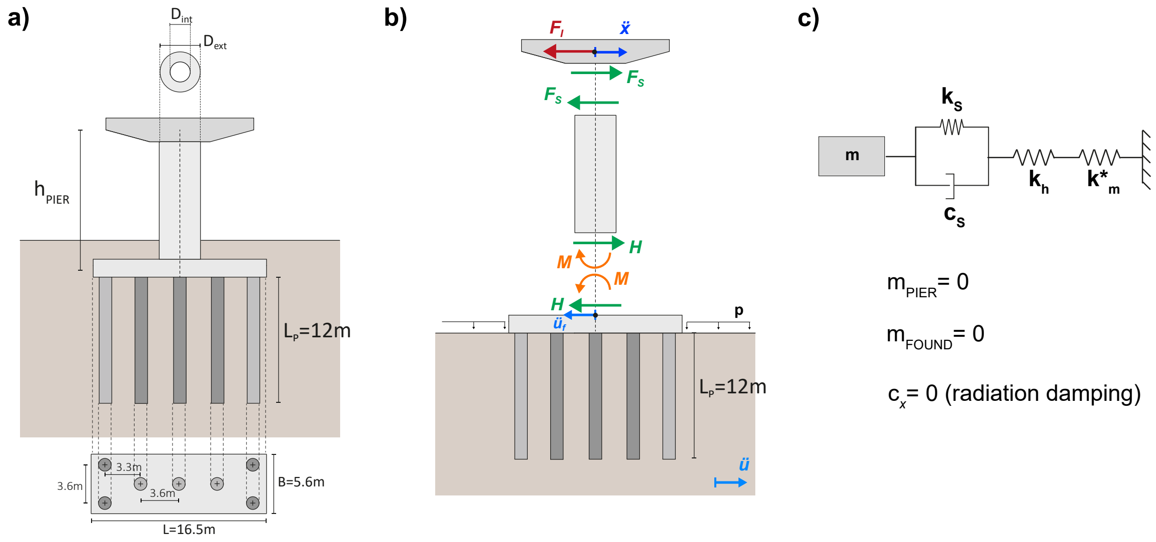

Figure 2: (a) Geometry of the pier and its foundation, (b) balance of momentum scheme, (c) constitutive model.

From the equilibrium on the pier, the actions acting on the foundation system, H and M can be evaluated. In particular, $H = F_S = F_I$ whereas $M = F_S \cdot h_s$.

Foundation displacements are evaluated according to the macroelement theory ([9]). Despite foundation response under cyclic loading is known to be hysteretic ([10], [11]), for the sake of simplicity, a linear-elastic macroelement is assumed, neglecting the coupling between horizontal and rotational degrees of freedom:

$$\begin{bmatrix} u_f \\ \theta_f \end{bmatrix} = \begin{bmatrix} 1/k_h & 0 \\ 0 & 1/k_m \end{bmatrix} \begin{bmatrix} H \\ M \end{bmatrix} \tag{5}$$

Due to this latter assumption, system mechanical response can be interpreted as a 1DOF linear oscillator (rheological scheme reported in Figure 2).

The equivalent elastic stiffness K_{eq} and an equivalent damping coefficient ζ_{eq} of the 1DOF can be evaluated as ([12], [3]):

$$k_{eq} = \frac{1}{1/k_s + 1/k_h + 1/k_m^*} \tag{6}$$

$$\zeta_{eq} = \frac{k_{eq}}{k_s}\zeta_s \tag{7}$$

where $k_m^* = k_m/h_s^2$.

The natural frequency of the equivalent system can be evaluated as $\omega_{n,eq} = \sqrt{k_{eq}/m}$ and correspondigly the natural period of the equivalent system $T_{n,eq} = 2\pi/\omega_{n,eq}$. The equation of motion for mass m has been integrated with time t considering a Newmark average acceleration method ([13]) which is unconditionally stable.

In this work, as it concerns the superstructure, concrete piers ($h_s = 13m$) are considered ($E = 30GPa$) with circular hollow core cross-section of external and internal diameter $D_{ext} = 3m$ and $D_{int} = 2m$, respectively. The deck mass m has been assumed equal to $2500t$. The macroelement elastic stiffness coefficients $K_h = 700MN/m$ and $K_m = 70000MNm/rad$ have been calibrated on finite element numerical analyses in which the contact between raft and soil is considered ([7]).

3 NUMERICAL RESULTS

In this section, the model has been used to simulate the dynamic response of viaduct piers subject to 20 seismic records taken from the Italian database ([14]), characterized by different Peak Ground Acceleration (PGA) values (Table 1).

n.	Station	Date	Motion component	PGA $[m/s^2]$
1	GMN - GEMONA	15/09/1976	North-South	3.18
2	GMN - GEMONA	15/09/1976	East-West	6.32
3	STR - STURNO	23/11/1980	North-South	2.20
4	STR - STURNO	23/11/1980	East-West	3.14
5	CAT - CATANIA	13/12/1990	North-South	2.46
6	CAT - CATANIA	13/12/1990	East-West	2.04
7	ASS - ASSISI	26/09/1997	North-South	1.64
8	ASS - ASSISI	26/09/1997	East-West	1.84
9	MRN - MIRANDOLA	29/05/2012	North-South	2.89
10	MRN - MIRANDOLA	29/05/2012	East-West	2.19
11	NRC - NORCIA	30/10/2016	North-South	3.65
12	NRC - NORCIA	30/10/2016	East-West	4.76
13	NRC - NORCIA	03/11/2016	North-South	0.33
14	NRC - NORCIA	03/11/2016	East-West	0.55
15	GSA - GRAN SASSO	18/01/2017	North-South	0.90
16	GSA - GRAN SASSO	18/01/2017	East-West	0.95
17	POZS - POZZUOLI	29/03/2022	North-South	0.60
18	POZS - POZZUOLI	29/03/2022	East-West	0.55
19	NAP - NAPOLI	27/09/2023	North-South	0.79
20	NAP - NAPOLI	27/09/2023	East-West	0.85

Table 1: Table of the 20 considered accelerograms with the correspondent values of PGA.

In Figure 3, the maximum bending moment transmitted by the superstructure to the foundation system as a function of PGA values for different seismic records, are illustrated. In particular, the predictions obtained under the rigid base assumption are compared with those considering SSI.
As was expected, in most of the cases, as PGA increases, maximum bending moment on the foundation (M_{max}) increases. Interestingly, in most cases, SSI is beneficial as it reduces the action on the foundation. For instance for PGA $1m/s^2 < PGA < 3m/s^2$, the reduction is up to 20% in M_{max}. In Figure 3 GEO, GEO-STRU IDs and EN are reported. GEO-STRU ID is slightly larger than EN, meaning that until the first pile fails, the behaviour can be assumed to be practically elastic. In many cases, the image point lies inside EN, testifying that the elastic base approximation is acceptable. In other cases, the point is outside EN, testifying the need for a more refined macroelement model accounting for the irreversible foundation system response. Only one point belongs to a domain outside the GEO ID. This corresponds to the seismic record n.2 and rigid base approximation. If SSI is considered, actions on the foundation significantly reduce and the correspondent point is inside GEO ID.

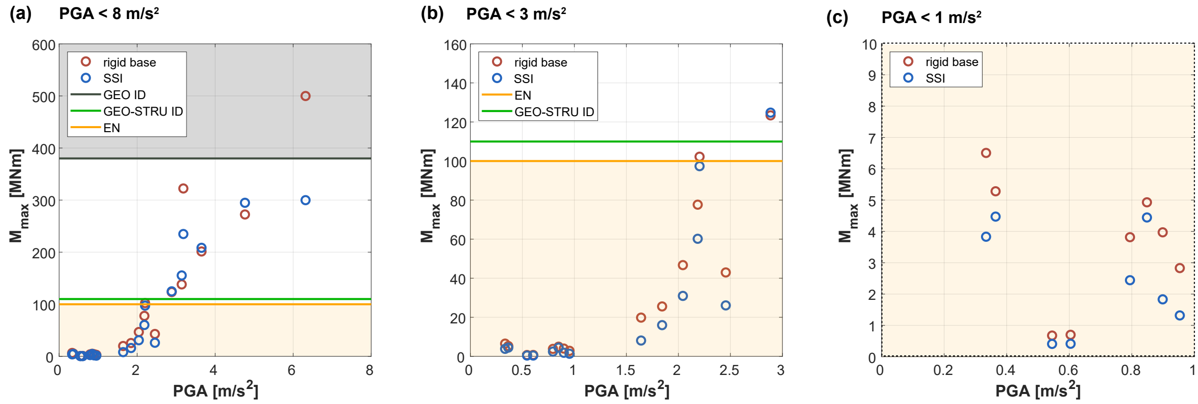

Figure 3: Maximum bending moment acting on the foundation as function of PGA for the 20 seismic records: comparison between rigd base approximation and SSI solution. (a) complete dataset and (b) data corresponding to $PGA \leq 2m/s^2$

In general, considering SSI allows to increase T_n , reduce S_a, giving rise to a reduction in both $M(t)$ and $\ddot{x}(t)$ (Figure 4 correspond to seismic record n.13).

In some cases (e.g., seismic record n.12, Figure 5), the choice of neglecting SSI may, conversely, lead to unsafe estimates of the actions on the foundation system. Indeed, for the oscillations of the function putting in relation S_a with T_n (Figure 5, seismic record n.12), an increase in T_n may cause an increase in S_a, giving rise to an increase in both $M(t)$ and $\ddot{x}(t)$ (Figure 5).

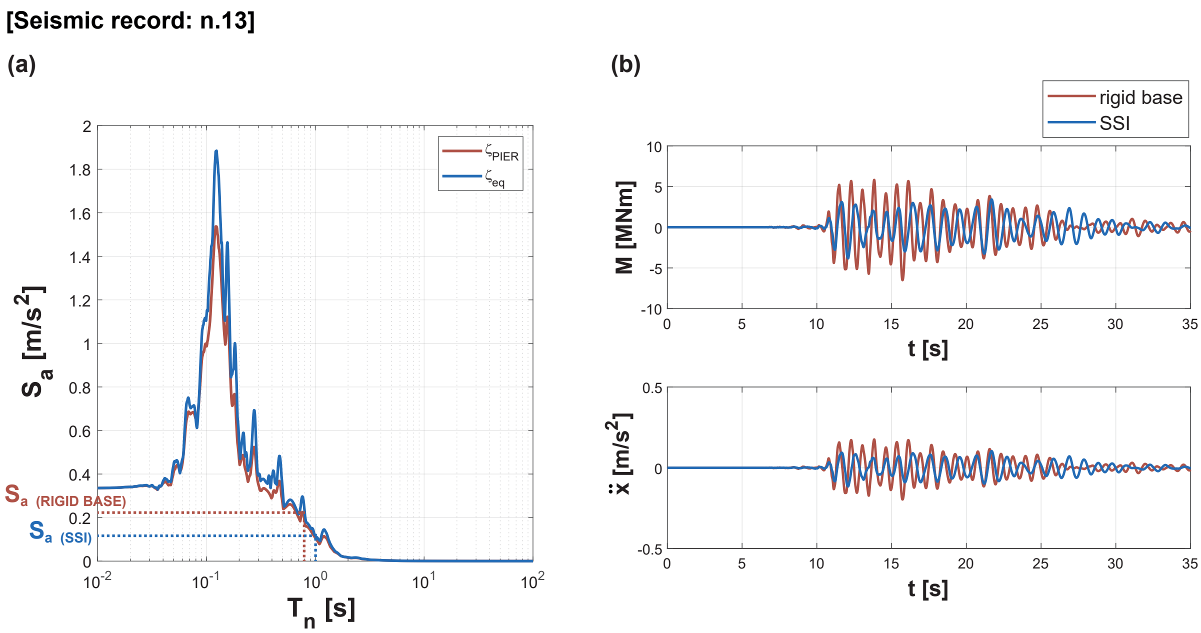

Figure 4: Response to earthquake n.13: (a) Response spectrum: comparison between S_a in case of rigid base and elastic base assumptions and (b) Time histories of overturning moment at pile base and deck acceleration.

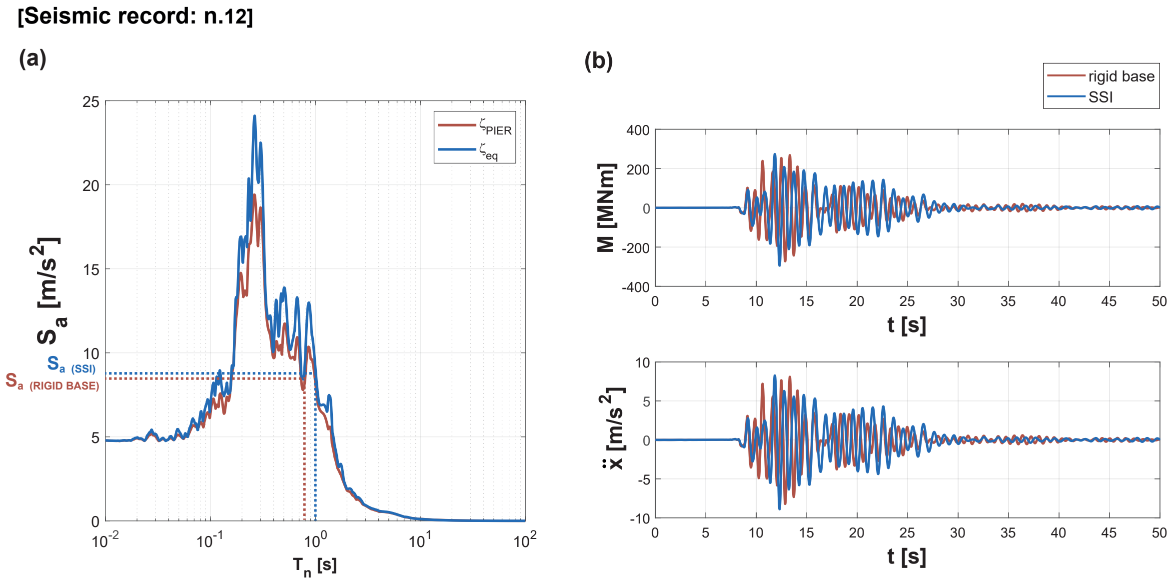

Figure 5: Response to earthquake n.12: (a) Response spectrum: comparison between S_a in case of rigid base and elastic base assumptions and (b) Time histories of overturning moment at pile base and deck acceleration.

4 CONCLUDING REMARKS

In this study, a conceptual model is introduced to discuss the dynamic behavior of viaduct piers on piled raft foundations in soft soils under undrained conditions. The model is obtained by: (i) idealizing the deck as a concentrated mass, (ii) assuming the involved mass of pier and foundation system to be negligible, (iii) modeling the pier behavior with an in parallel spring–dashpot system, (iv) incorporating additional degrees of freedom to account for foundation displacements; (v) evaluating foundation stiffness by using macroelement theory and by considering Piles-Raft-Soil Interaction. The model has been applied to simulate the bridge response under 20 different seismic records, and its outcomes are compared with those obtained by assuming the base to be rigid. Moreover, the results are compared with geotechnical and geo-structural interaction domains of the piled raft and with its elastic nucleus. The results demonstrate that neglecting Soil–Structure Interaction can lead to an overestimation of the forces acting on both the structure and its foundation, potentially resulting in an unrealistic assessment of bridge safety. In addition, numerical results have allowed to demonstrate that for $PGA < 2m/s^2$, the behaviour of the piled raft can be reasonably schematized by means of elastic springs. For higher PGA values, actions on the foundation exceed the elastic nucleus and the non-linear irreversible foundation response must be accounted for.

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