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INFLUENCE OF SCOUR OF FOUNDATIONS ON THE SEISMIC PERFORMANCE OF BRIDGES

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Abstract: *Infrastructure deterioration and ageing are growing challenges, also because of budgetary constraints on bridge maintenance and retrofitting. Specifically, scour of foundations is a significant issue for many bridges, particularly in a situation where global climate change is causing an increase in extreme alluvial events. In fact, it not only is the primary cause collapse of existing bridges but also lowers the ability to withstand following catastrophic occurrences, such as earthquakes. For the limited financial resources available for retrofitting, it is crucial to analyze the residual static and seismic capacity of bridges with accurate models. In this regard, soil-structure interaction plays a crucial role both in the assessment of current conditions and in the appraisal of expected performances. In fact, a lot of emphases has been paid in recent years to the use of dynamic testing on bridges to evaluate their current condition, specifically with regard to foundation scour. The fact that the dynamic response of the bridge is altered also when the scour hole is filled with sediment in the aftermaths of big events gives vibration-based monitoring approaches their principal benefit over conventional ones. On the other hand, scour of the foundation has a substantial impact on bridge dynamic response and ability to withstand future earthquakes. Modelling of these phenomena is often over-simplified by assuming homogeneous riverbed erosion as a reference condition, whereas the actual configuration of the scour hole can significantly affect the response of the pier. For proper use of resources, not only from an economic perspective but also for environmental sustainability, a more realistic appraisal is required. To do this, physical models can supply information for the calibration of numerical models, which can subsequently be applied to a realistic evaluation of the static and seismic performances.*

Introduction

Bridges are paramount, yet critical components of transportation infrastructures. Therefore, ensuring their structural safety and serviceability is crucial for the serviceability of the infrastructure itself. However, bridges over waterways are highly sensitive to hydraulic actions, especially foundation scour. Foundation scour is the lowering of the riverbed level due to water erosion, with the consequent partial or total exposure of bridge foundations. The loss of surrounding soil induces a reduction in the bearing capacity and stiffness of the foundation (e.g., Ciancimino, Jones, et al. 2022), with detrimental effects on the seismic performance of bridges (e.g., Ganesh Prasad and Banerjee 2013). Besides, scour-related bridge failures often occur without prior warning (e.g., Bao and Liu 2017), also because the visual identification of erosion phenomena is often challenging. For these reasons, scour is the main source behind bridge failure worldwide (Kirby et al. 2015). Specifically, many review studies agree that hydraulic actions and scour caused more than 50-60% of bridge failures in many countries (Wardhana and Hadipriono 2003; Lagasse 2007; Arneson et al. 2012; Chen et al. 2013; Schaap and Caner 2022; Xiong and Cai 2022). Looking from a prediction perspective, probabilistic models have shown an annual probability of scour-related bridge failure of 27% in the UK, that is, one out of three river bridges might collapse in the future due to foundation scour (Van Leeuwen and Lamb 2014).

Inadequate management of bridge scour has dramatic consequences in terms of casualties (e.g., Brandimarte et al. 2012; Argyroudis et al. 2019) and on the local society and economy, due to repair cost and indirect economic losses due to infrastructure disruptions (e.g., Xie and Levinson 2011). Some examples of scour-related economic costs, with both the original value and the value in US$ updated to February 2023 (in brackets), are reported below. The conversion is based on indicators provided by the

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Consumer Price Index (Office for National Statistics 2023; U.S. Bureau of Labor Statistics 2023) to account for inflation and on official exchange rate databases (European Central Bank 2023; HM Revenue & Customs 2023).

On the one hand, communities need to bear the direct economic effort required for bridge repair and retrofit. In the US and New Zealand, the annual repair cost spent by highway owners for hydraulic-related damage is about $50M ($105M) for hydraulic effects, of which $30M ($65M) are for scour consequences (Macky 1990; Rhodes and Trent 1993; Lagasse et al. 2012; Bao and Liu 2017). The expenditure peaks when natural extreme events such as floods, hurricanes and typhoons occur, due to the simultaneous severe damage or collapse of multiple bridges (e.g., Stearns and Padgett 2012; Yen et al. 2014). For instance, the 1994 flood in Georgia caused scour-related damage in more than 500 bridges and forced the local authority to replace 100 of them, for a direct cost of approximately $130M ($270M; Richardson and Davis 2001). More recently, 44 bridges faced extensive or complete damage due to Hurricane Katrina in 2005 in the US, forcing a replacement cost of over $1B ($1.6B; Padgett et al. 2008). In the aftermath of Storm Desmond in 2015, the UK infrastructure management had to carry out urgent inspections and repairs on 131 bridges, and the total economic damage was about £1.3B ($2.0B; Lamb et al. 2015).

However, bridge failures also disrupt the infrastructure network, which may take several weeks for full restoration. As an example, for a typical reinforced concrete bridge subjected to moderate damage, Mitoulis et al. (2021) predicted that traffic capacity can be restored only after 30 days if piers are supported by shallow foundations and 60 days in case of deep foundations. Instead, for a severe damage scenario, traffic interruption should last up to 120 days. Infrastructure disruption hinders emergency communications, and utility supply and induces trip delays in communications, with an exponential growth in the economic loss. For instance, Pregnolato et al. (2020) estimated the impact of a 500 years return period flood on a bridge, observing that the total economic loss mainly ensues from traffic rerouting, whereas direct repair cost is just a small fraction (around 6%). This issue is even more critical for railway bridges, due to the heavier traffic levels and the higher difficulties in finding alternative paths. Lamb et al. (2019) predicted a fragility model for flood events at a railway bridge in the UK, observing that infrastructure disruption affects 0.5% of the mean annual passenger flow on the national rail network. The consequent inconvenience to passengers can be quantified with an annual cost valued between £6M and £60M ($8.8M and $88M). Thus, the indirect economic cost of scour-related damage is much larger than the repair cost, although its quantification is rather complex due to the several components involved and their mutual interdependencies (e.g., traffic volume, network redundancy, the possibility of constructing emergency passages).

Another indirect consequence of scour-related damage is the increased emission of Greenhouse Gases (GHGs), especially when bridge failure occurs. Indeed, bridge construction is one of the most GHG-emitting operations in infrastructure construction, because of heavy material consumption (especially steel bars). As an example, Seo and Kim (2013) estimated that around 120 tCO_2/km are emitted due to bridge building, and this quantity is around 4 times the amount produced by the construction of tunnels and road sections. Furthermore, the CO_2 production due to traffic diversion has to be accounted for, as a function of the traffic volume and the entity of the detour (Coolings 2006). In turn, GHGs are a primary cause of Climate Change, which exposes bridges to increased hazard due to scour, much more than other infrastructure (Wilbanks et al. 2007; Wright et al. 2012). The most recent report published by the Intergovernmental Panel on Climate Change (IPCC 2023) highlights an increase in global population exposed to floods by 25-30%, even in the more optimistic scenario of global warming of 1.5°C and 2°C. Indeed, the increased thermal energy promotes stronger evaporation which leads to more intense precipitations in humid places such as North-Western Europe. The increased rainfalls are likely to result in stronger scouring (both in terms of extent and depth). Various studies have attempted to predict the future bridge scour vulnerability in the USA and Europe and the annual costs for scour risk mitigation, which is estimated to be more than €500M for the period 2040-2070 in Europe ($535M; HR Wallingford 2014; Yang and Frangopol 2019).

In this scenario of increasing sensitivity of the transportation infrastructure to climate hazards, a proper management of scour becomes crucial for resilient infrastructures and communities. This should account for difficulties or even the impossibility of visually detecting the presence of scour because pier foundations are often underwater or covered by debris. The latter issue is exacerbated by the limited knowledge of the foundation type and conditions of existing bridges (e.g., Arneson et al. 2012). Besides, even after scour identification, the limited financial resources available for maintenance and repair do not allow for an immediate and simultaneous retrofit of all bridges. Many of them often remain unchanged for several years. However, scoured bridges may experience new flood events or earthquakes, to which they may be more vulnerable due to the weakened support conditions. Therefore, multi-hazard vulnerability assessments should be carried out to define multi-hazard fragility surfaces for damage state parameters (e.g., Argyroudis and Mitoulis 2021) or restoration cost (e.g., Banerjee and Ganesh Prasad 2013) or service loss/passenger journey disruption (Lamb et al. 2019). These assessments can be included in multicriteria decision-making procedures to allocate maintenance funding, to rank interventions and find the optimum type and timing of retrofit actions for bridges in a network. Such optimization problem should balance the total cost of retrofit measures versus the network safety, robustness and disruption consequences (e.g., Dong et al. 2014; Lamb et al. 2019; Liu et al. 2020; Pregnolato et al. 2020; Loli et al. 2022) or considering the sustainability metrics including both economic, social and environmental metrics (Tapia and Padgett 2016).

On the other hand, advanced modelling of the system behaviour with a focus on the soil-structure interaction may help in reducing the entity of retrofit interventions and maintenance. For instance, Sakellariadis et al. (2019) investigated variations in foundation conditions of a highway bridge due to the deck widening. Although the increased loads may require a substantial retrofit of pier foundations, the Authors demonstrated that this operation is unnecessary for the case study under investigation. Indeed, the current soil-foundation system can carry the whole load thanks to its nonlinear response, as it mobilizes a ductile energy dissipation mechanism through soil yielding. This behaviour was anticipated by the concept of “rocking isolation”, proposed by Anastasopoulos et al. (2010), and it exploits the nonlinear foundation response to improve seismic performance. The main advantage is the high performance with a strong reduction of economic cost, machinery and time, as retrofit intervention can be significantly reduced. An effective planning of interventions based on multicriteria procedures and smart retrofit techniques is also environmental-friendly. For instance, short-term measures such as riprap may significantly reduce the increased scour risk due to Climate Change (Liu et al. 2020). This contributes to reducing GHG emissions, primarily by preventing post-disaster recovery actions such as debris management and rebuilding (Schwab and Brower 1999), with a savings of emissions equivalent to removing approximately 35M vehicles (Padgett and Tapia 2013).

Therefore, advanced modelling and an increased knowledge of the complex interaction between hydraulics, geotechnics and structures become crucial for a proper planning of bridge management and retrofit and towards the realization of resilient infrastructures. The paper starts with an overview of conventional approaches to assess the performance of scoured bridges against seismic actions, including an application to a reference case study. Then, the advantages of advanced modeling approaches are discussed.

State of the Art on seismic behaviour of scoured bridges

Natural hazards are traditionally considered independent actions on the structure, given the relatively small joint probability that two exceptional events may occur at the same time. Nevertheless, budget constraints often prevent the immediate retrofitting of scoured bridges after flood events. In such cases, the deterioration of the performance of the foundation system, especially in the horizontal direction, increases the seismic vulnerability of the damaged structures. For this reason, many studies have been devoted to assessing specific combined risks for bridge management (e.g., Alampalli and Ettouney 2008). Multi-Hazard strategies in bridge management have the goal to increase safety and security at reasonable costs, ensuring an adequate bridge capacity during its life cycle. Moreover, they constitute a significant budgetary control instrument to plan appropriate retrofitting measures on the most damaged structures.

The seismic vulnerability of bridges is usually expressed using seismic fragility curves, i.e. the conditional probability of failure as a function of a seismic demand parameter (Shinozuka et al. 2000). Different methodologies have been developed and employed to obtain the fragility curves, from empirical to analytical methods, under different conditions (e.g., Muntasir Billah and Shahria Alam 2015). Within this framework, flood-induced soil erosion and seismic hazards are usually combined evaluating the variations of the probability of failure due to scour effects (e.g., Alipour and Shafei 2012; Ganesh Prasad and Banerjee 2013; Wang, Dueñas-Osorio, et al. 2014). The main characteristics of this approach are common to all the studies in the literature. For this reason, just the approach described by Wang, Padgett, et al. (2014) is here presented to give an idea of the methodology usually adopted to define the seismic risk of bridges subjected to scouring.

The response of a bridge under seismic hazard can be described through a Probabilistic Seismic Demand Model, PSDM, which defines a relationship between the peak demand at a given component of the bridge and the ground motion intensity measure. A common seismic demand parameter for bridge piers is, for example, the maximum curvature of the column. At this step, also the input uncertainties are introduced into the model, related to the choice of adopting a given intensity measure as representative of the seismic action. The influence of scour can be implicitly included in the probabilistic analysis by assuming an initial scour depth in the numerical model used to predict the response of the bridge. Alternatively, a Multi-Hazard PSDM (MH-PSDM) can be defined by modelling explicitly the dependence of the demand from the scour depth.

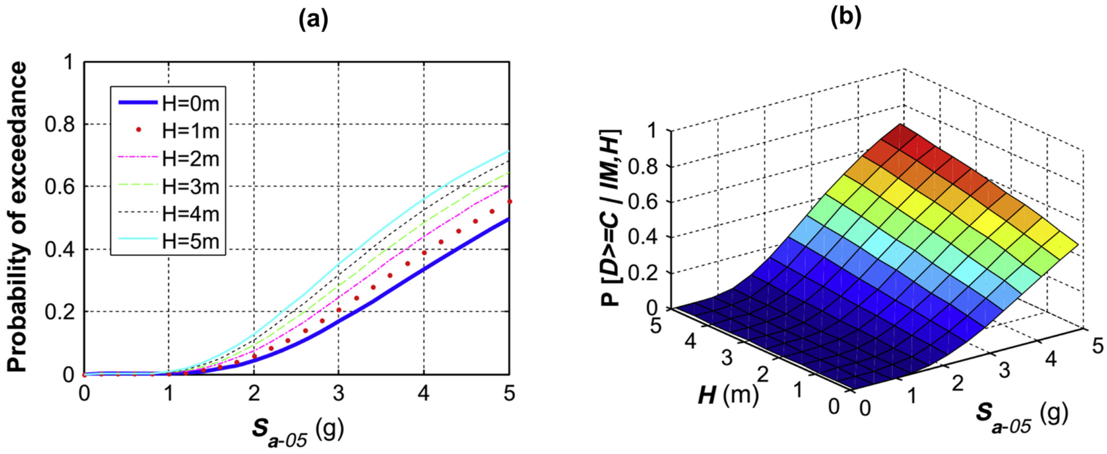

Figure 1. (a) Fragility curves and (b) fragility surface of a short-span bridge under combined scour and seismic hazard. The intensity measure is the spectral acceleration at a period of 0,5s $S_{a\text{-}05}$ *(from Wang et al., 2014b).*

Once defined the seismic demand, a capacity model for the bridge component is defined to compute the failure probability. Wang, Padgett, et al. (2014), for instance, selected the ultimate curvature limit state of the column according to the strain limit of the concrete and the longitudinal reinforcements. The conditional probability of failure is finally computed by combining the probability of occurrence of a given seismic (and scour in the case of MH-PSDM) demand with the capacity of the component. The product of a PSDM is a family of fragility curves (one for each scour depth considered) which defines the probability of failure of a bridge as a function of the intensity measure (see, for instance, Figure 1a). On the other side, when the scour depth is explicitly included, the MH-PSDM provides a unique failure surface describing the probability of failure under a given combination of scour depth and intensity measure (Figure 1b).

Finally, the combined risk is assessed through a convolution of the failure curve (or surface) and the seismic and scour hazard curves, which describe the annual exceedance probability of the hazard intensity measure (i.e., seismic intensity and scour depth).

The two types of risk analysis (i.e., PSDM or MH-PSDM) can also be considered representative of two different conditions. When a new bridge has to be designed no information about the effective scour depth at piers is available. As a consequence, the only way to assess a priori the combined seismic and scour risk is to develop a MH-PSDM, considering the uncertainties related to the expected scour depth. On the contrary, in the aftermath of a major flood, the seismic fragility assessment of an existing bridge has to be re-evaluated to consider the impact of the scour progress on the response of the bridge and, in turn, to plan eventual retrofitting activities. The scour depth, in this case, is known and a posteriori assessment of the seismic risk can be undertaken considering the scour hazard as an additional boundary initial condition rather than a proper hazard (as in the case of a PSDM).

Wang, Dueñas-Osorio, et al. (2014) assessed the combined seismic and scour risk for three different types of RC bridges (i.e., single concrete box-girder bridges with a shaft foundation, multi-span simply supported, concrete girder bridges with pile foundations, and multi-span continuous, concrete girder bridges with pile foundations) with short- and medium-span layouts. The soil-structure interaction was modelled through p-y, t-z, and q-z springs, which are progressively removed to model increasing scour depths. In each case, the scour progress has shown to have a significant influence only on the first few vibration modes in the longitudinal and transversal directions, lengthening the vibration periods. Subsequently, the fragility curves have been obtained for the six models, considering different scour depths and components of the bridges. The results highlight that a lower probability of failure of the column is expected with increasing scour depths. This is due to the isolation effect of the foundation system that counters the degradation of the support conditions. Conversely, the probability of a structural failure of the piles always increases with the scour depth.

Klinga and Alipour (2015) investigated numerically the lateral response of scoured bridges modelling in-depth all the components of the bridge (i.e., abutments, pile foundations and superstructure). The influence of scouring on the response of the structure was studied via pushover, buckling and modal analyses, considering five different soil profiles, namely four uniform soil profiles composed of medium/stiff clay or medium/dense sand and one non-uniform profile. The seismic performances of a pile-group foundation were analyzed for all the soil profiles, while a single pile shaft foundation was studied only for two uniform soil profiles. The soil-structure interaction was again simulated through springs with properties calculated accordingly to the hypothetical soil profiles. Results showed, firstly, that the scour process results in a degradation of the lateral support conditions of the structure with a significant decrease in the foundation stiffness. Moreover, increasing shear forces and bending moments were observed in the piles, causing large strains and ultimately, structural hinging. However, the analyses also highlighted a decrease in the shear force acting on the column, due once again to the soil isolation effects.

Although the growing interest regarding combined risk assessment, most of the numerical studies neglect the effects of scouring on the remaining soil layers. Moreover, no distinction is usually made between general and local scour. The scouring process is often simulated by simply removing the springs and the dashpots until the scour depth. However, as shown in the experimental studies by Qi et al. (2016), soil erosion affects the response of remaining layers of soil differently due to general or local scour. Moreover, even in the specific case of local scour the shape of the hole can significantly change the effects of foundation scour (Chortis et al. 2020). This can have a major impact on the results of risk analyses. For instance, general scour significantly reduces the lateral response of the remaining soil, potentially increasing the failure probability of the foundation. In turn, the isolation effect protects the column and, in general, the superstructure. The relative entity of these two effects can be different if local scour is considered. Unfortunately, it is not possible to define a priori which is the most critical situation, as often when dealing with seismic analyses. Consequently, it is crucial to be able to model the response of scoured foundations as close as possible to reality.

Simplified assessments of seismic behaviour of scoured bridges

This section deals with procedures adopted in the common practice to address the soil-foundation-structure interaction, with a focus on the modelling of the seismic performance of scoured piers. The section starts with the description of an ideal bridge pier, as a reference case study to compare different modelling approaches for the prediction of the response under seismic loading. Then, usual modelling assumptions are briefly addressed.

Case study

An overview of the investigated pier is provided in Figure 2. It is a 23 m tall, reinforced concrete pier, with a circular full section of diameter equal to 3.2 m. The pier is founded on a cylindrical caisson, with a diameter equal to 8.0 m and 10.0 m tall. It is assumed that the pier supports two spans of a girder bridge, with the deck composed of simply supported, isostatic, reinforced concrete beams. Thanks to this assumption, the pier can be schematized as a Single Degree of Freedom (SDOF) system, consistently with the recommendations for the dynamic analysis of simply supported bridges (e.g., CEN 2004). The corresponding mass *m* and stiffness *K* are reported in Figure 2.

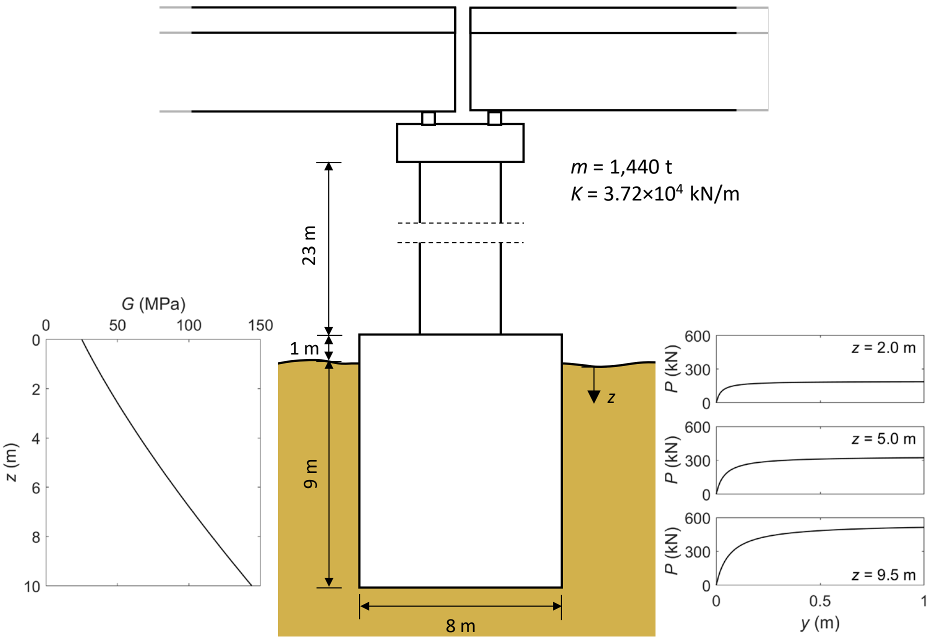

Figure 2. Case study with main information about geometry, structural and soil parameters. Description of soil behaviour is provided both in terms of G profile and p-y curves at different depths.

The mass is concentrated in correspondence of the pier cap: it includes both the upper half of the pier and the competent deck. As for the pier stiffness, the cracked stage value is assumed. The pier inelastic response is implemented through a lumped plasticity model, which prescribes an elastic behaviour for the whole structure with the inclusion of nonlinear elements at locations where the formation of plastic hinges is expected. In this case, a single plastic hinge is placed at the base, as it experiences the stronger bending moment, and the relevant parameters (i.e., length, yield bending moment, yield rotation and ultimate rotation) were designed according to the values suggested in the building codes (CEN 2004; MIT 2008).

The pier is founded on a medium-loose, homogeneous and isotropic sand, with unit weight equal to 20 kN/m^3, whereas the friction angle is 30°. It is characterized by a hyperbolic profile of shear modulus G as a function of depth z and growing from 25 MPa at the surface to 144 MPa at 10 m depth (Figure 2). Soil nonlinear behaviour is synthetically described through unit load transfer curves (or p-y curves; Matlock 1970), that represent the soil resistance under static loading. These curves relate the soil displacement y with the force p which is imposed to cause it. As an example, Figure 2 reports three p-y curves computed at three different depths (i.e., z equal to 2.0 m, 5.0 m and 9.5 m), using analytical formulations valid for the assumed stiffness profile.

Modelling schemes

The complexity in the estimation of the seismic performance of scoured piers calls for simplifying assumptions for both the dynamic soil-structure interaction schematization and the scour modelling. On the one hand, usual modelling of soil-structure interaction does not rely on an integral modelling of the ground, foundation and superstructure. Indeed, although it allows to properly incorporate geometric nonlinearities and the actual material constitutive behaviour, this approach is computationally demanding ad it often requires several parameters whose estimation is not trivial. Instead, a common strategy is the substructure method. This technique derives the response of the soil, foundation and superstructure independently, combining them according to the compatibility of forces and displacements. However, it assumes that the system behaviour is linear, soil included. Alternatively, a hybrid approach schematizes the superstructure connected to ideal springs and dampers in a single model. In both cases, the dynamic soil-foundation response and interaction effects are synthesized through a frequency-dependent dynamic impedance function. Such function includes the soil elastic response and geometric damping and maps the free-field response of the soil column into the response due to the presence of the structural system, thus reproducing the complex phenomenon of interaction. Gazetas (1991) provided closed-form solutions for such functions for the harmonic load, which can be generalized to earthquake loading by selecting the values corresponding to the superstructure fundamental-mode natural frequency.

A more refined approach is the beam on nonlinear Winkler foundation (BNWF) method, which is a simplified procedure that can account for soil nonlinear behaviour, for instance relying on p-y curves (e.g., Boulanger et al. 1999; Gerolymos and Gazetas 2006). This approach can be conceptualized through a series combination of linear and non-linear springs, as shown in Figure 3: i) a linear spring in parallel with a viscous damper simulates the elastic soil column response with radiation damping, with the viscoelastic response provided by elastic, dynamic impedance functions (e.g., Gazetas 1991); ii) an elastoplastic spring element simulates the soil nonlinear behaviour, which is calibrated to match the p-y curves computed for the caisson foundation. This model is recommended especially when dealing with the response of stiff structures (e.g., short piers) on deformable soils. Besides, it relies on a distributed spring scheme, thus it provides insight also on the foundation response.

The latter model is also suitable for introducing the presence of scour. Indeed, common procedures model variations in the pier supporting conditions through the removal of a uniform thickness of the surface soil. This corresponds to removing the shallow springs from the model (Figure 3). However, this scheme can be representative of general scour, in which the waterbed lowers in a uniform way. Instead, other phenomena as local scour cannot be modelled through this approach.

The inclusion of soil and foundation response induces higher flexibility in the foundation-structure system. For instance, the fixed-base natural period of the investigated pier is 1.35 s, whereas the natural period of the corresponding BNWF model equals 1.85 s. The increased vibration period is a consequence of the deformability of the base conditions, and this affects the dynamic response of the system. As a reference, Figure 4 shows the estimated seismic response of the considered bridge pier, subjected to the acceleration time histories recorded at Loma Prieta, Northridge and Tolmezzo events, and applied along the bridge longitudinal direction. These motions were scaled to a common peak ground acceleration, equal to 0.33g, to enforce similar amplitude, although they exhibit different frequency content, as shown in the response spectra in Figure 4a.

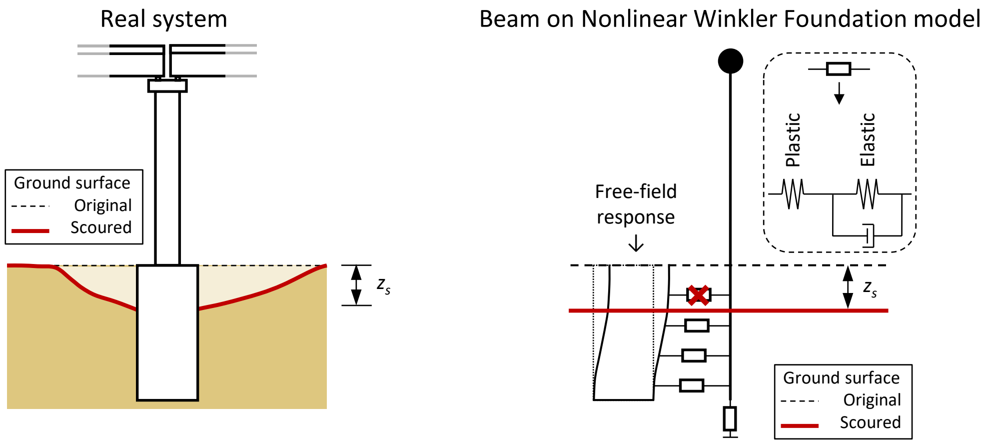

Figure 3. Real system vs. Beam on nonlinear Winkler foundation model.

The pier response is reported in terms of the moment-plastic rotation loops, which provides an insight into the structural demand, for the fixed-base and the BNWF model (Figure 4b-d). In general, considering soil-structure interaction mitigates the structural demand as highlighted by the decrease in the maximum plastic rotation experienced by the structure, because the soil response contributes to reducing it with both radiation damping and inelastic response. The benefit is relevant for the Tolmezzo event (Figure 4d), where the inclusion of soil-foundation deformability prevents any plasticity in the superstructure. However, the entity of reduction in the structural demand depends on the frequency content and duration of the earthquake motion, and it can even increase in some cases, e.g., for the Northridge event (Figure 4c). On the other hand, the reduction in the structural demand due to the inclusion of soil-structure interaction is balanced by larger displacements. For instance, Table 1 lists the estimated maximum global displacements at the pier cap, for the fixed base and the BNWF model. The increase in the entity of displacements is a direct consequence of the larger flexibility at the base. Neglecting this effect can lead to greatly underestimating the maximum displacements expected at the head of the piers and to having compatibility problems with the deck and supports.

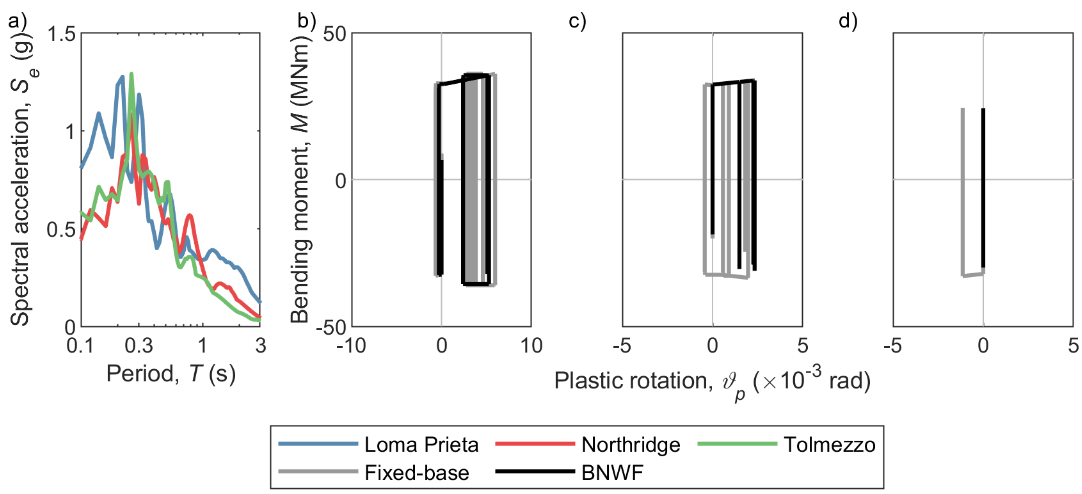

Figure 4. a) Response spectra of the considered input motions; b-d) Moment vs. plastic rotation of the pier for the Loma Prieta (b), Northridge (c), and Tolmezzo (d) motions.

Event	**Fixed-base**	**BNWF**
Loma Prieta	0.186	0.211
Northridge	0.092	0.139
Tolmezzo	0.071	0.070

Table 1. Maximum displacement at the pier cap for the considered input motions.

Assessment of seismic performance of scoured piers

Usual modelling of foundation scour adopts a simplified scheme for the soil-foundation system (e.g., the BNWF model) and it assumes uniform lowering of ground level. In this study, five depth levels z_s are considered: 1, 2, 3, 4, and 5 m. These modifications of supporting conditions alter the dynamic behaviour of the pier, as highlighted by the variation of the fixed-base fundamental period, which gradually shifts from 1.8 Hz to 2.6 Hz for increasing scour depth.

The quantification of scour effects on the bridge seismic performance commonly relies on fragility curves, which synthesize pier damage. Specifically, fragility curves provide the conditional probability of exceeding a defined level of damage in the investigated structure, as a function of a seismic demand parameter. The probabilistic framework allows to account for uncertainties both in the structural capacity and seismic demand, both modelled as a lognormal distribution.

The damage level is numerically quantified through the displacement ductility μ_d, defined as the ratio between the top pier maximum relative displacement $u_{max,pier}$ and the value at pier yielding $u_{y,pier}$ (Alipour et al. 2013):

$$\mu_d = \frac{u_{max,pier}}{u_{y,pier}} \tag{1}$$

The quantity μ_d is suitable for assessing the vulnerability of RC bridges not designed according to seismic provisions. In this study, two damage levels are considered: moderate damage state (i.e., $\mu_d = 2$) and complete damage state (i.e., $\mu_d = 7$). Instead, seismic demand is quantified through the spectral acceleration referred to the natural period of the structure, $S_e(T)$, as most significant for the actual structural response. The reference period T is taken as 2 s, as it is an average value across all the considered scour scenarios. This approach introduces an approximation because it neglects the differences in the vibration period and the spectral accelerations at different scour levels. However, this error is typically negligible and it allows an immediate comparison of fragility curves at different scour depths (Wang, Padgett, et al. 2014).

This study estimates fragility curves through an analytical procedure, based on non-linear dynamic analyses of the system (e.g., Karim and Yamazaki 2001; Nelson and DesRoches 2007). To ensure an effective exploration of all the damage levels, this study included various ground motion scenarios, each one including 7 natural acceleration time histories that are seismologically and spectral-compatible with the seismic hazard at the municipality of Savoca, in Italy, for return periods equal to 72, 224, 475, 975, 2475, and 4975 years. These are representative of the different intensities of the seismic action, in order to exhaustively explore the different levels of damage. In summary, 252 nonlinear dynamic simulations were carried out, as a function of the scour depth and the seismic input, wherein the pier foundation was subjected to bi-axial horizontal displacements corresponding to the seismic accelerations.

Figure 5 shows the estimated fragility curves for the damage scenarios under investigation. In general, the presence of scour on the foundation has a positive effect on the structure vulnerability, as the probability of exceeding the damage level at fixed seismic demand reduces for increasing z_s. Indeed, the increased deformability of the foundation system mitigates the entity of the seismic action carried by the structure and the consequent deflection and plastic rotations. Therefore, proper modelling of the actual supporting conditions demonstrates a significant damage reduction. On the other hand, the influence of scour depth becomes negligible when the severe damage scenario is investigated.

However, the reduction in the structural demand on the pier column is compensated by a significant increase of the total displacement of the system, due to the large rotations experienced by the foundation. For instance, Figure 6a compares the maximum displacement at the pier cap for high-intensity seismic motions, as a function of z_s. However, also the unscoured, fixed-base response is included, as a reference. The maximum displacement increases by more than 40% while shifting from the fixed-base scheme to the BNWF model, entailing that the sole inclusion of soil deformability (hence, the soil-structure interaction) results in dramatically larger displacements. Furthermore, the total displacement further increases by 10% in the presence of scour, as it reduces the stiffness of the foundation system.

The increased pier motion and its dependence on the scour depth may be critical for multi-span, simply supported bridges. Indeed, in bridges over waterways, different piers can face various scouring conditions (that is, different z_s), mostly dependent on the location of their foundations with respect to the main river channel. Different scour depths imply different supporting conditions, which results in an asynchronous motion between subsequent piers.

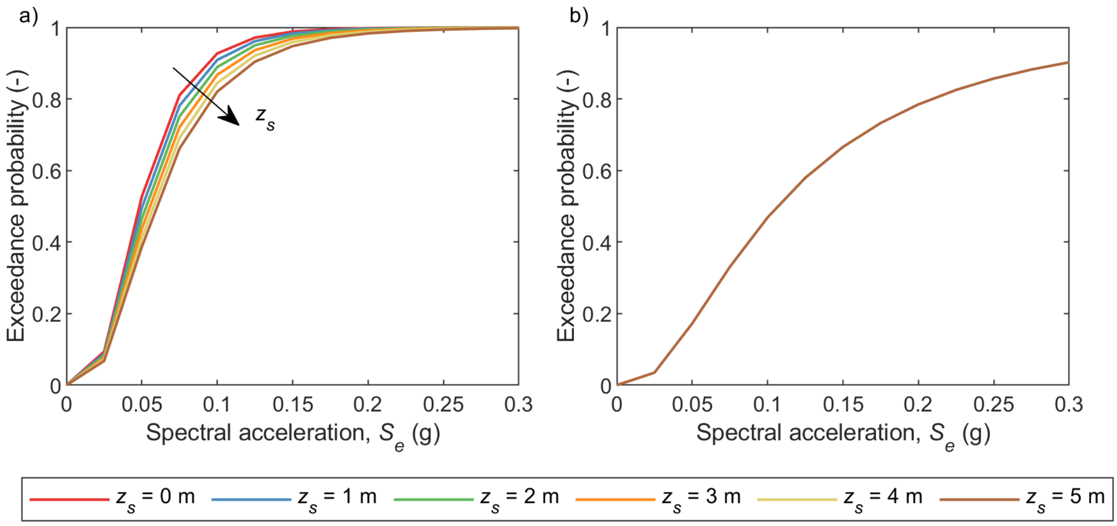

Figure 5. Fragility curves as a function of the scour depth z_s, for a) moderate damage stage and b) severe damage state.

When focusing on the transverse direction with respect to the bridge axis, such variability in the pier motion induces a significant rotation of the deck in the horizontal plane. For instance, Figure 6b reports the maximum rotation of a deck supported by a scoured pier and an unscoured one, as a function of the z_s and the span length. As expected, deeper scouring results in a significant increase of the rotation, which however decreases for longer spans. On the other hand, the rotation demand is still relevant at 20-30 m, which is the usual span range for simply supported decks.

The combination of large total displacement and significant deck rotations due to both soil deformability and scour depth, when not properly accounted, may lead to compatibility issues on the bearing devices. This might result in their damage, forcing the infrastructure manager to their untimely replacement. In more severe scenarios, even the loss of support may occur, with the consequent collapse of the deck.

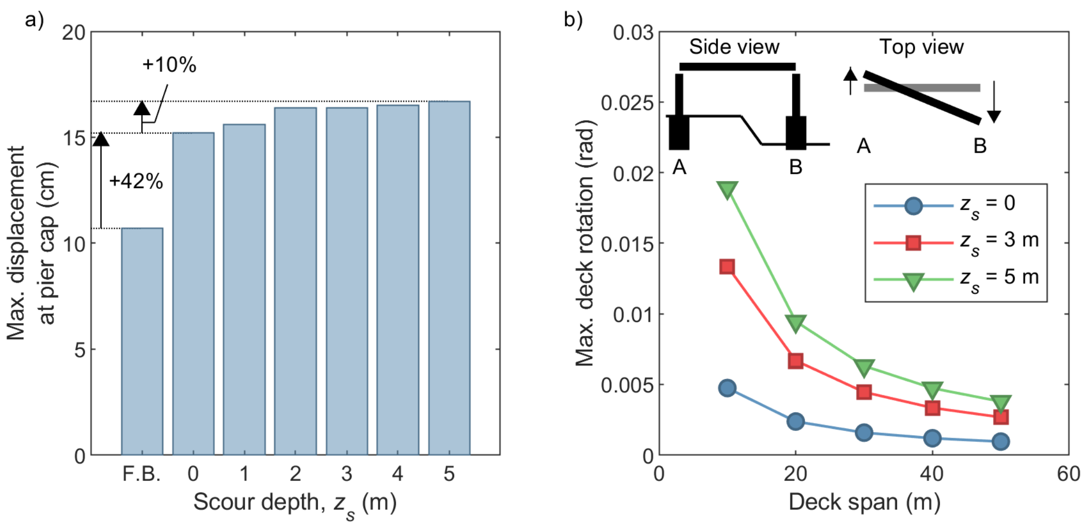

Figure 6. a) Maximum displacement at the pier cap for the fixed-base model (F.B.) and as a function of the scour depth; b) Maximum deck rotation as a function of the span length and the scour depth, under the assumption of deck supported by a scoured pier and an unscoured pier.

Advanced modelling of the performance of scoured foundations

The methodology introduced in the previous section allows studying the response of the seismic behaviour of bridge piers including the influence of soil-structure interaction phenomena, albeit in a simplified and expeditious manner. The BNWF approach is however suitable for modelling the problem in the small-to-moderate strain (or, equivalently, rotation when referring to the entire pier) range. Advanced numerical simulations are instead more suitable for investigating the pier response when the horizontal action is such as to bring the soil-foundation system towards large rotations and eventually up to failure.

In addition, simplified methodologies can hardly reproduce local scour phenomena, as soil erosion is usually represented by removing the shallow springs from the model (Figure 3). Such an approach is thus representative of a general erosion of the riverbed, except in the case of proper modifications are employed to adapt the stiffness of the remaining springs to local scour phenomena (see for instance Qi et al. 2016).

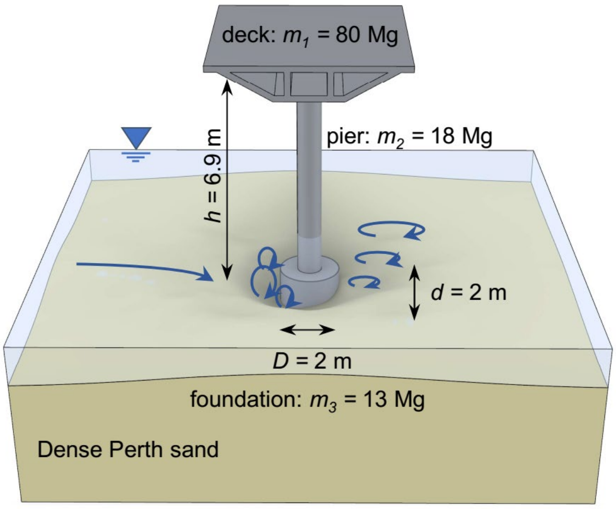

Figure 7. Problem definition of the validation study: SDOF bridge pier subjected to flood-induced scour (from Ciancimino, Jones, et al. 2022).

The impact of scouring on the performance of bridge piers can be properly assessed using advanced numerical simulations and employing adequate constitutive models to reproduce the soil response for a wide range of stress-strain conditions. Numerical modelling also allows representing the problem geometry rigorously and straightforwardly, with a view to discerning between general and local scour effects. Nevertheless, the reliability of advanced approaches is always constrained by their ability to reproduce the actual response of the soil-structure system.

This section presents the development of a numerical model suitable for reproducing the response of scoured caisson foundations. The results of physical modelling from Ciancimino, Jones, et al. (2022) are used as a benchmark for the simulations. The experimental methodology focused on both the reproduction of the hydraulic erosive phenomena and the study of the mechanical consequences, the latter modelled through centrifuge tests. The numerical model is firstly calibrated to reproduce the soil response at an element level and then it is validated against the results of the centrifuge tests (Ciancimino, Anastasopoulos, et al. 2022). The model is therefore employed to investigate the behaviour of the foundation system considered for the case study introduced in the previous section to highlight the impact of different types of scouring on the lateral response of the bridge pier.

Experimental study and numerical model validation

The structure experimentally investigated by Ciancimino, Jones, et al. (2022) consists of a single degree of freedom (SDOF) system which represents an idealized slender prototype bridge pier supported on a cylindrical caisson foundation of diameter D_f = 2 m, embedded for 2 m in a layer of dense Perth sand (Figure 7). The pier column is modelled as rigid to focus on the foundation performance, while the bridge deck consists of a concentrated mass defined to achieve a factor of safety against vertical loading before scouring equal to 8 (moderately loaded footing).

A novel experimental methodology was developed to study both the hydraulic and mechanical aspects of the problem. In the first step, the Miniaturised Tidal Generator (MTG; Jones and Anastasopoulos 2020) developed at the ETH Zurich (ETHZ) is employed to conduct hydraulic *1g* physical model tests (Figure 8-1). The MTG is used to impose pseudo-steady flows to a model of the idealized bridge pier to simulate the local scour processes under realistic and well-defined hydraulic scenarios. The morphology of the scour hole is detected through a 3D scanner (Figure 8-2) and the inverse of the surface is 3D printed to produce a mould of the scour hole. The mould is then employed to reproduce the realistic geometry of the scour hole (Figure 8-3). Finally, the mechanical aspect of the problem is investigated in *Ng* physical models in the ETHZ geotechnical drum centrifuge, thus achieving proper stress-scaling (Figure 8-4).

The methodology was applied to study the effects of scouring on the vertical, horizontal monotonic and horizontal cyclic performance of the caisson foundation under drained conditions before and after scouring. Although the study focused mainly on local scour, the effects of general scour was also investigated to quantify the differences between the two different phenomena. In order to allow for direct comparison, the general scour was experimentally modelled removing a soil layer of constant thickness, equal to the average scour depth observed in the local scour tests (i.e., 1 m).

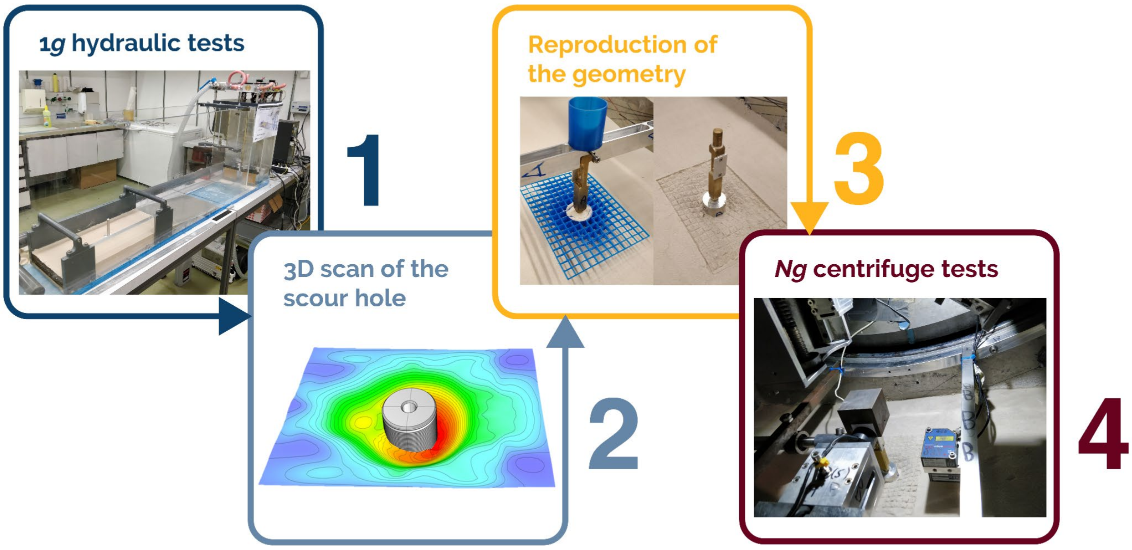

Figure 8. Experimental methodology: (1) development of the scour hole through the MTG; (2) 3D scanning of the scour hole; (3) reproduction of the scour hole geometry; and (4) study of the mechanical part of the problem through centrifuge model testing.

A numerical model was subsequently developed by Ciancimino, Anastasopoulos, et al. (2022) to reproduce the experimental results. The simulations modelled the SDOF system represented in Figure 7 adopting the Severn-Trent constitutive model to reproduce the nonlinear sand response (Gajo and Muir Wood 1999b, 1999a; Gajo 2010). The model is implemented as a user-defined material in the finite element code ABAQUS (Gajo 2017). The constitutive parameters were defined based on a thorough calibration procedure (Ciancimino, Anastasopoulos, et al. 2022).

Consistently with the centrifuge tests, the analyses are performed under drained conditions. An isotropic linear elastic constitutive law is adopted for the foundation, whereas a purely frictional contact algorithm is used to model the soil-structure interface, allowing sliding and detachment. The models are initialized adopting an initial void ratio $e_0 = 0.58$ defined based on the target relative density of the experimental study, namely 80%. To focus on the effects of scouring, the caisson is modelled as "wished in place". Such an assumption is however also consistent with the centrifuge experiments. The soil-caisson interface is modelled as purely frictional in the tangential direction while a "hard" pressure-overclosure relation is used in the normal direction. All numerical simulations are performed accounting for changes in the model geometry to capture the additional second-order moment given by the so-called P-δ effect.

Figure 9 presents the comparison between centrifuge test results and numerical simulations as concerns the lateral monotonic response of the footing. The local scour condition is analysed referring to the transversal (concerning the bridge roadway) direction, pushing the structure towards both the upstream and the downstream sides due to the asymmetry of the local scour hole. Further details (also regarding different loading conditions) can be found in Ciancimino (2021) and Ciancimino, Anastasopoulos, et al. (2022).

The model can properly reproduce the moment-rotation (M - θ) responses of the foundation and, in particular, the impact of local and general scour on the capacity of the caisson (Figure 9a). The effects of local scour on the moment capacity of the system are detrimental, leading to a reduction of about 25% if the structure is pushed towards the upstream side. The influence of general scour is even more significant with a reduction of the capacity of 43%. The numerical simulations also capture the nonlinear effects leading to the reduction of the rocking stiffness K_r of the footing with increasing θ. By looking at the comparison of Figure 9c, it is clear that local and general scour significantly affects K_r even for small rotations. The reduction is again more pronounced when dealing with general scour, although it is also quite relevant in the case of localized erosion.

Interesting insights can arise by observing the settlement-rotation (w - θ) responses represented in Figure 9b. The constitutive model slightly overpredicts the dilative response of the material at large strains. The latter partially compensates for the settlements induced by the bearing capacity mechanism developing below the footing, leading to the moderate uplifting of the caisson. The numerical prediction is however overall consistent with the experimental results. Indeed both in the numerical simulations and the centrifuge tests, the response is neither sinking- nor uplifting-dominated, as expected for a moderately-loaded foundation on dense sand (e.g., Anastasopoulos et al. 2012).

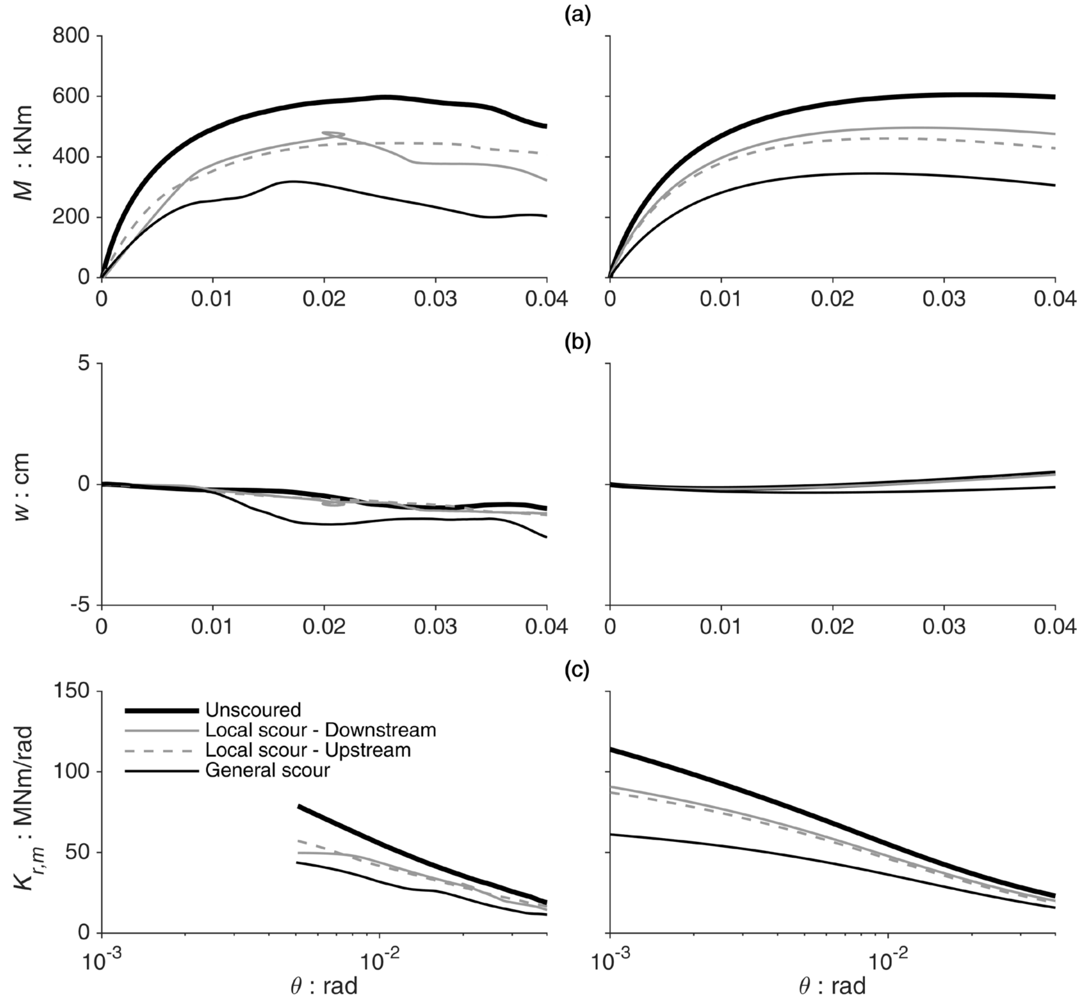

Figure 9. Experimental results (left) compared to numerical predictions (right): (a) moment-rotation; (b) settlement-rotation; and secant rocking stiffness-rotation response (from Ciancimino, Anastasopoulos, et al. 2022).

The numerical predictions were shown to be in good agreement with the experimental results, especially when looking at the effects of local and general scour. This is particularly relevant given the independent calibration of the constitutive model based on soil element tests. It may therefore be concluded that it is possible to infer the mechanical consequences of foundation scour through numerical simulations, provided that the geometry of the problem is properly considered. The latter can be estimated based on a large number of available numerical and experimental studies on the hydraulic processes which result in local scour holes around bridge piers (e.g., Melville and Coleman 2000; Richardson and Davis 2001).

Numerical modelling of the case study

The case study was analyzed in the previous section by means of simplified (from the geotechnical point of view) dynamic analyses. SSI phenomena were indeed reproduced by employing the BNWF approach, which allows to partially capture the increased flexibility of the soil-structure system due to the deformability of the soil itself. Such an approach can however be considered reliable just in the small-to-moderate strain field. At large strains, and especially if we are moving towards the failure condition of the foundation system, it becomes mandatory to employ more refined approaches to analyze the response of the system from a geotechnical perspective. A numerical model of the case study is developed to this end.

The model is built based on the framework previously introduced, which has been proven to be effective in reproducing the experimental results. The simulations analyze the response of the structure before scour, after local scour (with the structure pushed towards the upstream side) and after general erosion of the riverbed. The local scour condition is modelled adopting the scour hole geometry experimentally measured by Ciancimino, Jones, et al. (2022) scaled to the diameter of the footing (equal to 8 m). The resulting average scour depth (employed also for the uniform scour) is equal to 4 m. The structure is modelled as practically rigid, and the pier and the deck masses are introduced as vertical forces defined consistently with the scheme in Figure 2.

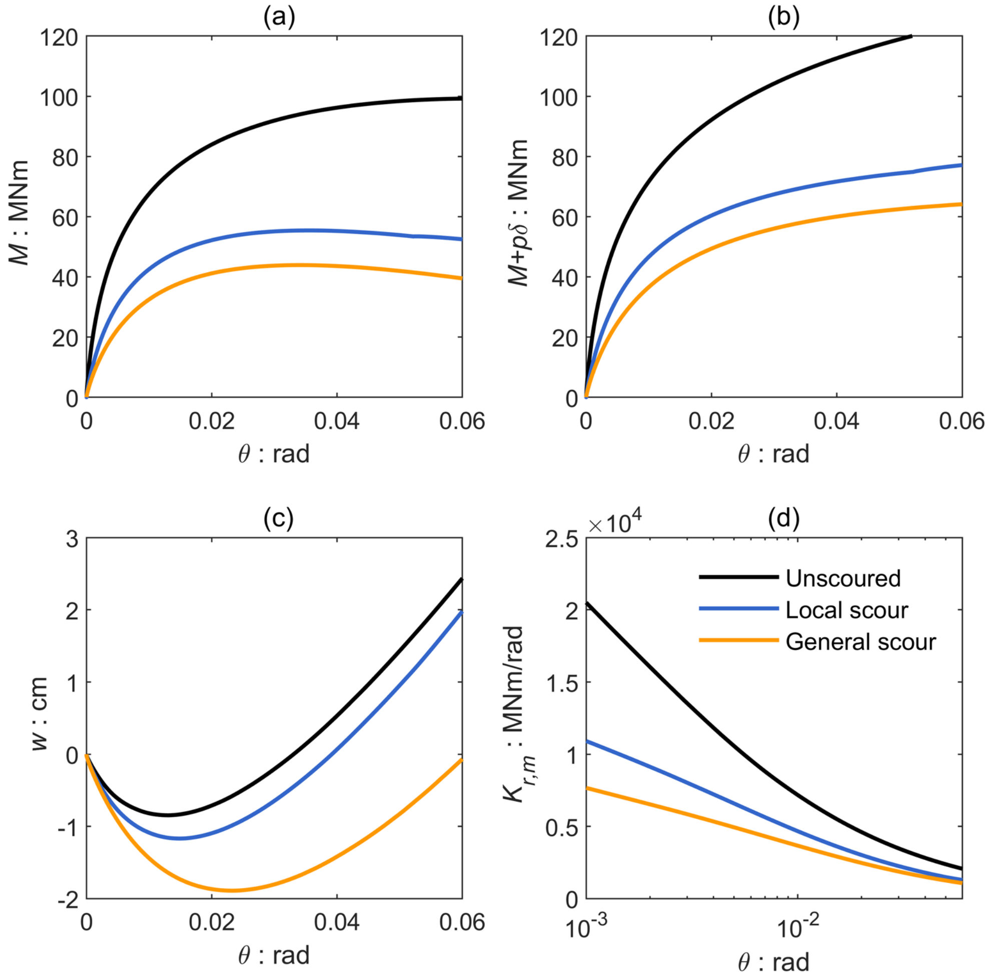

Figure 10. Results of the numerical simulations: (a) moment-rotation; (b) moment-rotation considering explicitly second-order effects; (c)settlement-rotation; and (d) secant rocking stiffness-rotation response.

The constitutive model is initialized adopting a void ratio $e_0 = 0.7$, corresponding to a medium-loose sand with $D_R = 45\%$. The structure is subjected to a horizontal monotonic loading under displacement control all the way up to failure. The horizontal displacement (and, thus, the corresponding load) is applied to the center of mass of the structure, consistently with classical pseudo-static approaches.

The results of the numerical simulations are presented in Figure 10. The detrimental impact of both general and local scour on the capacity of the foundation system is visible from the M - θ curves (Figure 10a). For the case study under consideration, localized erosion leads to a reduction of the foundation moment capacity of about 45%, increasing up to 55% when generalized erosion takes place. Such an impressive decrease may bring the footing towards the failure condition even before the plasticization of the soil column.

The response of the footing in terms of settlement accumulation seems instead not to be excessively influenced by the soil erosion (Figure 10c). General scour leads to a larger settlement concerning the unscoured reference case, but the maximum w value is however still less than 2 cm. This result can be explained by computing the safety factor of the footing under pure vertical loading FS_v, which is a key parameter to analyse the foundation response. For the unscoured reference case, FS_v is equal to about 9, the latter being computed according to vertical push simulations (see Ciancimino, Anastasopoulos, et al. 2022 for further details about the numerical model). Such value, characteristic of a moderately to lightly loaded footing, slightly decreases to about 7 in the case of general scour. As a consequence, the footing remains in the uplifting-dominated regime, and the increase of w is not particularly relevant. However, it should be noted that this relatively small increase under monotonic conditions may be relevant under dynamic loadings. As observed experimentally by Ciancimino, Anastasopoulos, et al. (2022), the effects of general scour on the bearing capacity mechanism developing in the soil below the foundation can be of great relevance under cyclic conditions.

A relevant aspect to consider when dealing with slender piers is related to the second-order (P-δ) additional moment arising from the accumulated rotations of the pier. Figure 10b represents the M+P-δ curves with increasing θ. When the total resisting moment exerted by the soil around the caisson is considered, the foundation response shows a continuous hardening trend, at least for the (quite wide) range of θ here considered (Figure 10b). However, this resisting moment is partially attained by P-δ geometrical effects, resulting in the reduced available foundation capacity of the curves represented in Figure 10a. This aspect is often neglected when simplified models are employed, albeit it can be crucial especially in combination with the scour hazard. For instance, referring to the curves of Figure 10b, an external action of 40 MNm would produce a rotation of $2.9\cdot10^{-3}$ rad for the unscoured footing, increasing up to $7.2\cdot10^{-3}$ rad and $12\cdot10^{-3}$ rad, respectively due to local and general scour. These values however increase when the additional P-δ moment is considered in the model (Figure 10a). For the unscoured case, θ is just slightly larger (~$3.1\cdot10^{-3}$ rad), while the increase is substantial for the local scoured footing (~$8.5\cdot10^{-3}$ rad). For the foundation subjected to generalized erosion the effect of P-δ is detrimental, leading to a 50% larger value of θ (~$18\cdot10^{-3}$ rad).

The effect of scouring is also relevant in terms of monotonic rocking stiffness K_r of the footing (Figure 10d). K_r decreases with θ due to nonlinearity effects. Besides, the unscoured K_r values are always substantially larger than corresponding scoured stiffnesses for the entire range of θ considered. The impact of scouring is particularly relevant at small strains, where K_r reduces of about 50% and 62% due to local and general scour, respectively. This result is qualitatively consistent with what has been observed from monitoring data of real scoured bridges, which highlight the impact of local scour on the dynamic response of bridge piers inferred at small-strains through ambient vibrations (e.g. Foti and Sabia 2010).

The reduction of the moment capacity due to scouring can be explained by looking at the resisting mechanism developing in the soil around the footing. The latter can be subdivided into two components: a bearing capacity mechanism takes place below the base of the caisson (M_{base}) and an additional resisting moment given by the soil along the sides of the footing (M_{sides}). The M_{base} and M_{sides} with θ curves are presented in Figure 11.

The M_{base} rapidly increases up to a rotation of about 0.02 rad for all the cases examined, then the bearing capacity failure mechanism is almost fully developed, and it tends to stabilize (Figure 11a). Local scour does not affect significantly the bearing capacity of the caisson foundation. No significant differences are therefore observed between the M_{base} curves of the structure before and after local scouring. On the other side, general scour leads to a slight reduction of FS_v, affecting to some extent also M_{base}.

The resisting moment at the sides of the foundation is instead affected by both local and general scour (Figure 11b). As expected, the maximum reduction is observed after general scouring with M_{sides} (for a rotation of 0.02 rad) decreasing from 47 to 7.5 MNm (i.e., about 84%). The local scour condition has also a significant influence on the lateral foundation resistance, inducing a reduction of M_{sides} of about the 72%. The influence of scouring is such as practically nullify the contribution of the soil along the sides of the caisson to the capacity of the foundation system. This detrimental impact, combined to the second-order (P-δ) effects, leads to the fragile M - θ responses shown in Figure 10a, which under extreme conditions may lead may cause a sudden failure of the bridge pier and, in turn, of the entire structure. These aspects cannot however be properly modelled by employing simplified methods which disregard both the actual hydraulic scenario (i.e., local or general scour) and the reduction of the actual capacity of the footing.

Conclusions

The impact of general and local scour on the mechanical performance of bridge piers can be detrimental to the extent of inducing high repair costs for retrofitting operations and, eventually, leading to the collapse of the entire structure. As shown by both physical modelling and numerical simulations, foundation scour decreases the moment capacity of the footing, reducing also its rotational stiffness and increasing, in turn, the amount of settlement accumulated.

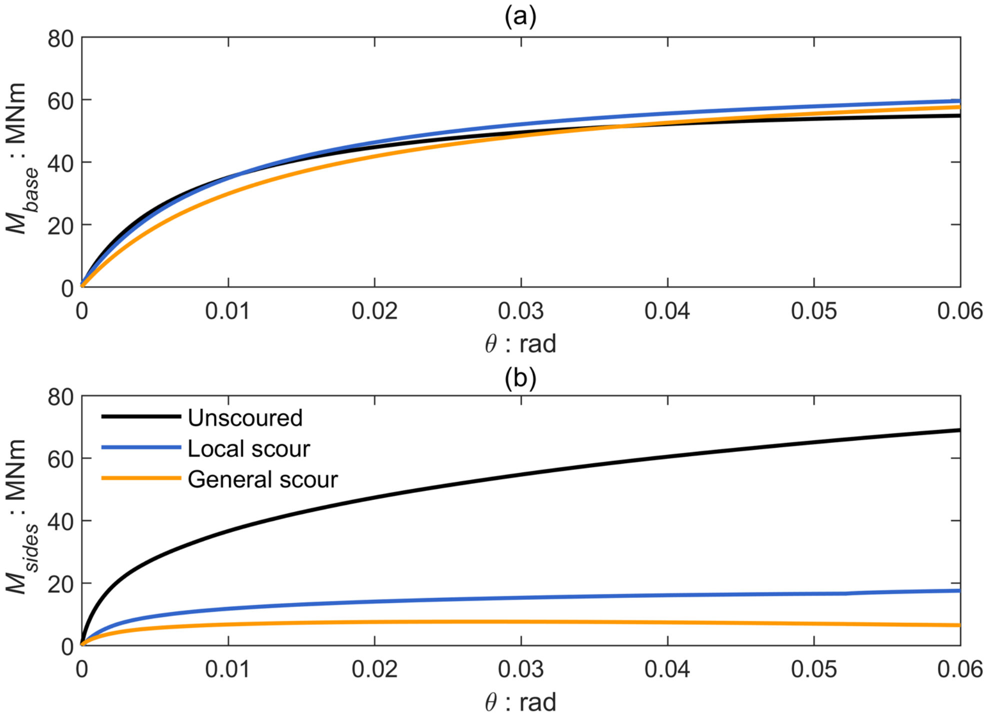

Figure 11. Resisting moment exerted by bearing capacity mechanism (a) and by the soil thrusts along the sides of the footing (b).

This is particularly relevant as budget constraints often prevent the prompt implementation of appropriate countermeasures. Under these circumstances, foundation scour can be seen as a long-term variation of the supporting condition of the structure. As a result, it strongly affects the performance of the bridge to multiple successive hazards, such in the case of seismic events which produce a considerable increase of the lateral loadings acting on the bridge piers.

The impact of foundation scour on the seismic vulnerability of the structure can be assessed, in the first analysis, by employing simplified methods for modelling soil-structure interaction phenomena. This is, for instance, the case of the BNWF approach. Such an approach is indeed able to partially capture the changes in the foundation stiffness due to scour by crudely removing springs representing the surrounding soil up to the measured (or expected, in the case of a design problem) scour depth. Albeit simplified, the results of these analyses can provide interesting information on the impact of scouring on the structural performance of the pier. For the case study considered in this research, foundation scour decreases the structural demand on the pier column leading to an apparent reduction of the expected damage under seismic loading. On the other side, it substantially increases the displacement demand on the bearing devices supporting the superstructure. This is even more significant when different scour conditions occur at different piers (as usual for real infrastructures). Such a condition may indeed induce large rotations of the deck which cannot be neglected.

The reduction of the seismic demand on the pier column is due to the softening of the foundation response caused by soil erosion. The drawback of this increased deformability of the foundation system is the reduction of the foundation capacity. The latter cannot be properly modelled employing the BNWF, and it has necessarily to be assessed by means of advanced numerical models able also to capture the different effects of local and general scour. The numerical simulations show that both the hydraulic phenomena lead to a substantial decrease of the resisting moment exerted by the soil along the sides of the footing. In addition, general scour also affects the bearing capacity mechanism developing below the caisson foundation. Such a massive reduction of the foundation capacity, in conjunction with increased lateral actions due to subsequent seismic events, can bring the foundation towards the failure. A proper modelling of the mechanical impact of either general or local scour is therefore essential for the optimization of available economic resources, to identify the crucial infrastructures on which immediate restoring operations are required in the aftermath of extreme flood events.

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