Interaction of Laterally Loaded Free Head Barrette Pile in Elastic Soils

Yasar Taner and Gurkan Ozden

Abstract Barrette piles are usually preferred over circular piles where larger bearing capacity, stiffness, and structural capacity are needed. Currently, design work with such piles is usually made assuming an equivalent circular pile diameter. Previous research did not cover pile-soil-pile interaction among piles with rectangular sections. In this study, the soil is assumed as elastic and the three-dimensional nature of the problem necessitated the establishment of 3D numerical analysis models. Piles are modeled as volume elements so that shape effects are properly studied. In this respect, the effects of cross-section and orientation of piles, spacing between piles, stiffness of the soil, and the magnitude of the loading were investigated on the behavior of group barrette piles. Considering these effects, interaction factors were calculated for different pile orientations in a group. Since barrette piles have rectangular cross-sections, the most important factor in their interaction with each other is the resistance of pile on the direction along which the load is acting on the pile. Circular and barrette group piles have been analyzed under horizontal loads. Analyses results showed that unlike circular piles, which have an equal moment of inertia in all directions the barrette piles were highly affected by loading direction and their orientation inside the group. This study emphasized that it is critical to determine the disposition of the piles considering the loading direction if less interaction among piles is desired.

Keywords Interaction factor · Barrette pile · Elastic soil · Pile orientation · Pile-soil-interaction interaction

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1 Introduction

Foundations that transfer structural loads to deeper soil layers are rarely designed with single piles. The interaction between a single pile and surrounding soil is relatively simpler than pile groups since complex interaction patterns exist among the piles and the soil inside a group.

Pile-soil-pile interaction has long been studied since the late sixties and early seventies. The pioneering work is attributed to H. G. Poulos, who studied interaction among group piles under vertical and lateral loads [5−7]. Following Poulos, contributions to the field were also made [1, 3, 8]. Kaynia and Kausel [2] extended Poulos' approach to dynamic loading conditions.

Previous research did not fully cover pile-soil-pile interaction among piles with rectangular sections. Currently, design work with such piles is usually made assuming an equivalent circular pile diameter. In this study, findings of finite element-based research are presented regarding the influence of loading direction, pile spacing, and the position of a pile in the group on pile-soil-pile interaction. The three-dimensional nature of the problem necessitated establishment of 3D numerical analysis models. Piles are modeled as volume elements to study shape effects appropriately.

2 3D Numerical Analyses

Pile groups consisting of 3×3 piles with rectangular cross-sections are subjected to finite element modeling in this study. The finite element model comprises three-dimensional 10-noded wedge elements to discretize the volume piles and the soil profile. The aspect ratio of the pile cross-section is set as L/B = 3.5, where L and B stand for length and width of the pile section, respectively. This assumption is based on the fact that barrette piles are usually constructed with L = 280 cm and B = 80 cm sectional dimensions. Only very deep super piles attain plan width that is B $\geq$ 100 cm.

In numerical analysis, two-layer profile is considered for barrette piles where stiffness of the upper layer was one half of that of the bottom layer. The thickness of the upper layer (h_1) is 10 m and the total thickness of the soil profile (h) is 40 m. Both soils are assumed to exhibit linear behavior under pile head lateral loading. The elastic soil parameters assigned to the soil layers of the model is shown in Table. 1.

The auto-meshing algorithm of the FE analysis software [4] is utilized while establishing the 3D-FEM model. The pile length to diameter ratio is kept equal to $L_{pile}/B = 25$ throughout the analyses. A 3D view of the model with solid piles is

Table 1 Elastic model parameters

E (kN/m^2)	γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)	N
30,000	17.0	19.8	0.3/0.5
60,000	19.0	20.6	0.3/0.5
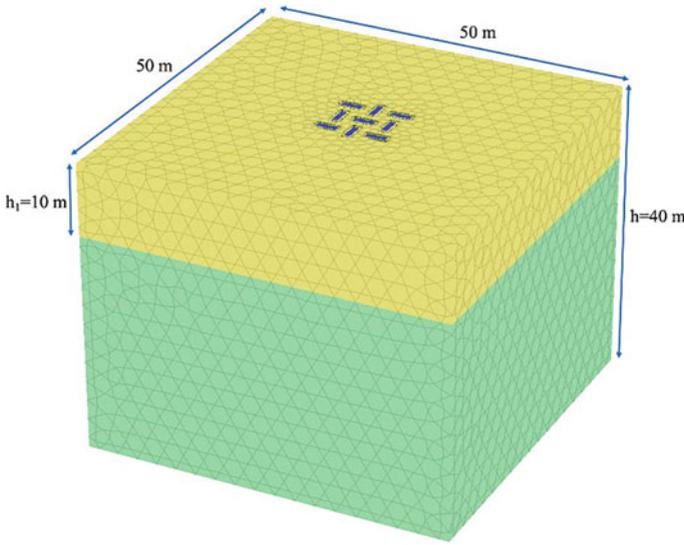
Fig. 1 FEM mesh for 3 × 3 barrette pile group (10-noded 31,028 elements)

shown in Fig. 1. It can be seen in this figure that the piles are positioned orthogonal to each other in the model.

The edge-to-edge orthogonal distance, s, between any two consecutive piles changes in direct proportion to the plan width of the pile (i.e. s = 2B−8B). Each pile is horizontally loaded at the head in both x and y directions.

Poulos' theory is based on some assumptions. First of all, the pile is assumed to be a thin rectangular vertical strip of width d, length L with a constant flexibility E_pI_p. It is also assumed that the pile and soil are fully compatible, ignoring the relative motion of the pile and soil. The soil is assumed to be elastic. The side shear, which is expected to be quite influential on lateral pile response for rectangular cross-sections, is not accounted for in Poulos' solution. Interaction factor is defined according to Poulos as in Eq. (1):

$$\alpha = \frac{Additional\ displacement\ caused\ by\ adjacent\ pile}{Displacement\ of\ pile\ under\ its\ own\ load} \tag{1}$$

The source pile was loaded by means of a distributed lateral load at the pile head with a magnitude of 100 kPa for an 80 × 280 barrette pile. Interaction factors are determined depending on pile orientation for rectangular cross-sections since loading the piles along their strong or weak axis would generate different effects on adjacent piles (Case-1 and 2). In Case-1 and 2, the source piles interact with each neighboring pile, and the amount of interaction varies depending on the position of each receiver pile, as shown in Fig. 2. The source and receiver piles in similar positions with respect to the loading direction are linked to the source pile with the same color.
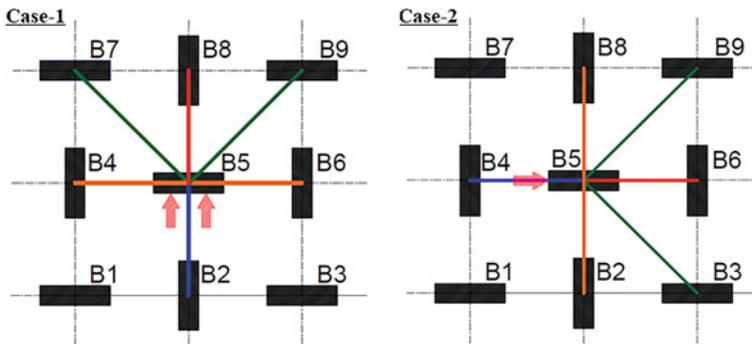
Fig. 2 Case-1 (loading along weak pile axis), and Case-2 (loading along strong pile axis)

Analyses revealed that the location and orientation of the receiver pile with respect to the source played an essential role on the lateral interaction factors. It was found that whether the strong axis of the receiver pile was parallel or perpendicular to the loading direction made the largest difference in pile response. While investigating the influence of pile position, it was noticed that the piles behind and in front of the receiver yielded same interaction factors irrespective of the pile spacing. Similar response existed for other pile pairs (i.e. B4 & B6; B7 & B9). This behavior may be attributed to the elastic nature of the soil medium and full bonding assumed between the soil and the pile.

Poisson's ratio affected pile response, albeit minor, causing larger lateral deformations resulting in larger interaction factors at the edge piles of the group. Interaction factors are plotted as a function of pile spacing and Poisson's ratio in Figs. 3 and 4 for Case-1 and 2, respectively. Figures 3 and 4 show that the piles are clustered as leading-trailing and side piles with respect to the central one (B5) on which the load is applied. It may be concluded upon elastic analyses that the orientation of the source pile or the piles positioned around the source is the dominant factor. For instance, if the source pile is loaded along its strong axis, its displacement decreases as compared with other direction resulting in higher interaction factors as shown in Fig. 4. This is also true for the receiver piles indicating that the bending stiffness governs pile response.

The interaction factors computed for 3×3 circular and barrette pile groups are compared in Figs. 5 and 6. It should be mentioned that the edge-to-edge spacing between two piles in a group is the same for both cases. It has been stated above that the interaction between the barrette piles varies according to the position of the pile just in front of the loaded pile. The authors found that in the analyses made with circular piles that have a sectional area equivalent to those of the barrettes, loading direction did not affect the interaction between the circular piles since they have the same inertia in all directions. It is clear from Figs. 5 and 6 that Case-1, in which the receiver pile was loaded along the weak axis, yielded lower interaction factors.
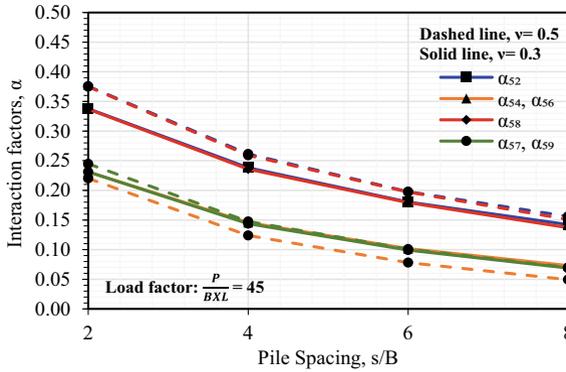
Fig. 3 Interaction factors between source pile B5 and receiver piles with different Poisson ratio in Case-1
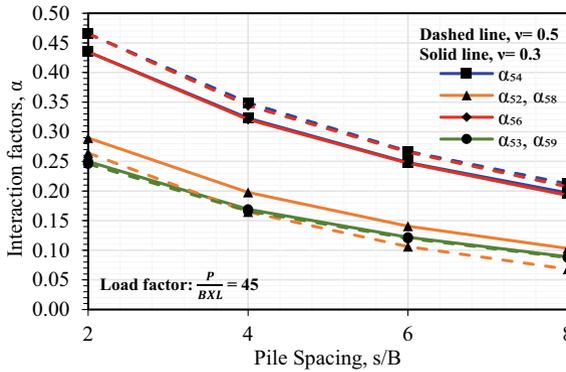
Fig. 4 Interaction factors between source pile B5 and receiver piles with different Poisson ratio in Case-2

The authors believe that the receiver pile exhibited larger displacement causing lower computed factors according to Eq. (1). In Case-2, however, the source pile has larger stiffness in the loading direction experiencing smaller displacement leading to higher interaction factors. Another aspect of barrette and circular pile group comparison is that the flexibility matrix is no longer symmetric for barrette piles whereas it is the opposite for circular piles. It may be concluded that what matters in elastic three-dimensional pile group analyses is the relative stiffness between the source and receiver piles.
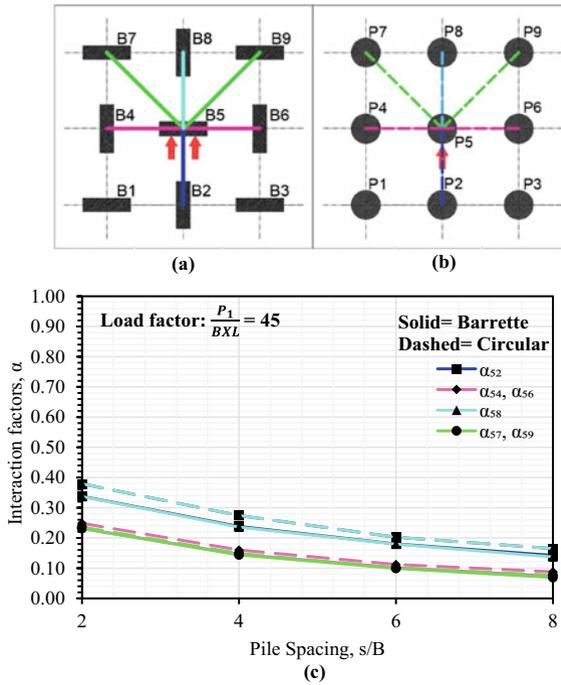
Fig. 5 **a** y-direction loading of barrette pile group, **b** y-direction loading of circular pile group, **c** Comparison of interaction factors for circular and barrette piles in y-direction loading

3 Conclusions

In this study, the pile-soil-pile interaction aspects of horizontally loaded barrette piles were studied based on numerical analysis models. While establishing the models, orientation and spacing of the piles in a group were set as basic variables. A 3 × 3 pile group was considered as the smallest possible unit cell in which orthogonal pile pairs are represented. among the pile head loading. Double layer soil profile was studied, and analyses were conducted assuming linear soil response. Besides, the piles were set as free head in a group. Following are the achieved results and recommendations for further studies.

Since barrette piles have rectangular cross-sections, the most critical factor in their interaction is the pile's potential in resisting the induced displacement along the loading direction. This potential is found to be strongly related with the pile's bending stiffness. Considering that the interaction factor between any two piles is defined as the ratio of the displacement of the receiver pile to that of the source pile (i.e. the head loaded pile), the pile that resists the loading with its stronger axis greatly affects the value of the interaction factor. This influence is prominent for cases where the receiver pile resists the loading with its stronger axis. Therefore, it can be said that
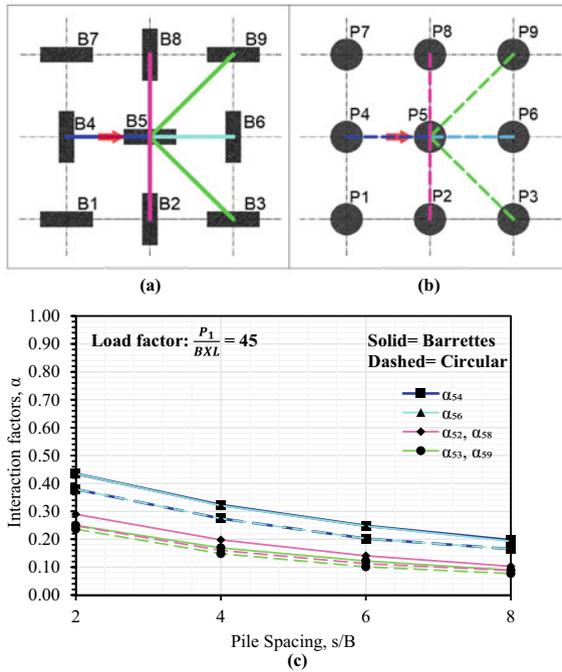
Fig. 6 **a** x-direction loading of barrette pile group, **b** x-direction loading of circular pile group, **c** Comparison of inaction factors for circular and barrette pilesin x-direction loading

piles' orientation in a group is one of the critical factors for pile-soil-pile interaction. Comparing the response of the circular and barrette piles, it can be stated that groups with rectangular pile sections behave quite differently than circular piles. First of all, the stiffness matrix becomes asymmetric due to pile orientation. Circular piles in a group, on the other hand, yield always symmetric stiffness matrix for elastic soil conditions.

In addition to strong influence of the loading direction, it is believed that findings of elastic finite element analyses shed lights on further non-symmetric pile response in a group when soil nonlinearity is also accounted for. Consideration of nonlinear soil response is expected to be quite essential on determining lateral load–deflection curves (i.e. p-y curves) along the strong and weak axes of the barrette pile. The authors believe that pile head fixity will affect the pile group response and load share, and this effect will be better observed in nonlinear soil.

Sectional dimensions of the barrette piles are fixed at L/B = 3.5 in the research. L/B ratios other than 3.5 shall also be studied in future research to gain more insight on the influence of pile flexibility on pile-soil-pile interaction.

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