Scour effects on the dynamic lateral response of composite caisson-piles foundations considering stress history of sand

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ABSTRACT

Scour effect have a significant impact on the dynamic lateral response of composite caisson-piles foundations (CCPFs) because of the removal of soils around the foundation and the change of stress history of remaining soil. Based on the simplified method with the dynamic Winkler model, a computational method for predicting the dynamic impedance of CCPFs influenced by scour is developed. Subsequently, theoretical results for the response of CCPFs are verified by the 3D finite element method with sponge boundary. Finally, results from a case study show that scour has a great influence on the dynamic stiffness and damping coefficient, and the deeper scour depth increases, the more remarkable influence on the results. Besides the removal of soil around CCPFs resulting from scour effect, it also shows that the change of stress history will further weaken the bearing capacity of composite foundation and enlarge the dynamic response. Thus, ignoring the change of stress history would result in an overestimate of the dynamic impedance. And stress history is also proved to be of great significance to increase the resonant response of composite foundation, while has little influence on the resonant frequency.

Keywords: scour, Winkler model, dynamic impedance, stress history, composite caisson-piles foundation

1 INTRODUCTION

Most offshore and coastal structures are subjected to large lateral loads due to a range of sea or riverbed conditions and these may even cause scour. In the past 30 years, more than 1000 bridges have collapsed and approximately 60% of their failures were reported due to foundation scour (Kong et al. 2013). The main cause of damage due to scour effect lies in the removal of soil around bridge foundation due to cumulative scouring action, which makes the elevation of riverbed lower constantly and even decreases the bearing capacity. Extensive research has been done on predicting the scour effect, all these mainly concentrated on two aspects. Some researchers focus on the evaluation of lateral load capacities of foundations under scour conditions. Kishore et al. (2009) carried out laboratory tests to investigate the scour effect on the behavior of model piles. Bennett et al. (2009) evaluated the scour effect on the behavior of a laterally loaded bridge pile group using the equivalent pile group method. Lin et al. (2012) proposed an integrated analysis technique which primarily aimed at gagging water, soil and some others factors on the performance of existing bridges under a scoured condition. Other researchers concentrated on the scour depth analysis and scour pattern around foundations. Richardson (1993) and Briand et al. (1999) proposed methods to predict the scour depth around a bridge pier in cohesive and cohesionless soils, respectively. Ataie-Ashtiani and Beheshti (2006) carried out an experimental study on pile groups and derived a correction factor to predict the maximum local scour depth for the pile groups. Amini et al. (2012) conducted wave flume studies on pile embedded in sand bed and indicated that scour depth can be related to the soil characteristics, pile diameter, pile group arrangements and submergence ratio. There are also many researchers obtain good results by using the numerical method and statistic model (Olsen and Kjellesvig 1998; Lee et al. 2007; Akib et al. 2014) and provide a reference for real engineering application.

For a cross river or sea bridge engineering, pile groups and caisson are the most common forms of deepwater foundation. But it is difficult to construct due to the long length when using the traditional pile groups and lower aseismic behavior compared with pile group when using the caisson foundation. Then the CCPFs emerge which can overcome the disadvantages mentioned above. As a new foundation type proposed in the pre-construction investigation report for the highway channel across Qiongzhou straits in South China Sea, the CCPFs is highly expected to behave better than the traditional caisson foundation when...
subjected to lateral and seismic loads. As a typical deepwater foundation form, CCPFs mainly subjected to wind or wave load, all of which are dynamic loads. However, until now only a few studies have been carried out on the lateral load capacity of CCPFs, particularly on how to evaluate the effects of scour on the dynamic characteristics of bridge foundation. Zhong and Huang (2013, 2014) proposed a simplified approach for the lateral vibration and seismic response of CCPFs based on the dynamic Winkler model. Consequently, further investigation is needed to gain more understanding about the effect of scouring on the dynamic lateral response of CCPFs.

In this paper, the effect of scour on dynamic lateral response of CCPFs with considering stress history of surrounding soils is investigated based on the dynamic Winkler model. In order to verify the results of proposed method, 3D finite element analyses are conducted. Finally, to study dynamic impedance and resonant characteristics, a comparison was made between the calculated results considering scour effects and those without considering the change of stress history of the remaining soil through a practical engineering example.

2 SCOUR EFFECT ON THE DYNAMIC IMPEDANCE OF CCPFs

A dynamic Winkler model is proposed by simplifying the soil resistances with a series of springs (associated with dashpots) for the lateral response of CCPFs (Zhong and Huang 2013), as shown in Fig. 1. The lateral equilibrium equation of caisson foundation in layered soils can be expressed as:

\[ (-\omega^2 \mathbf{M}_b + \mathbf{K}_s) \begin{bmatrix} u_b \\ \theta \end{bmatrix} = \mathbf{P}_b \]  

(1)

where \( u_b \) and \( \theta \) are the horizontal displacement and the rotation angle of the base center of the caisson part, \( \mathbf{P}_b \) is the load vector, \( \mathbf{M}_b \) is the mass matrixes, and \( \mathbf{K}_s \) is the impedance matrixes of caisson given by

\[ \mathbf{K}_s = \begin{bmatrix} \tilde{K}_{HH} & \tilde{K}_{HM} \\ \tilde{K}_{MH} & \tilde{K}_{MM} \end{bmatrix} \]  

(2)

Each element of \( \mathbf{K}_s \) could be obtained as

\[ \tilde{K}_{HH} = \tilde{K}_s + \sum_{j=1}^{n} \tilde{k}_j d_j \]  

(3)

\[ \tilde{K}_{HM} = \tilde{K}_{MH} = \sum_{j=1}^{n} \tilde{k}_j d_j z_j \]  

(4)

\[ \tilde{K}_{MM} = \tilde{K}_s + \sum_{j=1}^{n} \left( \tilde{k}_j d_j \left( z_j^2 + \frac{1}{12} d_j^2 \right) + \tilde{k}_d j d_j \right) \]  

(5)

where \( \tilde{k}_j \) and \( \tilde{k}_d j \) are the complex stiffness of the distributed translational and rotational springs of layer \( j \)  

\( j \) varies from 1 to \( n \), \( \tilde{K}_s \) and \( \tilde{K}_d \) are the complex stiffness of the concentrated springs at the base.

Fig. 1 Dynamic Winkler model of CCPFs

Since CCPFs always partially embedded in complex ocean environment, the distance from the center of layer \( j \) to the soil surface is given by

\[ z_j = d - \sum_{i=0}^{j-1} d_i - \frac{d_j}{2} \]  

(6)

where \( z_j \) is the distance from the center of layer \( j \) to the soil surface. \( d \) represents the embedment depth of the caisson, \( d_1-d_n \) are the thickness of the soil layers along the caisson shaft.

Combining the pile-pile lateral, axial interaction and the displacement compatibility conditions, the axial-lateral coupled vibration can be expressed as

\[ \begin{bmatrix} \mathbf{O} & \mathbf{A}_{12} & \mathbf{A}_{13} & \mathbf{A}_{14} \\ \mathbf{A}_{21} & \mathbf{A}_{22} & \mathbf{A}_{23} & \mathbf{O} \\ \mathbf{A}_{31} & \mathbf{A}_{32} & \mathbf{A}_{33} & \mathbf{O} \\ \mathbf{A}_{41} & \mathbf{O} & \mathbf{O} & \mathbf{A}_{44} \end{bmatrix} \begin{bmatrix} \mathbf{u}^o \\ \mathbf{H} \\ \mathbf{M} \\ \mathbf{V} \end{bmatrix} = \begin{bmatrix} \mathbf{P}^c \end{bmatrix} \]  

(7)

The detailed expressions in the above equation can be found in Zhong and Huang (2013).

Since the CCPF is a composition of a caisson and a pile group, its impedance matrix can be obtained by adding the impedance matrixes of the caisson and the pile group together. The lateral equilibrium equation of CCPFs in layered soils can be expressed as

\[ \mathbf{K}_{HR} \begin{bmatrix} \mathbf{u}_h \\ \theta \end{bmatrix} = \mathbf{P}_b \]  

(8)

\[ \mathbf{K}_{HR} = \begin{bmatrix} \mathbf{K}_{HH} & \mathbf{K}_{HM} \\ \mathbf{K}_{MH} & \mathbf{K}_{MM} \end{bmatrix} = \mathbf{K} + i\omega\mathbf{C} \]  

(9)

where \( \mathbf{K}_{HR} \) is the impedance matrixes of CCPFs, \( \mathbf{K} \) and \( \mathbf{C} \) are the stiffness and damping matrixes of dynamic impedance respectively.

To sum up previous studies, when a scour-affected foundation is evaluated, the soil around the foundation is simply removed to account for the scour effects and discuss the scour pattern or scour depth influence on the
foundation. However, removal of surrounding soil changes the properties of remaining soil, including its stress history. The remaining soil may be altered from normally consolidated to over-consolidated state during the process of scour (Lin et al. 2010). Certainly, the removal of soil will further increase the flowing load and its act area on foundation, this paper will ignore this point and focus on the change of the properties of remaining soil. For simplify the analysis, assuming the scour pattern is plane distribution mode, namely the soil is simply removed layer by layer.

Before scour, the mean effective stress can be expressed as

$$\sigma'_m = (\sigma'_1 + 2\sigma'_3) / 3 = (1 + 2K_0)Y_0'h_0 / 3$$  \hspace{1cm} (10)$$

Due to the removal of surrounding soil, the mean effective stress after scour is computed as follows

$$\sigma'_m = (\sigma'_1 + 2\sigma'_3) / 3 = (1 + 2K_0)Y'_0'h'_0 / 3$$  \hspace{1cm} (11)$$

While the change of gravity of soil is limited, the change of embedded depth has only been considered. Then the over-consolidation ratio can be expressed as

$$OCR = Y'_0'h'_0 / Y_0'h_0 = h'_0 / h_0$$  \hspace{1cm} (12)$$

where $K_0$ is coefficient of lateral earth pressure at rest, $K_0 = (1 - \sin \phi)OCR_{nmp}$ for over-consolidated soil and $K_0 = 1$-mp for normally consolidated soil, $\phi$ is the internal friction angle of soil, $Y'_0$ and $Y_0'$ are the soil gravity before and after scour respectively, $h_0$ and $h'_0$ are the embedded depth before and after scour respectively.

In the meantime, it is also a process of unloading rebound with the change of void ratio.

$$\Delta e = e'_0 - e_0 = -C_s \log(\frac{\sigma'_m}{\sigma'_m})$$  \hspace{1cm} (13)$$

As for the dynamic Winkler model of CCPFs, all the distributed springs is closely related to the soil properties (e.g. density and shear modulus). Then by Eq.(15), the lateral vibration characteristic of CCPFs after scour can be obtained.

$$G_0 = 6908 \frac{(2.17 - e)^2}{1 + e}(\sigma'_0)^{0.5}$$  \hspace{1cm} (14)$$

After scour, it can be expressed as

$$G_0 = 6908 \frac{(2.17 - e)^2}{1 + e}((1 + 2K_0)Y'h / 3)^{0.5}$$  \hspace{1cm} (15)$$

3 COMPARISON AGAINST 3D FINITE ELEMENT SIMULATION

The case presented here is a CCPF fully embedded and subjected to horizontal harmonic load with the amplitude of 100kN. The diameter ($D$), the height ($h$) and the mass density of caisson are 10m, 12.5m, 2700kg/m$^3$ respectively. Beneath the caisson there is a 3×3 pile group, whose diameter, length, spacing, Poisson’s ratio and Young’s modulus of pile are 1m, 2.5m, 0.3 and 2.06 × 10$^5$MPa respectively. The void ratio, mass density, friction angle and Poisson’s ratio of soil are 0.65, 1600kg/m$^3$, 28° and 0.3 respectively. Assuming the scour depth is 0.4D, the elastic shear modulus can be calculated by Eq. (15) with a reduction factor 0.2. Corresponding results are shown in Table 1.

| Soil depth (m) | No scour G (MPa) | Scour depth=0.4D OCR | Scour depth=0.4D $\Delta e$ (×10$^{-3}$) G (MPa) |
|---------------|-----------------|---------------------|-----------------------------------------------|
| 2.5           | 7.06            | 1                   | 1                                             |
| 5             | 12.26           | 1                   | /                                             |
| 7.5           | 15.80           | 5                   | 9.8                                          | 8.60 |
| 12.5          | 19.98           | 2                   | 4.4                                          | 15.22|
| 17.5          | 24.47           | 1.5                 | 2.6                                          | 20.83|
| 27.5          | 29.97           | 1.29                | 1.6                                          | 27.10|
| 37.5          | 36.01           | 1.18                | 1.1                                          | 33.68|

Table 1 indicates that the effect of scour has a limited depth, and the properties of soil below the critical depth will be the same as the original state. The finite element mesh used for the analysis is shown in Fig. 2 where the soft gray elements enveloping the soil elements are the sponge boundary elements for attenuating the wave reflection (Shin 1995; Varun et al. 2009).

Horizontal displacements and rotation angles atop the CCPFs as functions of the dimensionless frequency are shown in Fig. 3 and Fig. 4, where the dimensionless frequency is given as $\omega = \omega B / (2V_s)$, where $\omega$ is the circular frequency, $V_s$ is the shear wave velocity of the soil and $B$ is the caisson diameter.

These comparisons show that the theoretical method agrees well with the numerical method, ensuring the
reliability of the proposed method.

4 A CASE STUDY

In order to study the scour effect on the dynamic impedance and resonant characteristics of CCPFs, a practical engineering example under a lateral harmonic load is computed by the proposed method. The diameter and the embedment depth \((D)\) of the caisson are 90m and 40m. And the mass density of caisson is \(7850\text{kg/m}^3\). The thickness of top, bottom and side walls of caisson is 0.3m. Eight steel-pipe piles are located beneath the caisson. The diameter and length of each pile is 4m and 90m, and the wall thickness is 15cm. The Young’s modulus and Poisson’s ratio of pile are 206GPa and 0.25. The void ratio, mass density and friction angle and Poisson’s ratio of soil are 0.78, \(1500\text{kg/m}^3\), 30° and 0.3 respectively. Three different scour depths \((0, 0.25D\) and \(0.5D)\) are studied.

4.1 Scour effect on the dynamic impedance

Stiffness and damping of dynamic impedance as function of the dimensionless frequency considering...
stress history of soil after scour are shown in Fig. 5 and Fig. 6. Fig. 7 and Fig. 8 give the dynamic impedance considering stress history or not when the scour depth equals 0.5D. Results indicate that: (1) scour depth has a significant influence on the horizontal and rocking dynamic impedance, and the reduction of the impedance shows a non-linear increasing trend with the increasing scour depth; (2) not only the loss of soil supporting around the foundation will decrease the dynamic impedance of foundation, but also the change of stress history of remaining soils will further weaken the bearing capacity and enlarge the dynamic response.

4.2 Scour effect on the resonant response

Besides the dynamic impedance, the resonant response of foundation is also one of the main concerns of dynamic properties for engineers. Horizontal displacements and rotation angles (top center) of the CCPFs are shown in Fig. 9, in which the results are calculated by considering the stress history or not under different scour depth. It implies a non-linear increase of the displacements with the scour depth increased. Fig.10 further indicates that considering the effect of stress history of remaining soil results in increasing displacement magnitude, however, it has little influence on the value of resonant frequency.

5 CONCLUSIONS

In this paper, the computational method for predicting the dynamic impedance of CCPFs influenced the scour effect on the dynamic impedance of CCPFs and resonant characteristics has been analyzed. We can reach conclusions from this study as follows:

Scour depth has a significantly influence on the horizontal and rocking impedances, and the reduction of impedance shows a non-linear increasing trend with the scour depth increased; The loss of soil support around the foundation and the change of stress history of remaining soils are the basic reasons why the scour
depth leads to a decrease of the dynamic impedance of foundation, and the change of remaining soil properties will further weaken the bearing capacity and enlarge the dynamic response; Ignoring the change of stress history may result in an underestimate on the displacement amplitude, and the increase of scour depth is proved to be of great significance to increase resonant response of foundation, however, it has little influence on the value of resonant frequency.

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Fig.10 Lateral dynamic response of CCPFs (scour depth=0.5D): (a) horizontal displacement; (b) rocking angle