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Effect of Local Scour on Lateral Response of Single Bridge Pier in Different Soil Conditions (Article 1)

Nur Wahidatul Sakhinah Muhyidin[1], Nordila Ahmad[1,*], Zuliziana Suif[1], Jestin Jelani[1]

[1] Department of Civil Engineering, Engineering Faculty, National Defence University of Malaysia, 57000 Kuala Lumpur, Malaysia

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ABSTRACT

The phenomenon of scour, which involves the erosion or removal of material from a surface due to the action of water or flowing fluids, can significantly impact the lateral response of structures. Piers that are constructed in river environments are prone to scour, which is influenced by the characteristics of waves and currents, as well as the types of soil present. This study aims to investigate the effect of local scour and global scour on behaviour of laterally loaded piers installed in different soil conditions. Finite element model (FEM) using the software program PLAXIS were used in the analyses. Three different parameters were investigated such as depth of scour, magnitude of lateral load and soil types. The results showed that scour significantly affects piers installed in medium dense sand, and it has less of an effect on piers installed in stiff clay. The pier lateral displacement and bending moment dramatically increases in medium dense sand. The lateral load rises in tandem with the lateral displacement at various scour depths. Finally, a semi-empirical equation for lateral load capacity was presented and compared with existing equations from the literature. This method can be used quickly and accurately to calculate the effect of scour.

1. Introduction

The removal of soils from around foundations due to the action of currents and waves is termed as scour. This phenomenon has been a primary cause of failures for many water-related infrastructures, such as bridges and marine structures. Bored pile foundations are commonly used for long-span bridges and offshore constructions in waters deeper than three meters. Pile foundations submerged in water are particularly susceptible to scouring, which poses a significant threat to their structural integrity [21]. When water flows around a stationary structure, like a bridge pier supported by a pile foundation, a scour hole forms around the foundation. In analyzing the behavior of the pile foundation under scoured conditions, it's a common practice to entirely remove the soil around the foundation up to the scour depth, often neglecting the displacement and bending stress due to the the scour hole.

General scour, as defined by [1] and also known as local scour, typically refers to erosion over a seabed or riverbed. While numerous studies have investigated local scour around piers [2]–[7],

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[*] *Corresponding author.*
E-mail address: nordila@upnm.edu.my (Nordila Ahmad)

several numerical simulations have also been conducted to examine the impact of scour depth on the lateral behavior of piles. For instance, extensive research, including the use of three-dimensional (3D) computer models, has been undertaken by [8]–[14], [22-23] to analyze the influence of scour holes on the lateral behavior of piles [15-16]. Another study developed modified p-y curves to analyze the lateral response of piles subjected to lateral loads in soft clay, specifically aiming to evaluate the impact of scour on pile behavior [17]. These curves were employed to investigate the behavior of laterally loaded piles in soft clay. Meanwhile, [18] noted that scour had a more pronounced effect on sand than on clay. It is evident that different factors influence scour in sand and clay. However, most research has focused on sand and soft clay, with limited studies on stiff clay and a scarcity of investigations into the effects of local scour on lateral response using numerical analysis. Given this backdrop, there is a pressing need for systematic numerical studies to analyze the effects of scour on the lateral behavior of piles across different soil conditions.

The objectives of this study are: (1) to explore the impact of different scour types on the behavior of a single bridge pier in two soil conditions, and (2) to evaluate the existing semi-empirical formula for predicting the lateral load capacity of a single bridge pier across various soil conditions.

2. Methodology

In this study, the first step was to determine the properties of a concrete rigid pier (short pier) with a diameter (D) of 1.5 m and a length (L) of 7.0 m. The lateral load was applied 1 m above the submerged clay layer. The pier model had a boundary width equivalent to 11 times its diameter (11D), which corresponds to 16.5 m on each side. For a visual representation, see Figure 1.

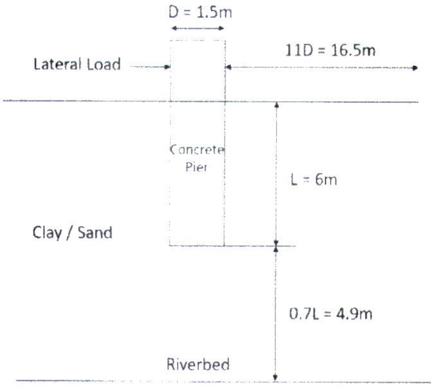

Fig. 1. Pier model

Next, parameter analysis was carried out, taking into account different lateral load capacities ranging from 0 to 3000 kN and four distinct local scour depths (Sl). The scour depths were expressed as Sl/D ratios of 1, 1.5, 2.0, and 3.0, where D denotes the diameter of the pier. These parameters facilitated a thorough examination of the influence of scour depth on lateral response.

To study the behavior of the bridge pier, a two-dimensional numerical model was developed using PLAXIS 2D, a software frequently used for geotechnical analysis. This model was employed to analyze data across three different scenarios: the influence of scour depth on lateral displacement, the impact of scour depth on bending moment, and the correlation between lateral load capacity and lateral displacement. These scenarios were assessed in two specific sediment types: medium-dense sand and stiff clay, to encompass varying soil conditions. The analysis covered a total of 72 scenarios, capturing the diverse combinations of lateral response as detailed in Table 1, which showcases the simulation framework used in this study. The results pertaining to the lateral response were validated by juxtaposing them with the latest existing equation that has been developed and authenticated.

Table 1
Data analysis framework

Type of sediment	Lateral Load (kN)	Scour depth (S_L/D)	Total cases	Analyses
Medium Dense Sand	1000, 2000, 3000	1.0 1.5 2.0 3.0	36	a) effect of scour on lateral displacement b) effect of scour depth on bending moment c) effect of lateral load capacity on lateral displacement
Stiff Clay	1000, 2000, 3000	1.0 1.5 2.0 3.0	36	

3. Results

72 numerical simulations were conducted, offering a thorough presentation of the results. The primary goal was to understand the influence of different parameters on scour around a bridge pier in different soil conditions. Furthermore, a semi-empirical equation for the H_R/H_{R0} ratio were introduced and elaborated. This comparison with established studies provides a holistic view of the research outcomes.

3.1 Effect of scour depth on lateral response

Figure 2 illustrates the scenario under a lateral load of 1000kN. In stiff clay, there is a marked rise in lateral pier head displacement with increasing scour depth. For local scour depths of 1.0D, 1.5D, 2.0D, and 3.0D, the peak pier head displacements recorded were 0.0128m, 0.0192m, 0.0204m, and 0.0488m, respectively. Notably, these peaks were observed at a 0.50m depth along the pile's length. The growth in scour depth directly affects the pier's lateral soil resistance. As scouring deepens, soil erodes around the pier, diminishing the support from the stiff clay. This reduced support, in turn, amplifies the pier head's displacement.

As depicted in Figure 3, under a lateral load of 1000kN, the lateral pier head displacement in medium-dense sand notably increases as the scour depth rises. For local scour depths of 0.5D, 1.0D, 1.5D, and 2.0D, the peak pier head displacements recorded were 0.0196m, 0.0249m, 0.0368m, and 0.1068m, respectively. It's noteworthy that these maximum displacements were observed at a depth of 0.50m along the pile's length. The depth of the scour directly influences the pier's lateral soil resistance. As scouring advances, the surrounding soil erodes, diminishing the lateral support from the medium-dense sand. This reduction in lateral soil resistance results in a greater displacement at the pier head.

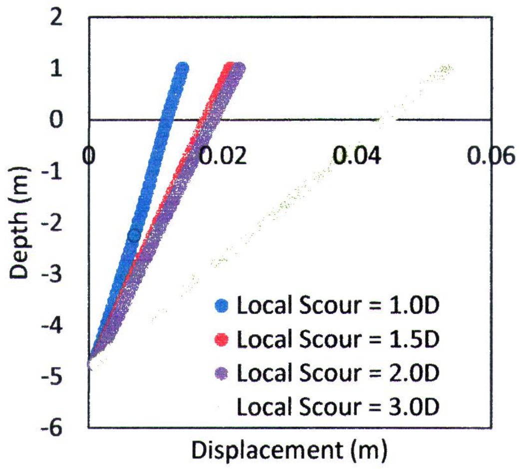

Fig. 2. Scour depth with lateral displacement in stiff clay (Lateral load = 1000kN)

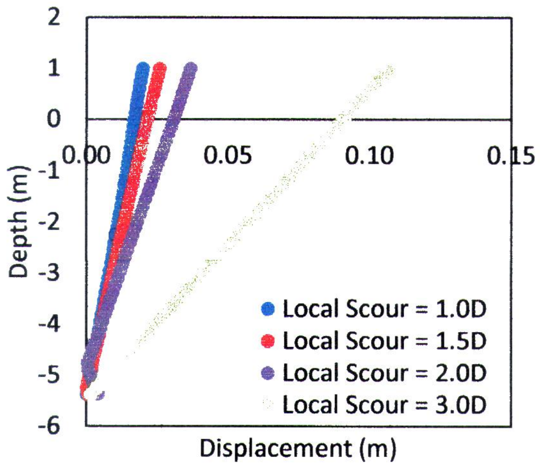

Fig. 3. Scour depth with lateral displacement in medium dense sand (Lateral load = 1000kN)

3.2 Effect of scour depth on bending moment

Figure 3 depicts the variation in the bending moment along the pier's length, influenced by the lateral load, type of scour, and scour depth in stiff clay. With a lateral load of 1000kN, the bending moment peaks at varying depths as the scour depth intensifies. Specifically, for scour depths of 1.0D, 1.5D, 2.0D, and 3.0D, the apex bending moments register at 568kNm, 593kNm, 595kNm, and 589kNm, occurring at depths of 3.61m, 3.72m, 3.72m, and 3.66m, respectively. A deepening scour results in diminished soil support around the pier. This reduced support compromises the pier's lateral resistance to the exerted load, causing greater displacement and consequently, elevated bending moments. While Figure 4 illustrates the variation in the bending moment along the pier's length, influenced by factors such as the lateral load, scour type, and scour depth in medium dense sand. The bending moment peaks at various depths along the pier under a 1000kN lateral force as the scour depth increases. Maximum bending moments for scour depths of 1.0D, 1.5D, 2.0D, and 3.0D are 810kNm, 1070kNm, 1424kNm, and 2517kNm, respectively, at depths of 3.33m, 3.46m, 3.75m, and 4.63m. This shows that the bending moment in medium dense sand is much higher than stiff clay in various scour depths. This may be due to sands are granular and a material with friction. As a frictional material, the strength increases up to a certain point with the application of normal stresses. As a result, when a footing or foundation strain is applied, the sand beneath and surrounding the footing becomes significantly stronger as the material moves and compresses. While clays are composed of platelets (flat particles that are much smaller than sand particles) and derive their strength for friction and cohesion. Typically, it loses strength when moisture is introduced, and apparent cohesion resulting from ion bonds is released when water molecules replace them. As a result, as the scour increases in depth, the adjacent soil support for the pier decreases. This weakened support reduces the pier's lateral resistance to the applied load, resulting in diminished bending moments.

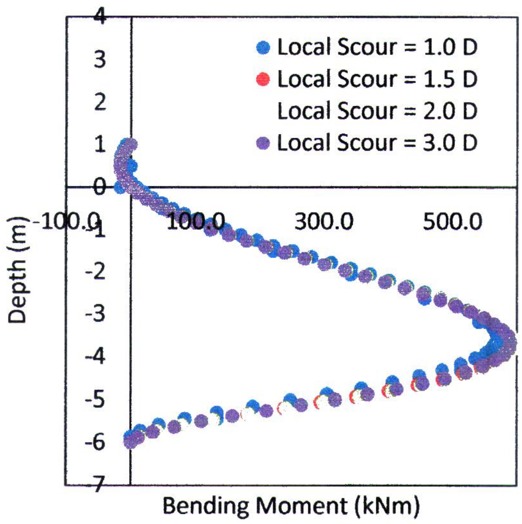

Fig. 3. Scour depth with bending moment in stiff clay (Lateral load = 1000kN)

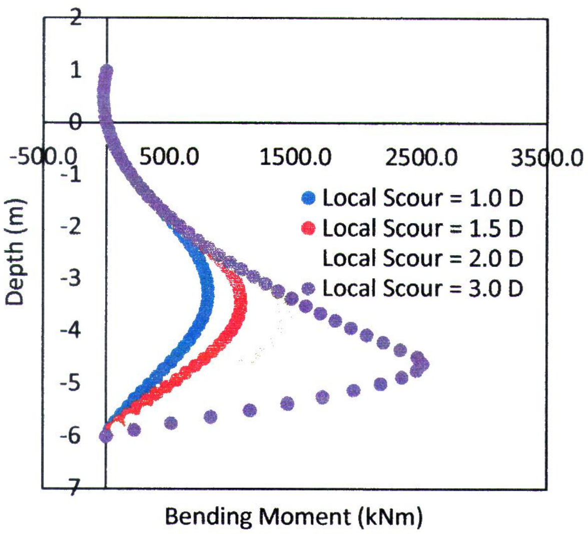

Fig. 4. Scour depth with bending moment in medium-dense sand (Lateral load = 1000kN)

3.2 A Semi Empirical Formula for lateral load capacity

Figure 5 illustrates the correlation between the lateral pile load and the pile head displacement, taking into account various local scour depths in stiff clay. The lateral load capacities are delineated for different Sl/D ratios: 1.0D, 1.5D, 2.0D, and 3.0D, with the corresponding values being 3000kN, 750kN, 500kN, 490kN, and 250kN. This visualization succinctly encapsulates the load capacity trends that are further elaborated in Figure 6 where it delves deeper, emphasizing the H_R to H_{R0} ratio. Here, H_R signifies the pier capacity post-scour, while H_{R0} denotes the pier capacity pre-scour. This ratio is pivotal as it gauges the scour's influence on the pier's ultimate capacity. A diminished ratio underscores a pronounced scour impact and the linear fitting show the results for scour depths spanning from 1.0 to 3.0D, which is the diameter of the local scour. The relationship is articulated in Eq. (1). The associated coefficient of determination (R^2) for this linear fit stands at 70.52%.

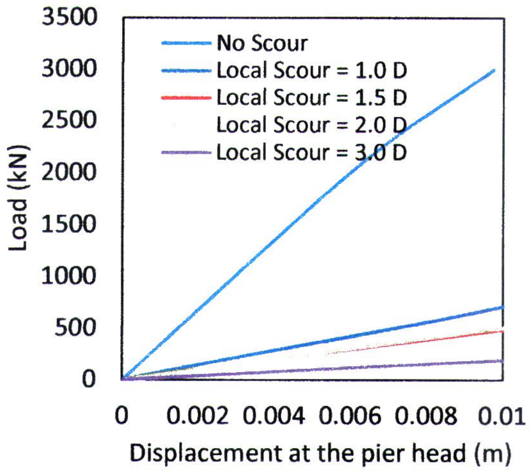

Fig. 5. Local scour effects on lateral load with lateral displacement in stiff clay (Lateral load = 1000kN, 2000kN, 3000kN)

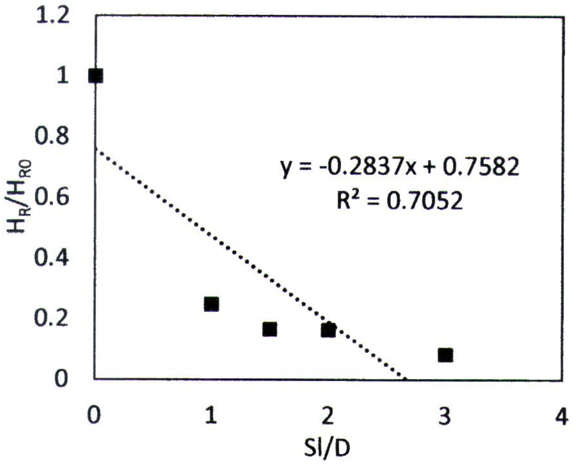

Fig. 6. Local scour effects on pier capacities in stiff clay

$$\frac{H_R}{H_{Ro}} = 0.7582 - 0.2837\left(\frac{S_l}{D}\right), 1.0 \leq \left(\frac{S_l}{D}\right) \leq 3.0 \quad (1)$$

Figure 7 depicts the relationship between lateral pile load and pile head displacement in medium-dense sand at various local scour depths. The lateral load capacities are given for the following Sl/D ratios: 1.0D, 1.5D, 2.0D, and 3.0D, with corresponding values of 3000 kN, 2200 kN, 1500 kN, 900 kN, and 300 kN. This visualisation depicts the load capacity patterns that are further discussed in Figure 8. This diagram emphasises the ratio used to assess the impact of scour on the final load capacity of the pier. A lower ratio implies that scour has had a significant impact on the pier's capacity. The solid blue line depicts the linear fitting results for scour depths ranging from 1.0 to 3.0D, reflecting the local scour diameter. Eq. (2) expresses the relationship. This linear fit's associated coefficient of determination (R2) is exceptionally high, at 98%.

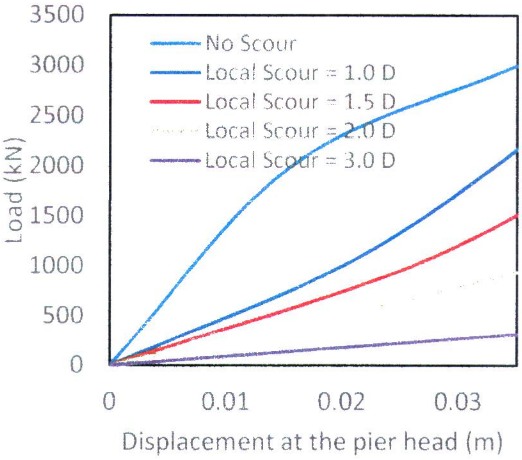

Fig. 7. Local scour effects on lateral load with lateral displacement in medium dense sand (Lateral load = 1000kN, 2000kN, 3000kN)

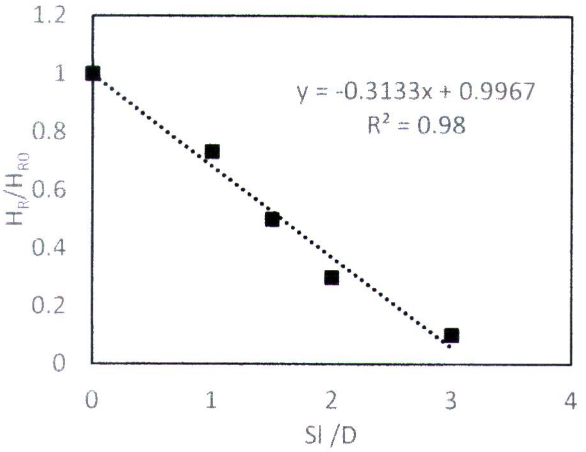

Fig. 8. Local scour effects on pier capacities in medium dense sand

$$\frac{H_R}{H_{Ro}} = 0.9967 - 0.3133\left(\frac{S_l}{D}\right), 1.0 \leq \left(\frac{S_l}{D}\right) \leq 3.0 \quad (2)$$

3.3 Comparison of semi-empirical equation with existing equations in the literature

The primary factor influencing the ultimate capacity of a scour-affected pier is the decrease in the initial embedding depth. To address this, Eq. (1) and Eq. (2) have been adjusted to become Equation (3) and Equation (4). This adjustment involves replacing the parameter D with L, which signifies the embedding depth, and multiplying the first-order coefficient by the L/D ratio. This alteration yields a new semi-empirical equation tailored for stiff clay, linking both local and global scour.

For this study, an L/D ratio of 4 has been established. Within the equations, H_R denotes the ultimate capacity post-scour, whereas H_{RO} signifies the ultimate capacity pre-scour. S_l and S_g represent the depths of local and global scour, respectively. By integrating these modifications and factoring in the L/D ratio, the revised Eq. (3) and Eq. (4) offer a more precise prediction of the pier's lateral capacity post-scour in stiff clay. In conclusion, the outcomes derived using the updated Eq. (4)

and Eq. (6) are compared with the results from previous research that employed this newly formulated semi-empirical equation.

Combination of new equation between local scour and global scour of stiff clay:

$$\frac{H_R}{H_{Ro}} = 0.7093 - 0.2837\left(\frac{S_l}{D}\right) - 0.3667\left(\frac{S_g}{D}\right) \tag{3}$$

New semi-empirical equation between local scour and global scour of stiff clay:

$$\frac{H_R}{H_{Ro}} = 0.7093 - 1.1348\left(\frac{S_l}{L}\right) - 1.4668\left(\frac{S_g}{L}\right) \tag{4}$$

Combination of new equation between local scour and global scour of medium dense sand:

$$\frac{H_R}{H_{Ro}} = 0.8434 - 0.3133\left(\frac{S_l}{D}\right) - 0.3400\left(\frac{S_g}{D}\right) \tag{5}$$

New semi-empirical equation between local scour and global scour of medium dense sand:

$$\frac{H_R}{H_{Ro}} = 0.8434 - 1.2532\left(\frac{S_l}{L}\right) - 1.3600\left(\frac{S_g}{L}\right) \tag{6}$$

In this study, the impact of scour on various lateral load capacities have been examined. Figure 9 presents the findings from both past research and this current investigation. Diamonds symbolize the data from [14], [19] by circles, [20] by blue squares, and [1] by crosses. Triangles represent the outcomes from this study for stiff clay, and for medium-dense sand by purple squares. These recent results were derived using semi-empirical equations that integrated both local and global scour information.

The inclusion of current results aimed to facilitate a comparison with data from previous research. However, the findings from [14], [19], and [1] predominantly ranged between 0.0 and 0.1, while other data spanned from 0 to 0.5. This discrepancy might stem from the employment of longer piers in the studies by Ni et al. [14], Li et al. [1], and Chentao Li et al [19]. The data from [20] was incorporated to enhance the dataset for shorter piers, aligning it with the current study for comparison purposes. Figure 10 underscores that scour exerts a more pronounced effect on piers situated in sand than those in clay. This heightened sensitivity to scour in sand is especially evident in the study by [1]. Scour compromises the lateral load capacity by eroding the soil surrounding the pier, and the degree of this reduction is intrinsically tied to the characteristics of the eroded soil.

From these observations, it can be deduced that the coefficient reflecting the weakening due to scour is modulated by various elements, including the nature of scour, soil attributes, and lateral load capacity. Eq. (4) offers a preliminary estimation of the H_R/H_{R0} value for piers in stiff clay, while Eq. (6) forecasts the H_R/H_{R0} value for piers situated in medium-dense sand.

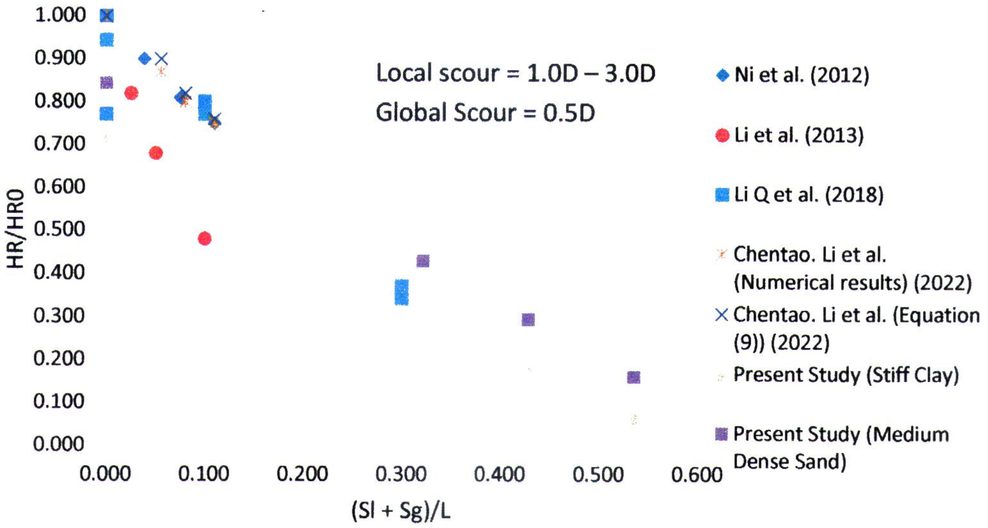

Fig.9. Validation of present semi-empirical result with the previous studies

4. Conclusions

This study explored the impact of scour depth on the lateral response of a single bridge pile, focusing on sand, stiff clay, and medium-dense sand. The findings revealed that sand is more susceptible to scour-induced changes in lateral load capacity than clay. As the scour depth intensified, there was a noticeable decline in the pier's ultimate lateral load capacity and stiffness, while its lateral displacement surged. The research introduced innovative equations to forecast the lateral load capacity post-scour, taking into account variables such as scour depth and soil attributes. Through numerical simulations, the interplay between lateral pile load and pile head displacement across varying scour depths in both clay and sand was explored. The results underscored the criticality of factoring in the repercussions of scour when designing and assessing piers. More numerical simulations are needed to verify this complicated scour phenomenon.

Acknowledgement

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