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Research Paper

Effects of scour-hole dimensions and soil stress history on the behavior of laterally loaded piles in soft clay under scour conditions

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ABSTRACT

Bridge pile foundations in the midst of water current are often subjected to scour, which induces the loss of soil support around the piles and thus results in a significant decrease of foundation capacities or even the failure of bridges. In the current practice, when the scour-affected behavior of the pile foundations is analyzed, either the whole scour-hole geometry or the possible changes in the stress history of the remaining soils is often ignored. In reality, however, scouring creates scour holes with certain dimensions around the pile foundations and the remaining soils that are not scoured away undergo an unloading process at the same time, which will increase the over-consolidation ratios of the remaining soils and accordingly changes of their mechanical properties. This paper examines the behavior of laterally loaded piles in soft clay under scour conditions by using the *p-y* method. The conventional *p-y* curves have been modified appropriately to reasonably reflect the effects of three-dimensional scour-hole geometry as well as the stress history of the soils, with the aid of integration of Mindlin's fundamental solutions. A field test is used to serve as a reference case and to investigate the effects of stress history, scour depth, scour width, and scour-hole slope angle on the responses of laterally loaded piles in soft clay. The results indicate that neglecting the stress history effect can be unconservative for scour-affected pile foundations in soft clay, whereas neglect of the scour-hole dimensions and geometry would lead to over-conservative predictions/design of the laterally loaded piles under scour condition.

1. Introduction

Scour is a natural phenomenon caused by erosion or removal of streambed or bank material from bridge pile foundations due to flowing water, which can thus result in a reduced capacity of the pile foundations in either lateral or vertical direction. It is well known that scour is a major cause of the bridge failures [4], producing significant financial losses and threats to public safety [21,22,8]. Therefore, it is of great importance and demand to have rational analysis methods for evaluating the scour susceptibility of bridge pile foundations.

In contrast to the extensive research on the evaluation of the scour behavior, only limited number of studies have been conducted to investigate the scour effects on the responses of pile foundations and their supporting bridges. Daniels et al. [5] investigated the pushover failure of pile bent bridges under extreme flood/scour conditions. Bennett et al. [3] evaluated the behavior of a laterally loaded bridge pile group under a scour condition using the equivalent group pile method. Lin et al. [11], Lin et al. [12] examined the scour effect on the behavior of laterally loaded piles considering the stress history of sands and soft clay, respectively. Li et al. [9] conducted a parametric study using the three-dimensional finite-difference software (*FLAC3D*) to investigate the effects of scour depth, scour width, and slope angle on the behavior of laterally loaded piles in marine clay. Liang et al. [10] presented an analytical model with modified lateral subgrade modulus to investigate the extreme scour effect on the buckling of bridge piles in soft clay considering the stress history of the remaining soils. By using the wedge failure model and accordingly the modifications of the widely used *p-y* curves for piles, Lin et al. [13], Lin et al. [14] developed a simplified method to analyze the effects of scour-hole dimensions on laterally loaded piles in both sand and soft clay.

The above-mentioned literatures have been largely limited to ignoring either the effect of scour-hole geometry, or that of the stress history. In reality, however, for the isolated pile foundations

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in the midst of water current, scour holes formed around the piles usually involve certain shapes and sizes and meanwhile, the remaining soils have undergone an unloading process associated with new stress states. The latter of unloading produces the changes of stress history of the remaining soils and hence their resistances provided to the pile foundations as well. Note that the soil stress history can be characterized by the over-consolidation ratio (OCR), which is generally defined as the ratio of the historically maximum stress the soil has experienced to its current stress.

The objective of this paper is to present a simplified method for the analysis of laterally loaded piles in soft clay under scour conditions, which can account properly for the effects of three-dimensional scour-hole dimensions and the soil stress history simultaneously. In the proposed model, the stress changes of the remaining soils at the corresponding pile location due to the three-dimensional scour-hole formation are first determined based on the Mindlin's elastic solutions. Then, the calculated new soil stresses are adopted to re-examine the undrained shear strength and other properties of the remaining soils undergoing a stress history due to scour. With these key soil parameters obtained, the widely used *p-y* curves proposed by Matlock [15] are further modified to reasonably reflect the effects of three-dimensional scour-hole geometry as well as of the stress history of the soils. A field test reported in Matlock [15] is subsequently used as a case-study example to analyze the scour-affected behavior of laterally loaded piles in soft clay. Finally, the effects of stress history, scour depth, scour width, and scour-hole slope angle on the laterally loaded piles are discussed based on the computed results from the simplified method.

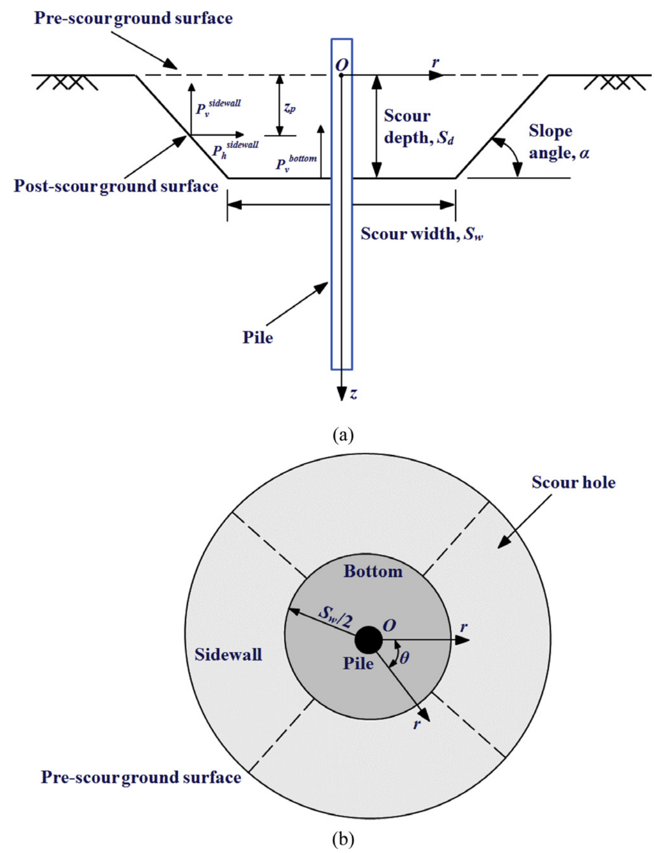

Fig. 1. Soil and pile profile for studies under scour conditions: (a) front view and; (b) plan view.

2. Analysis method

2.1. Definition of the problem

The pile is assumed to be embedded in a normally consolidated homogenous soft clay before the scour event, which has an effective unit weight of γ', Poisson's ratio of v, and effective internal friction angle of φ'. Furthermore, the scour hole, which is modeled as a truncated circular cone with the dimensions defined by the scour depth, the scour width and the scour-hole slope angle, is assumed to be formed symmetrically around the pile as shown in Fig. 1. In this figure, the center of the scour hole at the ground surface is set to be the origin of the axisymmetrical cylindrical coordinate system (r,θ,z). S_d is the scour depth at the pile, i.e., the distance between the pre-scour and post-scour ground surface; scour width, S_w, refers to the bottom width of the scour hole throughout this study for simplicity, which is measured from one edge of the scour hole to the other; the slope formed inside the scour hole is represented by the scour-hole slope angle, α. It should be noted that the scour shapes and dimensions are assumed to be known in this study for the demonstration purposes, although their determinations were focused in other research [4,21,18,1].

2.2. Calculation for the scour-induced stress changes of soils

Consider the scour-hole geometry and its symmetry as shown in Fig. 1. The circular uniform loads P_v^{bottom}, which can be calculated by $\gamma' S_d$, are acted vertically on the scour-hole bottom before the scour is underway. Simultaneously, based on Mohr's stress circle, the triangle distributed loads $P_n^{sidewall}$ that are acted normal to the surrounding sidewalls of the scour hole can be expressed as

$$P_n^{sidewall} = \frac{(1+K_0)}{2}\gamma' z_p + \frac{(1-K_0)}{2}\gamma' z_p \cos 2\alpha \tag{1}$$

Similarly, the triangle distributed loads $P_p^{sidewall}$ that are acted parallel to the surrounding sidewalls of the scour hole can be written as

$$P_p^{sidewall} = \frac{(1-K_0)}{2}\gamma' z_p \sin 2\alpha \tag{2}$$

In Eqs. (1) and (2), z_p is the depth coordinate of loading action point (ranging from 0 to S_d) and K_0 refers to the earth pressure coefficient at rest. In the absence of test data, the empirical formula [16] can be used, as shown in Eq. (3)

$$K_0 = (1-\sin\varphi')\mathrm{OCR}^{\sin\varphi'} \tag{3}$$

where OCR denotes the over-consolidation ratio and particularly, for the normally consolidated homogenous soft clay before scour, the earth pressure coefficient at rest is thus given by

$$K_0 = 1-\sin\varphi' \tag{4}$$

When the scour hole is formed, equivalent values of P_v^{bottom}, $P_n^{sidewall}$ and $P_p^{sidewall}$, which have been changed into opposite direction, are applied to the bottom and surrounding sidewalls to simulate the scour-induced unloading effects. Then, Mindlin [17] Green's function for vertical and horizontal loads in a semi-infinite half-space can be thus used to calculate the scour-induced soil unloading stress. To facilitate the use of the Green's function, the triangle distributed loads $P_n^{sidewall}$ and $P_p^{sidewall}$ need to be rewritten as the corresponding triangle distributed vertical loads $P_v^{sidewall}$ and horizontal loads $P_h^{sidewall}$, which are also acted reversely on the surrounding sidewalls of the scour hole to simulate the unloading effects. Hence