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Influence of flood-induced scour on dynamic impedances of pile groups considering the stress history of undrained soft clay

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ABSTRACT

Flood-induced scour causes loss of lateral support at bridge foundations and thus modifies their dynamic impedances, which will in turn influence the dynamic behavior and the seismic response of bridges located in seismically active flood-prone regions. When evaluating the seismic performance of scoured bridges, however, few efforts have been made to analyze the dynamic impedances of their foundations, and possible changes in stress history of the remaining soils are also ignored. In reality, the remaining soils around pile foundations undergo an unloading process due to scour and their over-consolidation ratios are increased, which can be expected to change the properties of the remaining soils. Therefore, a three-dimensional numerical model, in which the pile-soil-pile interaction and the radiation problem are accounted for by means of the elastodynamic Green's functions that permit the mutual interactions between all the piles of the group consistently and simultaneously, is employed in this paper to investigate the influence of flood-induced scour on the dynamic impedances of pile groups in soft clay. Accordingly, the key soil parameter of the elastodynamic Green's functions, i.e., Young's modulus of soft clay, is modified in this model to take into account the stress history effect due to scour. A case study to evaluate the dynamic impedances of 3×3 and 4×4 pile groups with various scour depths and pile spacing, considering or ignoring stress history effect, is discussed in this paper. The results show that ignoring the effect of stress history of the remaining soft clay will overestimate the scour affected dynamic impedances of pile groups, which are found to be reduced significantly as the scour depth increases.

1. Introduction

Flood-induced erosion of soil around bridge foundation, commonly defined as scour, causes loss of lateral support at the bridge foundation, and thus results in a degradation of the foundation capacity or even failure of the bridge [44,48,7]. In addition, the scoured bridge in flood-prone regions may be further subjected to other hazards, including earthquakes [43,45,46]. For example, an earthquake of magnitude 4.5 struck the state of Washington on 30 January 2009, which occurred within three weeks after the occurrence of a major flood event (caused by the Pacific Northwest storm) in the same region [5]. Intuitively, the exposure of the bridge foundation due to scour and thus the degraded conditions can also influence the seismic performance of bridges and lead to possible structural collapse during earthquakes.

Although a great number of studies have focused on the response of pile foundations and their supported bridges given scour conditions alone [11,22–31,6], relatively limited research, including the experimental tests and numerical modeling methods, has been performed so far to investigate the dynamic behavior and seismic response of scoured bridge with pile/caisson foundation. For instance, based on in-situ tests, Chang et al. [8] studied experimentally the seismic performance of a bridge with caisson foundation before its demolition due to accumulated scouring problem. Then, Wang et al. [47] further investigated the seismic performance and soil-structure of a scoured bridge models with pile foundation by shaking table tests using a biaxial laminar shear box, and found that the seismic demand on scoured pile foundations may be underestimated and misinterpreted to a certain degree with consideration of soil-structure interaction (SSI).

Additionally, by means of a finite element model based on the OpenSees software, Wang et al. [46] performed the nonlinear dynamic analyses of the bridges subjected to earthquake loads and scour effects. Alipour et al. [2] developed a multi-hazard reliability-based framework to evaluate the structural response of RC bridges considering the scouring and earthquake effects, and calibrated the scour load-modification factors for the design of bridges located in high seismic areas. Based on different levels of flood events, Banerjee and Prasad [5] used a combined seismic and flood hazard model to evaluate the seismic risk of two reinforced concrete bridges located in a flood-prone region. Song

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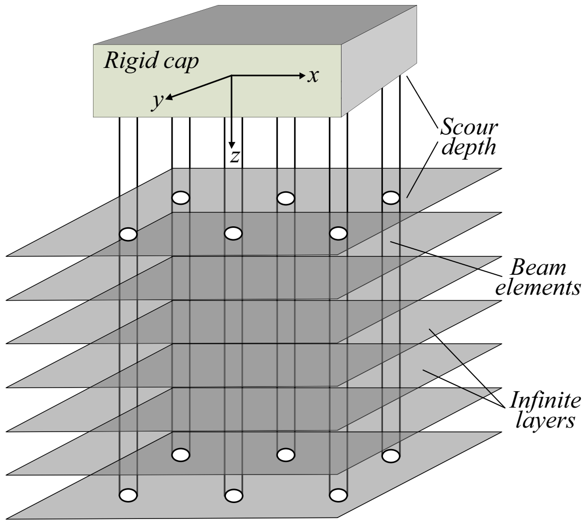

Fig. 1. Schematic model of the scoured pile groups embedded in the Winkler-type medium and connected by a rigid cap.

et al. [45] presented an analytical approach to assess the earthquake damage potential of bridges with foundation exposure and identify the critical scour depth that causes the seismic performance of a bridge to differ from the original design. Guo et al. [17] adopted time-dependent fragility analysis to investigate the seismic performance of box-girder concrete bridge systems under multiple seismic and scour hazards over their whole service life. As will be reviewed further subsequently, most of the existing numerical investigations ignored possible changes in the stress state and material properties of the remaining soils that are not scoured away. In reality, however, the remaining soils around a pile foundation after scour undergo an unloading process and their over-consolidation ratios (OCRs) are increased, which can be expected to change the stress history and thus the properties of soft clay [28].

Also, when both seismic attacks and flood-induced scour are considered in conjunction for the purpose of designing new bridge systems, another significant difficulty is that flood-induced scour leads to adverse impact on foundations by modifying their linear-elastic impedance [10,18]. In other words, if introducing the suitable impedances that can represent the dynamic characteristics of soil-foundation system under scour condition, the domain decomposition technique which considers the soil-foundation system and the superstructure on deformable restraints separately can be easily and efficiently used to study the seismic performance of scoured bridge with pile foundation. Although the beam model on Winkler soil was commonly used to evaluate the dynamic impedances of pile groups for design purposes because of its versatility in accounting for various complex conditions [14,16,33], however, all these methods did not involve the scour effect and were based on the use of dynamic interaction factors by considering two piles at a time: the loaded source pile and the unloaded receiver pile.

Hence, this paper presented a simplified numerical procedure to investigate the flood-induced scour effect on the dynamic impedances of bridge pile groups considering the stress history of undrained soft clay. The major contribution to this procedure included (1) the application of a numerical model for 3D kinematic interaction analysis of fully embedded pile groups [12] to further consider the exposure of the pile due to scour, in which the pile-soil-pile interaction and the radiation problem are accounted for in the frequency domain by using the elastodynamic Green's functions that permit the mutual interactions between all the piles of the group consistently and simultaneously without using the dynamic interaction factors and the stepped analysis; and (2) the modification of the key soil parameter for the elastodynamic Green's functions given in this model (Young's modulus of soft clay) to consider the stress history effect, whose procedures are similar to those presented by Lin et al. [28] for the analysis of laterally loaded piles in soft clay under scour conditions. With the simplified procedure, a case of 3×3 and 4×4 pile groups subjected to the combined hazards of flood-induced scour and earthquakes was studied, and all the components of the impedance matrix including the rocking-translation coupling were calculated with various pile spacing and scour depths. Furthermore, the calculated results considering and ignoring the stress history effect were also compared and discussed in this paper.

Table 1
Properties of soft clay.

Effective unit weight, γ' (kN/m^3)	Water content, w (%)	Effective friction angel, φ' (°)	Undrained shear strength, C_u (kPa)
10	44.5	20	32.3
Compression Index, C_c	Mass density, ρ_s (Mg/m^3)	Poisson's ratio, υ	Hysteretic damping ratio, ξ
0.4	2.0	0.4	0.05

Table 2
Calculated soil properties considering stress history effect (h =1d).

Soil depth from mud line before/after scour (m)	γ'_{sc} (kN/m^3)	c_u^{sc} (kPa)	E_s (MPa)	E_s^{sc} (MPa)	OCR
0.57/0.19	9.88	27.1	12.92	10.84	3.0
0.95/0.57	9.95	29.8	12.92	11.90	1.7
1.33/0.95	9.96	30.6	12.92	12.24	1.4
1.71/1.33	9.97	31.0	12.92	12.42	1.3
2.09/1.71	9.98	31.3	12.92	12.51	1.2
2.47/2.09	9.98	31.5	12.92	12.58	1.2
3.99/3.61	9.99	31.8	12.92	12.72	1.1
7.03/6.65	9.99	32.0	12.92	12.82	1.1
10.07/9.69	10.00	32.1	12.92	12.86	1.0
16.15/15.77	10.00	32.2	12.92	12.88	1.0

Table 3
Calculated soil properties considering stress history effect (h =2d).

Soil depth from mud line before/after scour (m)	γ'_{sc} (kN/m^3)	c_u^{sc} (kPa)	E_s (MPa)	E_s^{sc} (MPa)	OCR
0.95/0.19	9.83	25.0	12.92	10.02	5.1
1.33/0.57	9.91	28.2	12.92	11.28	2.4
1.71/0.95	9.94	29.4	12.92	11.75	1.8
2.09/1.33	9.95	30.1	12.92	12.02	1.6
2.47/1.71	9.96	30.4	12.92	12.17	1.5
3.99/3.23	9.98	31.2	12.92	12.50	1.2
7.03/6.27	9.99	31.7	12.92	12.69	1.1
10.07/9.31	9.99	31.9	12.92	12.76	1.1
16.15/15.39	10.00	32.1	12.92	12.84	1.0

2. Analysis procedure

A generic group of n scoured circular piles having length L and diameter d, connected at the heads by a rigid cap, is considered as shown in Fig. 1. The scour affected dynamic impedance of the pile group considered herein, which has not been sufficiently studied before, is analyzed in the frequency domain by means of the numerical procedure proposed by Dezi et al. [12]. Further, in the analysis procedure, to satisfy the scour conditions, soils around the pile