Numerical prediction of the eigenfrequencies of an idealized bridge pier under local scour

M. Aimar[1], S. Foti[1]
1. Department of Structural, Building and Geotechnical Engineering, Politecnico di Torino, Torino, Italy.

Abstract

Foundation scour is a major cause of bridge collapse worldwide (e.g., [1]). Indeed, several studies have demonstrated its detrimental effects on the soil-structure system, both in terms of the foundation capacity and stiffness (e.g., [2]). Furthermore, the difficulty in detection of foundation scour and the budgetary delays in retrofitting increase the likelihood that scour-prone piers will be exposed to events as earthquakes. For this reason, it is essential to investigate the dynamic response of bridge piers before and after foundation scour. This study addresses the dynamic behavior of an idealized reinforced concrete bridge pier supported on a cylindrical caisson foundation embedded in sand, and it estimates the system eigenfrequencies under various scour scenarios.

Keywords: Foundation scour, soil-structure interaction, dynamic response.

Introduction

Foundation scour is the process of excavation of the soil around the foundations of structural components inserted in water bodies (rivers, lakes, seas), due to the erosive action exerted by the water flow. Although this contribution focuses on bridge crossings over rivers, scour phenomena also occur in other geotechnical systems, for instance at foundations of offshore constructions.

In geotechnical and hydraulic engineering, two main types of scour are identified. On the one hand, general scour (or global scour) is the uniform lowering of the riverbed, due to both the reduction of the river cross-section by the presence of the bridge itself and aggradation and degradation phenomena occurring at the whole scale of the river. Instead, local scour is the localized erosion in correspondence of bridge piers and abutments, caused by flood-induced vortices around their base.

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The prediction of the response of these systems should incorporate an accurate model to account for soil-structure interaction. Indeed, the presence of stiffer or more deformable support conditions at the base significantly alters the flexibility in the foundation-structure system, resulting in the variations of eigenperiods and in significant changes in terms of vibrational energy dissipation [3].

Usual modelling of soil-structure interaction is often performed through the substructure method, which derives the response of the soil, foundation and superstructure independently, combining them according to the compatibility of forces and displacements. Commonly, a hybrid approach schematizes the superstructure connected to ideal springs and dampers in a single model. These synthetize the dynamic soil-foundation response and interaction effects, through a frequency-dependent dynamic impedance function (e.g., [4]) which maps the free-field response of the soil column into the response due to the presence of the structural system. Alternatively, soil-structure interaction can be introduced through suites of linear (or nonlinear) distributed springs along the foundation surface, capable of capturing more complex interaction phenomena due to material and interface nonlinearity (e.g., [5]; [6]).

Simplified methodologies can be adapted to capture some of the phenomena induced by the presence of scour. For instance, the variations in the pier supporting conditions can be modeled through the removal of a shallow layers of springs from the model, thus simulating the removal of a uniform thickness of the surface soil. Besides, the dynamic impedance functions include the dependence of the embedment thickness, which allows for considering this term to adapt the system behavior. However, this scheme can be representative of general scour, in which the waterbed lowers in a uniform way. Instead, these approaches can hardly reproduce local scour phenomena, although some studies attempted to adapt the stiffness of the remaining springs to local scour phenomena (e.g., [7]). Furthermore, these methodologies are suitable for modelling the problem in the small-to-moderate strain range, whereas they show limitations when strong nonlinearities are involved. This scenario occurs under strong seismicity and/or close to the bearing capacity of the foundation system.

In this context, advanced numerical simulations become a valuable tool for investigating the pier response, as they allow representing the problem geometry rigorously and incorporating adequate constitutive models to reproduce the soil response for a wide range of stress-strain conditions.

This study presents the development of a numerical model to reproduce the dynamic behavior of an idealized reinforced concrete bridge pier supported on a cylindrical caisson foundation embedded in sand, and it estimates the system eigenfrequencies focused on the lateral, rocking response, under various local scour scenarios. This specific response was the focus because it dominates the lateral and seismic behavior of slender structural elements founded on rigid foundations. The complex geometry involved due to the presence of the local scour hole allows to investigate the capability of the COMSOL software to deal with geometrically complex domains.

Case study

The investigated pier is schematically described in Figure 1a. It is a 6 m tall, reinforced concrete pier, with a circular full section of diameter equal to 1.6 m. The pier is founded on a cylindrical, reinforced concrete caisson, with diameter and height both equal to 6 m. For both the pier and the caisson, the reinforced concrete has mass density equal to 2450 kN/m^3, Young's modulus of 30 GPa and Poisson's ratio of 0.3. It is assumed that the pier supports two spans of a girder bridge, with the deck composed of simply supported, isostatic, reinforced concrete beams. Thus, the pier can be schematized as a Single Degree of Freedom (SDOF) system, consistent with the recommendations for the dynamic analysis of simply supported bridges (e.g., [8]). The corresponding mass m is 4.3×10^5 kg and it is concentrated in correspondence of the pier cap, and it includes the competent deck. This bridge is representative of a typical existing river crossing in the Po plain in Italy, with span of 20-25 m.

The pier is founded on a 25 m thick deposit of dense, homogeneous and isotropic sand, with unit weight equal to 17 kN/m^3 and Poisson's ratio of 0.3. It is characterized by a parabolic stiffness profile with depth, to account for the effect of confinement on its behavior. This variation is described through the following relationship for the shear modulus [10, 11]: G (MPa) = $133.2(p'/p_{atm})^{0.42}$, where p' is the mean stress and p_{atm} = 101.325 kPa is the atmospheric pressure. The deposit overlies a rigid formation, that can be modeled as a rigid bedrock.

Due to flowing water, the sand around the foundation is partially removed, with the creation of a scour hole partially exposing the foundation. The shape of the excavation is consistent with the typical shape observed in hydraulic engineering (an example is reported in Figure 1b), characterized by an asymmetric geometry with sharp changes in depth over a narrow region around the foundation.

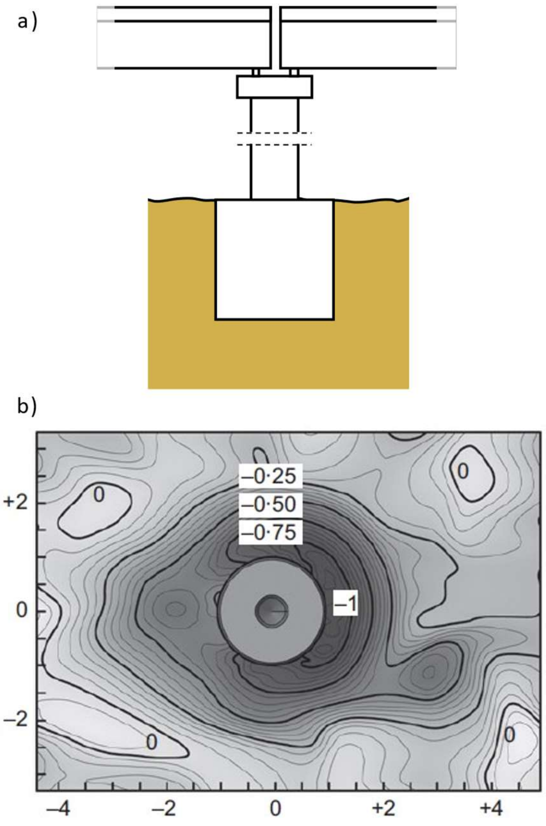

Figure 1. a) Sketch of the pier-caisson system considered in this study; b) Top view of a local scour hole, with the contour lines indicating the depth – values are normalized with respect to the maximum depth (after [9]).

This study addresses the dynamic response of the system considering the foundation fully embedded (label "S00") and for five local scour scenarios, with foundation scour to a maximum depth equal to 38%, 50%, 63%, and 75% of the caisson height (labels "S38", "S50", "S63", and "S75", respectively). The behavior is investigated focusing on the first rocking mode of the pier-caisson system, which dominates the response of relatively slender structures under lateral loading conditions (such as earthquakes; e.g., [12]). For simplicity, the response is analyzed in fully drained conditions, without an explicit modeling of the presence of water.

Numerical Model

The numerical model was implemented using the Structural Mechanics module of the COMSOL Multiphysics® software.

The "Beam" interface was used to model the bridge pier and the deck mass, that were included as Euler-Bernoulli beams. As mentioned above, there is no need for an explicit modeling of the deck, which was introduced as a "Rigid Domain", with section and length calibrated to correctly reproduce its mass distribution along the height.

Instead, the "Solid Mechanics" interface was used to model the caisson foundation and the sand deposit. The connection between the superstructure and the foundation was provided by a "Solid-Beam Connection" node. As for the soil deposit, this was introduced as a box with width and length both equal to 75 m, to minimize the possible influence of domain boundaries on simulation results. The depth was limited to 25 m, thus not explicitly including the bedrock (which was replaced by suitable boundary conditions) as it does not contribute to the deformability of the system. In the foundation scour scenarios, scour was easily introduced by modifying the geometry of the soil domain to create an excavation around the caisson, using the available Boolean operations and solid primitives. For simplicity, also the soil was modeled as isotropic linear elastic, with a pressure-dependent stiffness for the sand to account for the effect of confinement on its behavior. The pressure-dependent behavior required the inclusion of a "Weak Contribution" node to update this parameter as a function of the soil stress state. Ideally, the model should include friction, by means of the introduction of a "Contact Interface", to reproduce the possible slippage along the interface between the caisson and the sand (e.g., [6]). However, this aspect is deemed to be negligible for the purposes of a modal analysis, hence perfect bonding at the boundaries was assumed.

In terms of the boundary conditions, the base is fully constrained, a pair of parallel sides was left free to move horizontally, and periodic boundary conditions were applied at the other pair. This specific set of restraints forces pure shear deformation in the soil deposit, which occurs when affected by the vertical propagation of horizontally polarized shear waves. This is quite a common scenario in geotechnical earthquake engineering [13], and it also offers the possibility for a comparison with known solutions.

A special note should be made about the mesh. The large size of the model and the geometric complexity induced to generate a partially structured mesh based on hexahedral elements (Figure 2). Specifically, the domain region delimited by the scour hole was discretized starting from an unstructured quadrilateral mesh applied on the bottom boundary, calibrated to ensure that the average element size close to the foundation to be around 50 cm. Indeed, the largest displacement gradients are expected in this region. Instead, a structured mesh was used on the external region, with the mesh element size increasing exponentially towards the external boundary of the domain. This solution allowed the mesh to be reduced to 15,000 elements. For comparison, a purely unstructured mesh with the same element density close to the caisson (obtained using the "Physics controlled settings" for the mesh sequence generation with the "Extremely fine" element size) would have resulted in more than 900,000 solid elements.

For all the models, the modal response was obtained through an Eigenfrequency analysis.

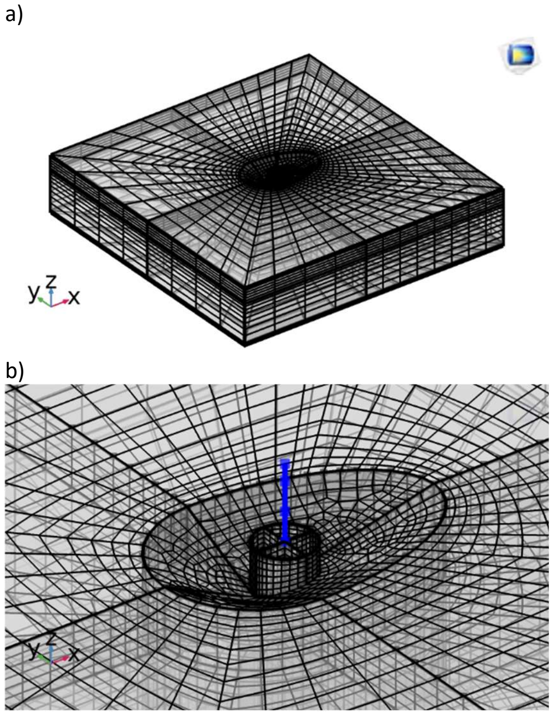

Figure 2. a) Overview of the numerical mesh generated for the whole domain; b) Zoomed view on the region containing the pier-caisson system and the scour hole.

Simulation Results

Validation

For validation purposes, the numerical model was tested for the fully embedded ("S00") configuration, focusing on two specific modal features.

On the one hand, the validation was performed on the first rocking mode of the caisson-pier system (Figure 3), which is indeed the dynamic feature investigated in this study. For this purpose, an independent simulation of the response of the soil-structure system was carried out with the SAP2000 software [14]. In this case, the structural system composed by the deck mass, pier and caisson was modeled through frame objects, which is equivalent to a beam element. Instead, soil compliance was reproduced through a set of springs and dashpots applied at the base of the caisson. Their parameters correspond to a frequency-dependent dynamic impedance function, obtained through the formulations proposed by Gazetas [4], which synthetizes the soil compliance. The calculation was performed assuming an equivalent homogeneous medium with shear stiffness of 132 MPa, which is the average of the G profile in the volume of influence of the caisson foundation [4], and a reference frequency equal to the fixed-base first flexural eigenfrequency of the pier-deck system. The resulting eigenfrequency from COMSOL equals 2.9 Hz, whereas that obtained through SAP2000 is 2.8

Hz. The near equality in the estimates proves the goodness of the implemented numerical model.

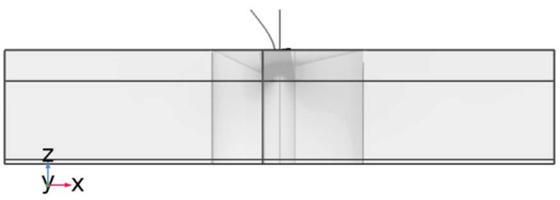

Figure 3. Deformed shape corresponding to the first rocking mode of the caisson-pier system.

Furthermore, the eigenfrequency of the first shear mode of the sand deposit (Figure 4a) was checked against the location of the peak of the shear-induced displacement transfer function between the top surface and the base, predicted by the Deepsoil software [15] (Figure 4b). Note that the implementation of the considered soil model into this software required a discretization of the stiffness profile into a stack of horizontal, homogeneous layers, properly defined to well capture its continuous variation with depth. Nonetheless, the perfect compatibility between these two estimates confirms the correctness in terms of soil model implementation.

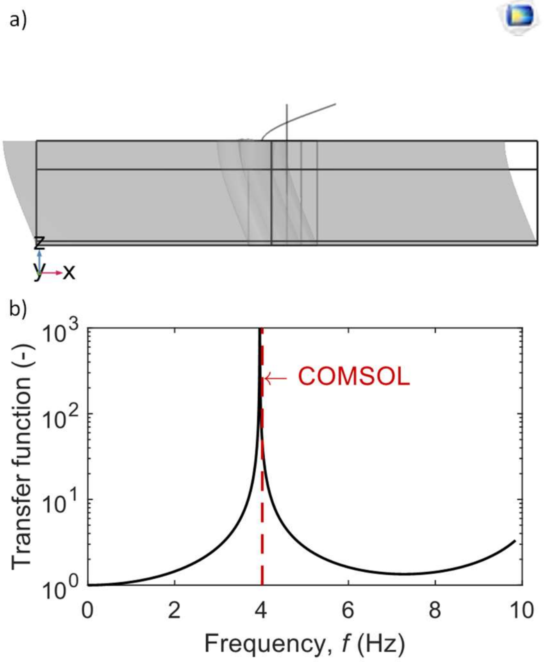

Figure 4. a) Deformed shape corresponding to the first shear mode of the soil deposit; b) Comparison between the horizontal displacement transfer function in shear mode versus frequency between the top surface and the base, obtained through Deepsoil [15], and the estimated first-shear mode eigenfrequency obtained with COMSOL.

Parametric study

The modal response of the pier under different scour scenarios was investigated with a focus on the first rocking mode. Figure 5 describes the variation of the estimated eigenfrequency and of modal shape descriptors, as a function of the considered scour scenario. As for the modal shape, the adopted parameters are the foundation rotation and the pier curvature – the latter computed through the finite difference formula. All these parameters were computed after normalization of the estimated modal coordinates, to ensure comparability of results, and they were normalized with respect to the fully embedded ("S00") configuration, to better appreciate scour-related variations in the modal response. In general, the presence of a deeper scour hole results in a reduced eigenfrequency and a large increase in the caisson rotation, up to 75% (Figure 5a). This is partially compensated by a smaller curvature in the pier (Figure 5b).

Figure 5 also includes a comparison with "general scour" scenarios, corresponding to a uniform lowering of the ground surface down to the considered scour depth, in contrast to the simulated "local scour" schemes. This simplifying scheme is often adopted in the practice thanks to the symmetry and the possibility of exploiting simplified approaches (e.g., those mentioned above). However, it results in much larger variations in both eigenfrequencies and mode shape parameters. Such a discrepancy highlights the importance of properly modeling the hydraulic scenario when dealing with the dynamic response of bridge piers under scour.

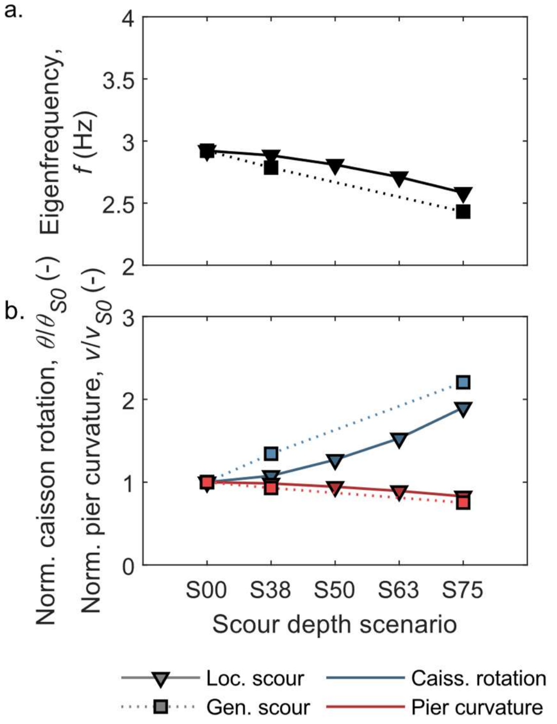

Figure 5. Influence of the scour depth on the modal parameters of the first rocking mode of the caisson-pier system: a) Eigenfrequency; b) Caisson rotation and pier curvature. The "Loc. scour" label refers to scenarios

characterized by the creation of an excavation around the pier, whereas the "Gen. scour" label corresponds to a uniform lowering of the ground level.

Discussion and Conclusions

This study has addressed the influence of local scour on the modal response of a bridge pier supported by a caisson foundation. Local scour was simulated by modifying the shape of the solid domain, following a morphology consistent with typical geometries of erosion experimentally observed. The numerical model was first validated against alternative numerical schemes, with reference to the first rocking mode of the pier-caisson system and the first shear mode of the soil deposit. Then, the analysis focused on the first rocking mode, which typically dominates the dynamic response of this type of soil-structure systems. Specifically, a parametric study where the scour depth was varied up to reducing by 75% the foundation embedment highlighted a reduction of the system eigenfrequencies and an increase of base rotations, with a simultaneous slight decrease of pier curvature. Indeed, the increased deformability of the foundation response due to scour results in higher rotations and a reduction in the structural demand of the structural component – indeed, the curvature is directly proportional to the bending moment inside the pier. However, it has to be highlighted that such variations are less strong compared with that obtained with the removal of an equivalent, uniform thickness of soil. Although this scheme allows for the use of simplified numerical strategies, this would result in misleading estimates in terms of the dynamic response (e.g., [2]).

This study demonstrated the importance of an accurate modeling of the hydraulic scenario in predicting the dynamic response of scoured bridge piers. However, this requires advanced numerical simulations that take into account both complex geometries and complex material behavior. COMSOL Multiphysics® provides rather useful tools for this purpose, proving that it can be a promising software for successfully handling this type of problems.

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