Behavior of Laterally-Loaded Piles Under Scoured Conditions at Bridges

Jie Han

Abstract Scour often occurs around bridge piers and abutments, which are commonly supported by piles. This paper evaluates the effects of global scour and local scour on the behavior of laterally-loaded single piles and pile groups in sands and clays based on recent studies. The recent studies have been focused on stress history changes of remaining soils after scour, local scour-hole geometry and dimensions, and their effects on the behavior of laterally-loaded piles under scoured conditions. Experimental, numerical, and analytical studies have been conducted for these investigations and are discussed in this paper. Scour depth is identified as the most important influence factor, followed by scour width and slope. This paper also presents an integrated analysis of the effect of scour on the performance of pile-supported bridges that considered hydraulic, geotechnical, and structural aspects.

Keywords Deformation · Lateral load · Pile · Scour

1 Introduction

Scour is a process of erosion or removal of streambed or bank materials due to flowing water. Briaud [3] pointed out that erodibility depends on soil type or properties and water velocity. Scour can happen under different environments, e.g., around bridges and in marine environments. This paper will focus on scour around bridge piers and foundations. There are three common types of scour around bridge foundations: (1) general scour, (2) contraction scour, and (3) local scour. Arneson et al. [2] referred to the general scour as long-term degradation of a river bed. The general scour occurs even without any obstructions in a river channel and typically happens between large open spaces outside and between bridge foundations thus having shallow depths. The contraction scour happens when a water channel becomes narrow due to some

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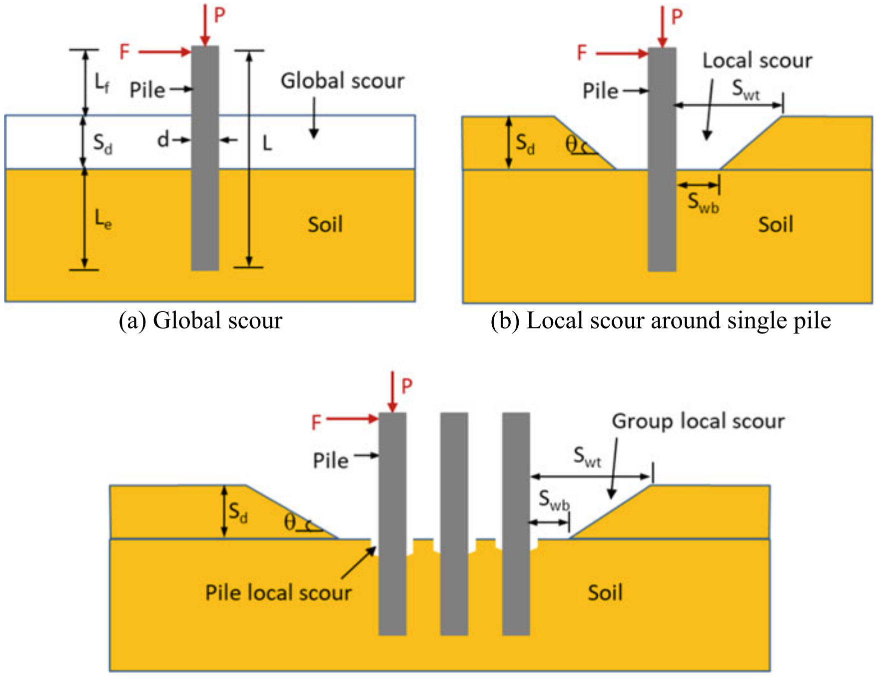
obstructions (e.g., bridge abutments and piers), thus changing water flow velocity and direction, which increases the ability of water to remove soils (i.e., higher erodibility). The contraction scour typically occurs between bridge piers or between bridge piers and abutments. The general scour and the contraction scour often result in relatively uniform lowering of streambeds and they are together referred to as global scour in this paper. Around bridge piers, local scour can develop and extend below bridge foundations or pile caps if a pile foundation is used. Melville [24] provided the physics or mechanisms of local scour at bridge piers and illustrated local scour for six types of bridge piers: (1) uniform pier, (2) slab footing, (3) upwards tapering, (4) downwards tapering, (5) caisson foundation, and (6) pile foundation. Pile foundations and caisson foundations are two commonly used foundation types, especially for large-span bridges. In addition, pile foundations and monopiles have been increasingly used to support offshore structures and wind turbines, which may be subjected to scour. Piles under bridges and offshore structures are required to resist not only vertical loads but also lateral loads due to water flow, debris, and wind. Figure 1 shows the common types of scour around single piles and pile groups for analysis. Lin et al. [18] conducted a case history analysis of bridge failures due to scour and found that 63% of failures were caused by local scour. For pile groups, there are two types of local scour, which are referred to as group local scour and pile local scour in this



(c) Local scour around pile group

Fig. 1 Common types of scour around piles for analysis paper. Global scour is commonly considered in the design of laterally-loaded single piles or pile groups under scoured conditions due to its simplicity and conservative nature in practice. Bridges on scoured foundations may also be subjected to seismic loading, which can have combined effects on the performance of the bridges [31]. Due to the page limit, the effect of seismic loading on the behavior of laterally-loaded piles under scoured conditions will not be discussed in this paper.

Wang et al. [31] conducted a comprehensive review of bridge scour in terms of mechanism, estimation (evaluation), monitoring, and countermeasures. Evaluation of scour at bridges involves hydraulic, geotechnical, and structural aspects. Depth of scour depends on many factors. Melville [24] grouped 13 specific influence factors into four key influence factors (flow rate, bed sediment, bridge geometry, and time). In the literature, a number of methods are available to estimate maximum scour depths around bridge piers and most of these methods are empirical and based on laboratory-scale data. Among these methods, the HEC-18 equation [2] is the most widely used, which considers local scour as a function of characteristics of riverbed material, bed configuration, flow characteristics, fluid properties, and the geometry of the pier and footing. Shape of scour hole depends on several factors. Arneson et al. [2] pointed out that the top width of a scour hole could range from 1.0 to 2.8 times the scour depth and depended on the bottom width of the scour hole and composition of the bed material but suggested that in practical applications the top width of the scour hole should be selected as twice the depth of the scour hole. Arneson et al. [2] also pointed out that the angle of repose of a cohesionless material in water is less than that in air. Around bridge foundations, Butch [6] found that the scour hole had an irregular shape, i.e., a steep slope in the upstream side and a gentle slope in the downstream side. For evaluating the effect of local scour on bridge piers and foundations, most researchers assumed a scour hole as an inversed truncated cone shape (e.g., Mostafa [25]; Li et al. [10]; Ismael [8]; Lin et al. [12, 13]; Zhang et al. [32]).

This paper presents recent studies on the behavior of laterally-loaded piles under scoured conditions and reviews the analyses done based on global scour and local scour with cone-shaped scour holes. In these analyses, the scour depth was assumed to be known. The behavior of laterally-loaded piles without any scour can be evaluated by different methods: (1) experimental, (2) analytical, and numerical. The behavior of laterally-loaded piles under scoured conditions can be evaluated by these methods as well. For example, Ismael [8] and Ismael and Han [9] conducted physical model tests to evaluate the effect of global and local scour on the lateral load-displacement curves of single piles. Lin et al. [12–15, 17], Zhang et al. [32], Lin and Wu [22], and Lin and Lin [20] developed analytical solutions to examine the effects of stress history of remaining soils and the scour-hole geometry and dimensions on the behavior of laterally-loaded single piles. The analytical solutions have been mostly based on the *p*-*y* curve concept (*p* is the lateral soil reaction and *y* is lateral pile displacement) because it is easier to understand and adopt. The *p*-*y* curve is to describe the interaction between pile and soil under loading by a series of linear or non-linear springs. Mostafa [25] and Li et al. [10] adopted numerical methods to evaluate global scour and local scour and their effects on the laterally-loaded single piles under scoured conditions.

Mostafa [27] and Lin and Lin [21] also evaluated the scour effects on lateral behavior of pile groups in sands. Lin [11] and Lin et al. [16] performed an integrated analysis of pile-supported bridges under scoured conditions, which is reviewed at the end of this paper.

2 Behavior of Laterally-Loaded Piles Under Scoured Conditions

2.1 Overview

Behavior of laterally-loaded single piles in sands or clays has been well researched in the past through laboratory model tests, full-scale field tests, numerical analyses, and analytical solutions. The commonly used methods for evaluating the behavior of laterally-loaded single piles are mostly analytical or empirical. For example, Broms [4] developed analytical solutions and design charts for lateral load capacities of single piles in sand. In the practice, Reese's method [28] is commonly used to analyze laterally-loaded single piles in sand while Matlock's method [23] is used for laterally-loaded single piles in clay. To consider the pile group effect, Brown et al. [5] proposed the method of p-multiplier, which has been widely used in practice to evaluate the behavior of laterally-loaded pile groups. These methods may still be used to evaluate the behavior of laterally-loaded single piles and pile groups under global scour but need to be modified under local scour.

2.2 Single Piles

Effect of Global Scour. Diamantidis and Arnesen [7] found that when the scour bottom width was six times the pile diameter, local scour could be considered as global scour. Ismael and Han [9] conducted physical model tests with a scour width at least 6.3 times the pile diameter to evaluate the effect of global scour on the lateral load-displacement curves and lateral load capacities of single piles in dry sand. In their study, the pile was pinned at its bottom but it could have free rotation. Ismael and Han [9] found that the increase of the scour depth significantly reduced the lateral load capacities of the piles as shown in Fig. 2. The lateral load capacity ratio is defined as the ratio of the capacity with scour to that without scour. The calculated ratios were obtained using the design chart developed by Broms [4] without scour. The design chart considered the eccentricity of the lateral load relative to the ground surface. The increase of the scour depth is equivalent to the increase of the eccentricity and the reduction of the embedment of the pile. This excellent match indicates that the design chart developed by Broms [4] can be used to evaluate the lateral load capacities of piles due to global scour.

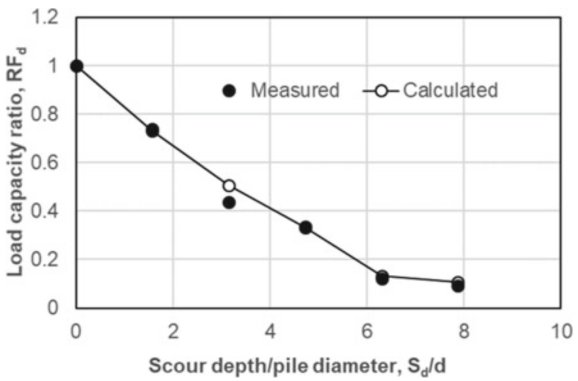


Fig. 2 Lateral load capacity ratio versus scour depth/pile diameter ratio for global scour (modified from Ismael and Han [9])

Ismael [8] also evaluated the bending moment change along the height of the pile with the increase of the scour depth at the failure load as shown in Fig. 3. The bending moment was normalized by the maximum moment in the pile without scour. Since the lateral load capacity of the pile decreased with the increase of the scour depth, the bending moment in the pile decreased with the increase of the scour depth. Figure 3 shows the maximum bending moment along the pile moved downward with the increase of the scour depth because the embedment depth of the pile decreased with the scour depth.

Removal of soil around piles changes stresses around the piles, which may affect the behavior of laterally-loaded piles. In the reduced-scale physical model tests, Ismael [8] did not simulate the process of soil removal around the pile; therefore, the effect of soil removal to cause possible stress history change cannot be evaluated. Lin et al. [17] theoretically investigated the effect of the stress history change of the

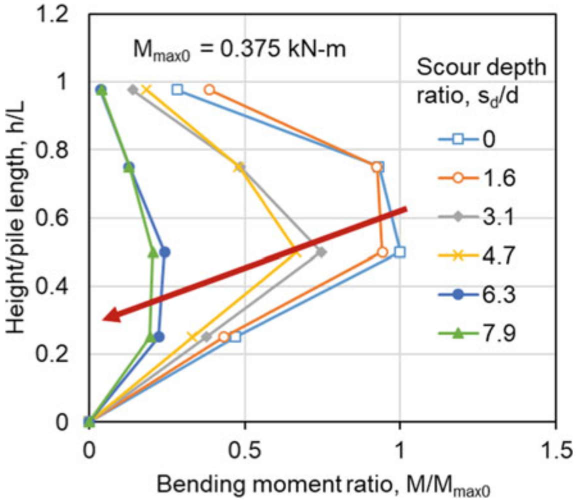


Fig. 3 Bending moment along the height of the pile at different scour depth (modified from Ismael [8])

remaining soil after global scour on the behavior of laterally-loaded piles in sands under a scoured condition while Lin et al. [14] investigated this effect on the behavior of laterally-loaded piles in clays. Lin et al. [14, 17] followed the concept of the CamClay model for soil rebound and the over-consolidation ratio and undrained shear strength relationship for the remaining soil. Lin et al. [14] found that global scour reduced the vertical stresses in the sand and increased its friction angle considering the stress-dependent friction angle and the over-consolidation ratio thus increasing the coefficient of lateral earth pressure at the interface between pile and sand. As a result, the lateral load capacity of the pile in the sand increased and its displacement decreased after considering the stress history effect. When piles were in clays, Lin et al. [17] found that global scour had more effect on the reduced effective stress than the increased over-consolidated ratio, thus reducing the undrained shear strength of the clay. As a result, the lateral load capacity of the pile in the clay decreased and its displacement increased after considering the stress history effect. In other words, ignoring the stress history effect due to global scour is conservative for the behavior of laterally-loaded piles in sands but un-conservative for that of piles in clays.

Lin et al. [19] investigated the global scour effect on the buckling loads of single piles fixed the base but having different pile head fixities. The soil support was modeled by multilinear stiffness springs in a structural software or by non-linear *p-y* curves in the Lpile software. These two methods resulted in similar lateral deflections under the same lateral loads. The analysis showed that the buckling loads decreased with the scour depth for all head fixities and the reduction of the buckling load was more significant at a smaller scour depth.

Effect of Local Scour. The effect of local scour on the behavior of laterally-loaded single piles may be considered as that of global scour to be conservative in practice. However, Lin et al. [13] found that considering local scour as global scour led to 49–68% larger groundline lateral displacements of single piles in sands under typical lateral loads. This difference implies that proper consideration of local scour is necessary and has been increasingly researched in recent years. Most recent studies on local scour around single piles have been based on circular piles. Square-shaped piles are also used in practice. Sheppard and Renna [29] suggested the use of equivalent or effective diameter based on the direction of water flow relative to the orientation of a pile. Ismael [8] conducted physical model tests to investigate the effect of scour-hole geometry and dimensions on the load capacities of laterally-loaded piles in sand as illustrated in Fig. 4 for some of the test setups as examples. Ismael [8] simulated the scour hole as a wedge cone with two symmetric scour slopes along the direction of lateral loading on the pile. In addition to the tests on global scour, these tests include four different scour bottom widths (0, 3.8d, 6.3d, and 10.5d), two scour slope angles (15° and 30°), and four scour depths (3.2d, 4.8d, 6.3d, and 7.9d) of scour holes. Details of these tests can be found in Ismael [8].

Based on the test results provided in Ismael [8], the effect of the slope angle on the lateral load capacity of the pile can be evaluated by calculating the ratio of the load capacity with a slope to that without a slope (i.e., global scour) at the same scour depth. Figure 5 shows that the scour slope increased the lateral load capacity of the

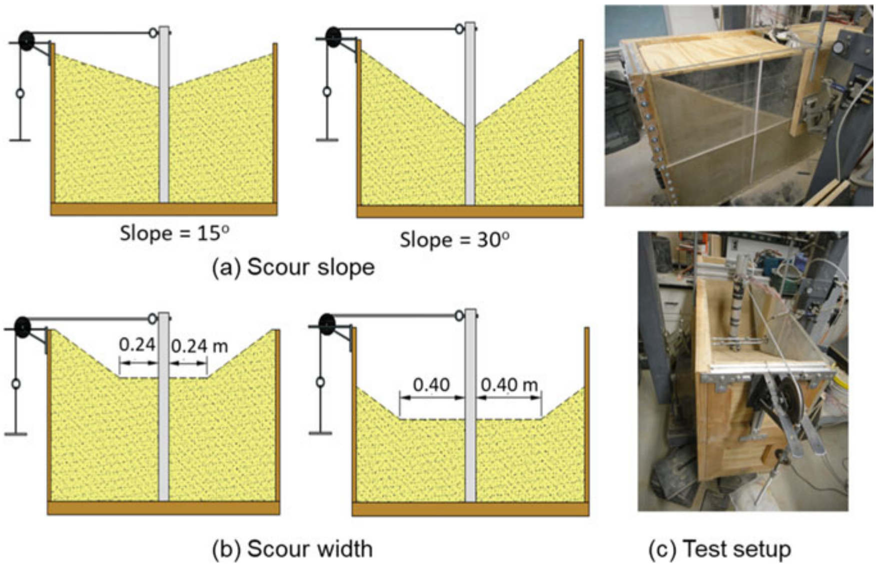
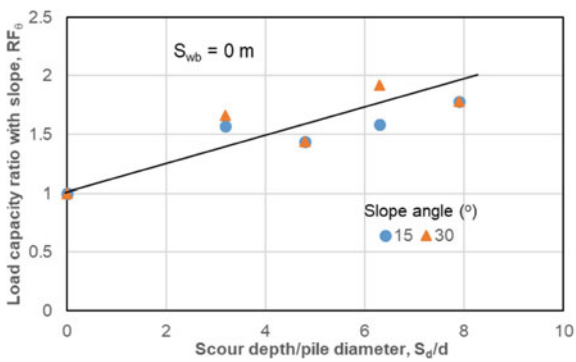


Fig. 4 Model tests for effects of scour-hole dimensions [8]

Fig. 5 Effect of scour slope on lateral load capacity ratio (generated from the data in Ismael [8])



pile within the scour with zero scour width at the bottom; however, the slope angles of 15° and 30° did not make much difference. The increase of the scour depth shows more effect of the scour slope on the lateral load capacity because of the increase of the surcharge by the remaining soil slope.

Figure 6 shows the effect of the scour width at the bottom on the lateral load capacity ratio, defined as the ratio of the lateral load capacity of the pile at the scour width at the bottom to that due to global scour at the same depth. This ratio clearly shows that the increase of the scour width reduced the pile load capacity and the increase of the scour depth increased the effect of the scour width.

Ismael [8] also investigated the effect of scour depth on the lateral load capacity of the single pile under different scour slope and scour width, which is presented

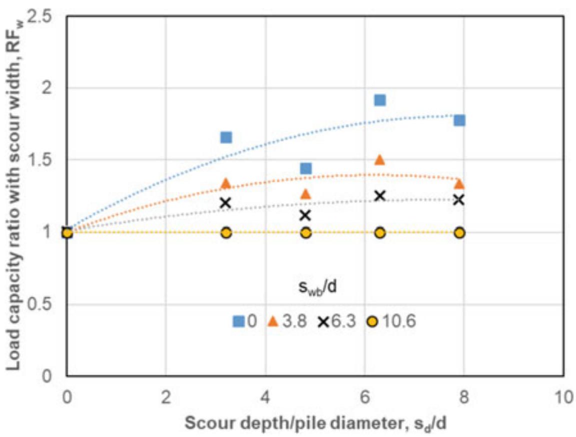


Fig. 6 Effect of scour width at bottom on lateral load capacity ratio (generated from the data in Ismael [8])

herein. This effect can be evaluated by combining the test results for global scour in Fig. 2 and the ratios of load capacities under local and global scour as presented in Figs. 5 and 6.

Lin et al. [13] proposed an analytical method to modify the failure mode of the soil wedge subjected to a lateral load from a pile in sand as proposed by Reese et al. [28] by considering a local scour hole in an inversed truncated cone shape as shown in Fig. 7. In this method, Lin et al. [13] proposed a concept of an equivalent soil wedge depth to the pile in the sand without scour based on an equal lateral load capacity to the pile with local scour. The local scour resulted in a reduced soil wedge depth so that the lateral load capacity of the pile decreased. Lin et al. [13] found that an increase of the scour depth significantly increased the pile lateral displacement and

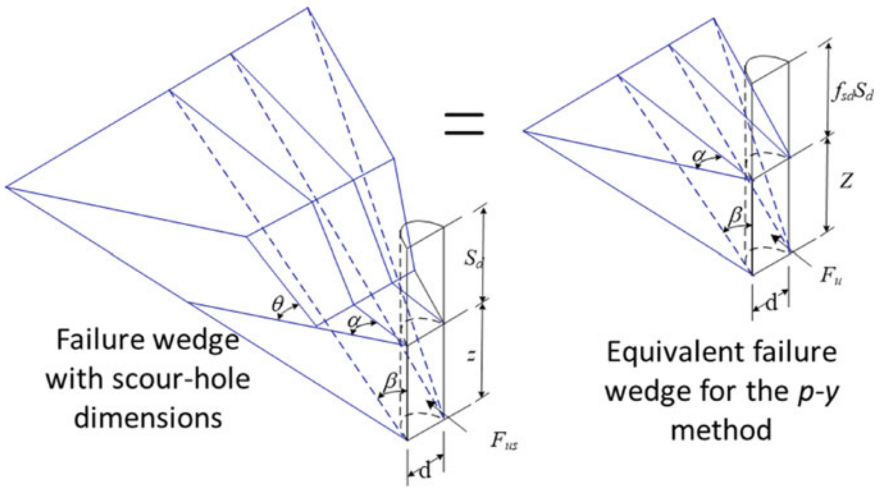


Fig. 7 Modified failure mode for a laterally-loaded pile in sand with local scour [13]

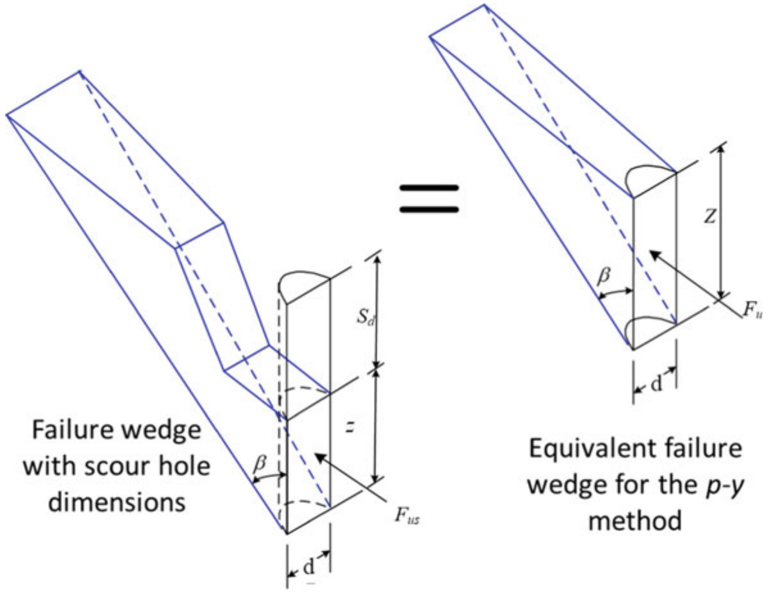


Fig. 8 Modified failure mode for a laterally-loaded pile in clay with local scour [12]

the maximum bending moment but the scour width and the scour-hole slope angle had relatively less effects, especially when $S_{wb} > 8d$. In addition, Lin and Lin [20] found that local scour reduced lateral load capacities of piles in dense sand by 10% more than those in loose sand.

Lin et al. [12] proposed another analytical method to modify the failure mode of the soil wedge subjected to a lateral load from a pile in clay as proposed by Matlock [23] by considering a local scour hole in an inversed truncated cone shape as shown in Fig. 8. In this method, Lin et al. [12] also adopted the concept of an equivalent soil wedge depth to the pile in the clay without scour based on an equal lateral load capacity to the pile with local scour. The difference of this method from that for the pile in the sand is the angle of the distributed wedge. For the clay, this angle is equal to zero. The local scour also resulted in a reduced soil wedge depth so that the lateral load capacity of the pile decreased. These two analytical models were verified by the three-dimensional numerical analyzes conducted by Lin et al. [12, 13]. It should be pointed out that they did not consider the effect of stress history change due to global and local scour.

Similar to the experimental study on global scour, Ismael [8] did not simulate the process of soil removal around the pile due to local scour; therefore, the effect of soil removal to cause possible stress history change cannot be evaluated either. Zhang et al. [32] theoretically investigated the effect of the stress history change of the remaining soil after local scour on the behavior of laterally-loaded piles in clays. Zhang et al. [32] simulated the local scour hole in an inversed truncated cone

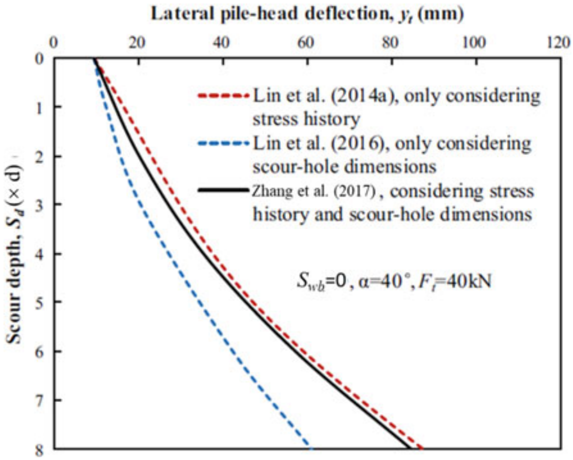


Fig. 9 Effect of stress history and scour-hole dimensions [32]

shape and used Mindlin Green's function for vertical and horizontal loads in a semi-infinite half-space to calculate the scour-induced stress reduction in the soil. As a result, the over-consolidated ratio and undrained shear strength of the clay after local scour were estimated using the same concept of the CamClay model for soil rebound and the over-consolidation ratio and undrained shear strength relationship for the remaining soil as used by Lin et al. [14]. By considering the reduction of the embedment length of the pile and the reduced undrained shear strength of the clay due to local scour, Zhang et al. [32] used the Matlock method [23] to predict the p-y curve of the pile due to local scour. Figure 9 shows the comparison of the calculated results considering stress history only, considering scour-hole dimensions only, and both stress history and scour-hole dimensions, indicating the stress history had more effect on the behavior of laterally-loaded single piles in the clay than the scour-hole dimensions in this analysis.

Lin and Wu [22] evaluated different calculation models for vertical stresses after local scour including the US Federal Highway Administration (FHWA) method for driven piles (FHWA-DP), the FHWA method for drilled shafts (FHWA-DS), the American Petroleum Institute method (API), the improved method proposed by Lin and Wu [22], and the simplified method proposed by Lin and Wu [22] as shown in Fig. 10. The FHWA-DP method did not consider the local scour effect while the FHWA-DS method considered a linear reduction of the vertical stresses from the bottom of the scour hole to the depth of 1.5 times the scour depth. The API method considered a linear reduction of the vertical stresses from the bottom of the scour hole to the depth of six times the pile diameter. Lin and Wu [22] proposed an improved method to estimate the reduced vertical stresses along the center of the pile at different depths by using the Boussinesq solution for an embankment type of loading. Based on the parametric study, Lin and Wu [22] found that their improved method could be simplified by setting the influence depth equal to 3.5 times the scour depth. After the calculation of the reduced vertical stress at a specific depth below the

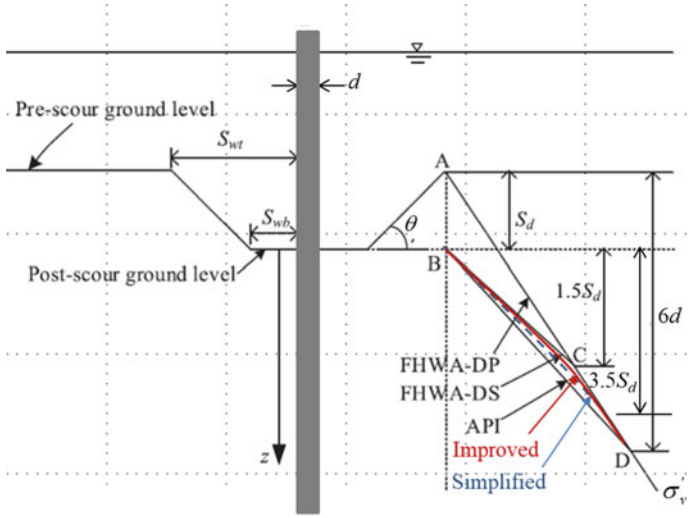


Fig. 10 Reduced vertical stress calculation models after local scour (modified from Lin and Wu [22])

bottom of the scour hole, the p-y curve at this depth can be calculated using available methods for laterally-loaded piles in soil without scour by the reduced vertical stress replacing the overburden stress and the equivalent depth depending on whether it is above or below the influence depth. Lin and Wu [22] examined the differences of the calculated lateral load capacities of single piles by these different methods as presented in Fig. 11. The lateral load capacity ratio was defined as the ratio of the lateral load capacity of the pile after scour to that before scour. Figure 11 shows that the API method, the improved method, and the simplified method calculated similar lateral load capacity ratios; however, both FHWA methods over-predicted the lateral load capacity ratios. Instead of the calculated reduced vertical stress, Lin and Lin [20] suggested to convert the vertical stress into an equivalent depth by dividing the vertical stress by the soil effective unit weight. This equivalent depth can be used in the *p*-*y* curve solution by Reese et al. [28] as Lin et al. [13] did to consider the local scour effect.

2.3 Group Piles

Behavior of laterally-loaded group piles in sands or clays has also been well researched in the past through laboratory model tests, full-scale field tests, numerical analyzes, and analytical solutions. Under lateral loads, an individual pile in a pile group often behaves weaker and softer than a single pile due to overlapping of stresses in soil between neighboring piles (i.e., pile-soil-pile interaction). To consider

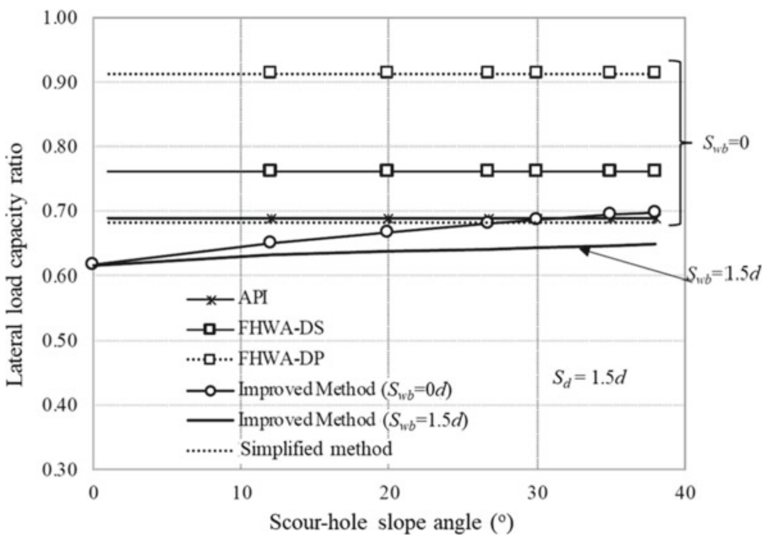


Fig. 11 Effect of calculated vertical stresses after local scour by different methods on the lateral capacity ratio (modified from Lin and Wu [22])

the pile group effect, the method of p-multiplier proposed by Brown et al. [5] has been widely used in practice to evaluate the behavior of a laterally-loaded pile group. The p-multiplier method includes applying a reduction factor, i.e., so-called a p-multiplier (f_m) to the *p*-*y* curve of a single pile to generate a modified *p*-*y* curve of a corresponding individual pile in the pile group under lateral loads. The p-multiplier depends on pile spacing, pile relative location (front, middle, rear, edge, or corner) in the pile group, soil properties, and pile head fixity conditions. The sum of the *p*-*y* curves for all piles in the group results in a *p*-*y* curve for the pile group.

Scour around group piles is more complex than that around single piles. There may be three types of scour: (1) global scour, (2) local scour around a pile group (i.e., group local scour), and (3) local scour around an individual pile (i.e., pile local scour). Based on the laboratory tests conducted for six pile groups of different pile spacing, Sumer et al. [30] found pile local scour holes developed around individual piles inside a group local scour hole around the largely-spaced pile group (pile spacing $s = 5d$). For the closely-spaced pile groups ($s \leq 3d$), however, pile local scour holes overlapped with each other. Since individual piles within a pile group are typically spaced at $3d$ or $4d$ in most practices, pile local scour can be ignored and a single group scour hole can be used to represent the local scour around a pile group.

To estimate group local scour depths, Sheppard and Renna [29] suggested three different cases before scour: (1) pile caps above riverbed (i.e., group piles exposed), (2) pile caps partially exposed, and (3) pile caps completely buried). These conditions affect scour-hole geometry and dimensions including scour depths. Sheppard and Renna [29] provided detailed procedures for estimating scour depths for these cases. Mostafa and Agamy [27] conducted an experimental study to evaluate scour-hole geometry and dimensions around the pile groups with two piles in a side-by-side arrangement, two piles in a tandem arrangement, and three piles in a triangular arrangement versus those around single piles. Based on the reported photos, the scour-hole shape for two piles was approximately elliptical while that for three piles was approximately circular. They found that the scour depth for the case with the pile group was generally greater than that for the case with a single pile depending on the group configuration and the gaps between piles. Amini et al. [1] showed that scour holes generated around 3 × 5 pile groups during the flume tests had a rounded square shape. Lin and Lin [21] pointed out that group piles under scoured conditions have two group effects: (1) group effect due to overlapped stresses and (2) group effect due to increased scour depths by increased flow velocity and turbulence between piles. As a result, the load capacity of an individual pile in the pile group is lower than that of a single pile.

Effect of Global Scour. The double group effect on the lateral load capacity of an individual pile in the pile group may be evaluated by two group reduction factors or efficiencies as shown in Eq. (1):

$$F_{\mathrm{gs}} = F_1 f_{\mathrm{m}} f_{\mathrm{s}} \tag{1}$$

where F_{gs} = the lateral load capacity of an individual pile in the pile group under global scour, F_1 = the lateral load capacity of a single pile without scour, f_{m} = the p-multiplier for the group effect due to stress overlapping in pile-soil-pile interaction, and f_{s} = the group reduction factor due to global sour.

Mostafa [26] used the software program GROUP V.7.0 to generate the lateral load-head displacement curves for laterally-loaded single piles and group piles in a side-by-side arrangement or a tandem arrangement with and without global scour and investigated the effects of scour depth, pile spacing, pile arrangement, and pile slenderness ratio. As expected, an increase in the scour depth and/or a decrease of the pile spacing reduced the lateral load capacity of the pile group. Mostafa [26] also showed that pile groups in the side-by-side arrangement had larger displacements and bending moments as compared with single piles and pile groups in a tandem arrangement due to the combined effect of scour depth and pile-soil-pile interaction and scour had more effect on the lateral group load capacity and displacement than the pile-soil-pile interaction. Furthermore, Mostafa [26] concluded that shorter piles are more vulnerable to global scour and the effect of the pile slenderness on the reduction in the lateral pile group capacity became insignificant after the pile slenderness ratio was greater than approximately 12.5.

Effect of Group Local Scour. Lin and Lin [21] extended their approach developed by Lin and Lin [20] for single piles in sand under pile local scour to analyze laterally-loaded pile groups in sand with group local scour. In this extended method, they estimated the reduced vertical stress for the central pile using the Boussinesq solution for the condition after scour and then converted the reduced vertical stress into an equivalent depth, which is used for the *p*-*y* curve analysis. This method adopted the procedure recommended by Sheppard and Renna [29] to estimate the equivalent or effective diameter of a pile group based on the direction of water flow relative to the orientation of a pile. Lin and Lin [21] made two important assumptions: (1) the p-multiplier (f_m) for each pile is unchanged by scour and (2) the bottom scour width around the pile group is zero. The first assumption was verified by numerical results. Their results showed that treating the group local scour as a global scour by removing the whole scoured soil resulted in lower lateral group load capacities, indicating the benefit of considering the geometry of a group local scour hole in practice. However, limited studies have been conducted so far considering the geometry of the group local scour hole for pile groups, clearly, future research is needed to develop more general solutions for evaluating the behavior of laterally-loaded pile groups in sands and clays.

3 Lateral Behavior of Pile-Supported Bridges Under Scoured Conditions

3.1 Overview

The above sections discusses the behavior of laterally-loaded single piles and pile groups in sands or clays under scoured conditions. In actual applications, single piles and/or pile groups are only foundations to support bridges. The behavior of pile foundations may affect the behavior of pile-supported bridges. However, interactions among pile foundations, bridge structures, and abutments contribute to the performance of pile-supported bridges. As discussed earlier, global scour and local scour affect the behavior of laterally-loaded single piles and pile groups in sands and clays under scoured conditions. It is expected that they should affect the lateral behavior of pile-supported bridges under scoured conditions.

3.2 Integrated Analysis for Pile-Supported Bridges Under Scoured Conditions

To evaluate the influence of laterally-loaded piles or pile groups under scoured conditions on the performance of pile-supported bridges, integrated analysis of interactions among pile foundations, bridge structures, and abutments is necessary. Lin [11] and Lin et al. [16] developed a structural analysis model for a pile-supported bridge under a scoured condition as shown in Fig. 12. In this model, a structural software was used to model the bridge girders, abutment supports, piers, pile caps, and group piles with soil supports as springs. These springs were placed at different depths of each pile and had non-linear (i.e., multilinear) reaction-displacement behavior as described by a *p-y* curve. The scour around each pile was modeled by removing springs according to the scour depth. The *p-y* curve for each remaining spring was

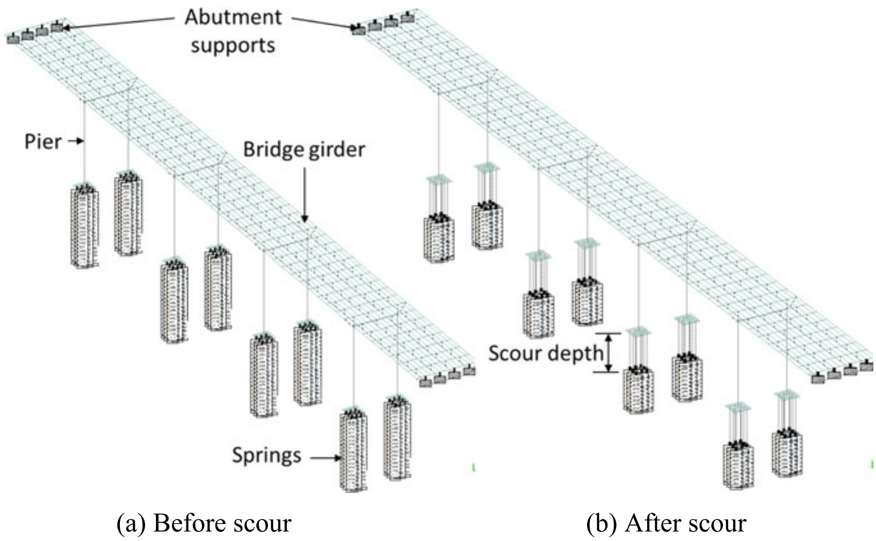


Fig. 12 Integrated analysis model for a pile-supported bridge under a scoured condition (modified from Lin [11])

determined by a calculation module developed by Lin [11] to account for the scour effect. Lin et al. [16] considered global scour but ignored the stress history effect while Lin [11] considered both the global scour and the stress history effect. The analyses in both studies considered vertical loads (dead and live loads), water loads, wind loads, and debris loads. Both analyses showed that an increase of the scour depth significantly increased the upstream and downstream pile group deflections but slightly increased the abutment deflections. At the same time, the increase of the scour depth significantly increased the shear forces at the abutments but slightly increased the shear forces at the pile caps. Lin [11] showed that the stress history change of the remaining soil had less effect on the behavior of the pile groups under the bridge than that without a bridge. This is because the girders and the abutments restrained the pile group movement in the bridge system. Lin et al. [16] also showed that the increase of the scour depth reduced the buckling load of the individual pile in the pile group and the reduction was the most for the upstream pile, followed by the middle and downstream pile due to the water loads, the wind loads, and the debris loads applied from the upstream to the downstream.

4 Conclusions

This paper reviewed the recent studies on the behavior of laterally-loaded piles under scoured conditions at bridges. The effects of global scour and local scour on the behavior of laterally-loaded single piles and pile groups were examined. Removal of soil by scour changes the stress history of the remaining soil, which increases the strengths of the remaining sand but reduces the strength of the remaining clay. The geometry and dimensions of a local scour hole affect the lateral load capacity of a single pile or a pile group. The scour depth has more influence on the behavior of laterally-loaded piles than the scour-hole width and slope angle. The scour-hole effect can be evaluated by a reduced equivalent soil depth based on the reduced wedge lateral resistance or the reduced vertical stress, which is used to modify the p-y curve of the pile in the soil under a scoured condition. Individual piles in a pile group under a scoured condition have double group effects due to overlapped stresses (pile-soil-pile interaction) and increased scour depths so that the group lateral load capacity is more significantly reduced. Scour also reduces the buckling load of piles in soils. The effect of scour on the performance of pile-supported bridges should be evaluated by an integrated analysis that considers hydraulic, geotechnical, and hydraulic aspects. The scour effect in the integrated analysis can be considered by removing soil springs around piles based on the scour depth and adjusting the spring stiffness in terms of the modified p-y curve accounting for the stress history change and the scour-hole dimensions. Further research is needed to better evaluate the behavior of laterally-loaded pile groups under group local scour and pile local scour.

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