

3D numerical analysis of passive pile groups adjacent to deep braced excavation in soft clay

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Abstract - This paper analyzes responses of pile groups adjacent to deep braced excavation in soft marine clay by 3D finite element method, based on field instrumented case history. Pile groups comprising of 2×1, 4×1, 8×1 and 8×2 piles with center-to-center spacing of 2d and 3d, respectively, were numerically investigated. The group factor in terms of the maximum pile bending moment is carried out to examine the effects of pile diameter, pile spacing, and pile number on the group effects. The group factor for the center piles and edge piles, as well as the front piles and rear piles in a two-row pile group, are compared. Conclusions arrived at in this study can provide design guidelines for deep braced excavations with adjacent foundation piles considering the pile-soil interaction and pile group effect.

Keywords: Finite element analysis, Braced excavation, Pile group factors, Soft clay, Soil-pile interaction.

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1. Introduction

Deep braced excavations may lead to surrounding soil movement and introduce passive loading onto the nearby piles, which poses a significant threat to the

serviceability of the pile group or even causes failure. Plenty of research have been conducted via the in-situ test, centrifuge model test, and numerical methods to investigate the pile responses induced by adjacent excavations and tunnelling operations [1-11, 27-29].

In practice, piles are closely spaced in a group manner when used for ground reinforcement; the existence or installation of piles nearby can affect the subsequent behaviour of each pile. [12] have recognized that the piles within a group may have a smaller bearing capacity compared with the single, isolated piles due to the pile-soil-pile interaction effects. However, due to the lack of a systematic and distinct quantitative understanding of pile group interaction effects, the solution proposed for a single pile is commonly used in engineering practice, even for pile groups [13]. Therefore, it is essential to get a better understanding of complex pile-soil-pile interaction within the pile group subjected to lateral soil movement induced by adjacent deep excavation.

During construction, there are some circumstances under which the foundation bored piles are installed and left aside with free head and no axial loading[15]. When encountering the simultaneous construction of the adjacent braced excavation, it concerns the usability of the bored piles in the future. Researchers such as [16-18] have studied the group

factors of free head pile groups subjected to lateral soil movement. However, most of the studies were based on active soil pressure caused by lateral loadings on the piles, or by applying soil flows around the pile through the model test apparatus. Therefore, it cannot clearly explain the behaviours of passive piles near excavations. The soil around the pile is subjected to a stress release process caused by the nearby excavations, in which the unloading soil strength is much smaller than the loading condition.

This paper analyses a series of pile groups adjacent to deep braced excavation in soft marine clay by 3D finite element method, based on field instrumented case history. Pile groups comprising of 2×1 , 4×1 , 8×1 and 8×2 piles with center-to-center spacing of $2d$ and $3d$, respectively, were numerically investigated. The group factor in terms of the maximum pile bending moment is carried out to analyze the effects of pile diameter, pile spacing, and pile number on the group effects. The group factor for the center piles and edge piles, as well as the front piles and rear piles in a two-row pile group, are compared. Conclusions arrived at in this study can provide design guidelines for deep braced excavations with adjacent foundation piles considering the pile-soil interaction and pile group effect.

2. Finite element methods

2.1. Model validation

This study analyses a series of 3D FE models of the pile groups subjected to braced excavation in soft marine clay using the numerical package Plaxis3D[14], and investigates the influences of the pile diameter, pile spacing, and pile number on piles' bending moments and pile group factors. Before that, a well-instrumented case history validated the 3D finite element analysis.

The prototype of the FE simulation is an actual full-scale instrumented deep cut-and-cover tunnel [15]. The excavation was supported by diaphragm walls of 31.0 m length and 0.8 m thickness, as well as six levels of struts. A row of bored piles of 1.0 m diameter and 46.0 m length were located 3.0 m behind the wall. The final excavation level was 16.0 m below the ground surface, and the maximum lateral pile deflection was 28.0 mm.

The hardening soil (HS) constitutive model is adopted for the soft caly. Table 1 shows the properties of the soil layers. Sand fill and loose sand are considered as drained using c' and φ' , while clays are considered as undrained using c_u . The Plaxis3D default values are used to define the coefficient of earth pressure at-rest K_0^{nc} , the

Poisson's ratio ν_{ur} and the reference pressure p^{ref} with $K_0^{nc} = 1 - \sin\phi$, $\nu_{ur} = 0.2$ and $p^{ref} = 100$ kPa, respectively, and the power values for stress level dependency of the stiffness m are 0.8 and 1.0, respectively for sand and clay. The soil is modelled using 10-node tetrahedral elements, and 12-node interface elements are used to simulate the soil-structure interaction behaviour. According to [19-20], for simulating the piles subjected to lateral loading, the embedded beam has a trend of overestimation in modelling the pile with the "smoother" shaft surface. However, in this study, the interface factor R_{inter} is considered as 0.67 for the soft marine clay layer. Therefore, in this study, piles are simulated using 10-node tetrahedral volume elements with the material of non-porous linear-elastic material, instead of commonly used 6-noded plate elements as the embedded beam. The typical 3D numerical mesh comprising of 35,817 nodes and 53,954 elements is shown in Figure 1. The mesh density of soil elements around the piles is enhanced.

Table 1: Summary of soil parameters (HS model).

Parameters	E_{50}^{ref} (kPa) $\times 10^3$	E_{oed}^{ref} (kPa) $\times 10^3$	E_{ur}^{ref} (kPa) $\times 10^3$	c_u (kPa)	φ ($^\circ$)	m	γ (kN/m 3)
Loose sand	8	8	24	-	30	0.8	17
Sand fill	20	20	80	-	30	0.8	17
Soft marine clay	10	10	30	25	-	1	16
Old alluvium I	107	107	320	150	-	1	19
Old alluvium II	270	260	900	500	-	1	19

Figure 1 shows the geometry and typical mesh of the FE model. The nodes on the four side boundary surfaces were fixed horizontally, and the nodes on the bottom boundary surfaces were constrained from moving both horizontally and vertically. The right vertical boundary extends sufficiently far from the excavation area to minimize the boundary effects. The mesh density of soil elements around the piles is enhanced to obtain the precise soil pressure that acts on the piles. Table 2 shows the construction sequence of the FE model.

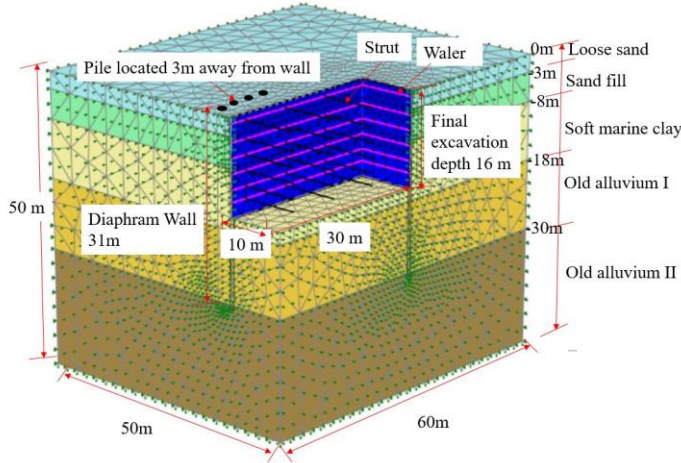


Figure 1. Geometry and mesh of the FEM model.

Table 2: Construction sequences.

Phase	Construction activities
Initial Phase	Balance the initial effective stress of the strata with k_0 procedure
1	Install piles (ground surface at $y = 0$ m)
2	Reset displacement to zero, install diaphragm walls
3	Excavate to $y = -1$ m;
4	Install struts at $y = -1$ m
5	Excavate to $y = -4$ m
6	Install struts at $y = -4$ m
7	Excavate to $y = -6.5$ m
8	Install struts at $y = -6.5$ m
9	Excavate to $y = -9$ m
10	Install struts at $y = -9$ m
11	Excavate to $y = -11.5$ m
12	Install struts at $y = -11.5$ m
13	Excavate to $y = -13.5$ m
14	Install struts at $y = -13.5$ m
15	Excavate to $y = -16$ m

Figure 2 shows the validation of the FEM analysis, which compares the calculated and measured lateral pile deflection and bending moment profiles. The plots indicate that the computed lateral deformation and bending moments are generally in good agreement with the measured results, in both magnitude and shape of the profile. Considering that the bending moments are governed by the curvature of the pile displacement, it is not surprising that the measured and FE moments are not exactly the same. The measured bending moments were obtained by finding an equation that fits the pile

displacement (using a curve fitting software), and then differentiating the equation twice to obtain the bending moments (from structural mechanics) [15], so the measured bending moments are also not that accurate. Last but not the least, there is certain spatial variability of the soil properties which influence the measured results. However, this part was not revealed and considered in the current numerical simulation.

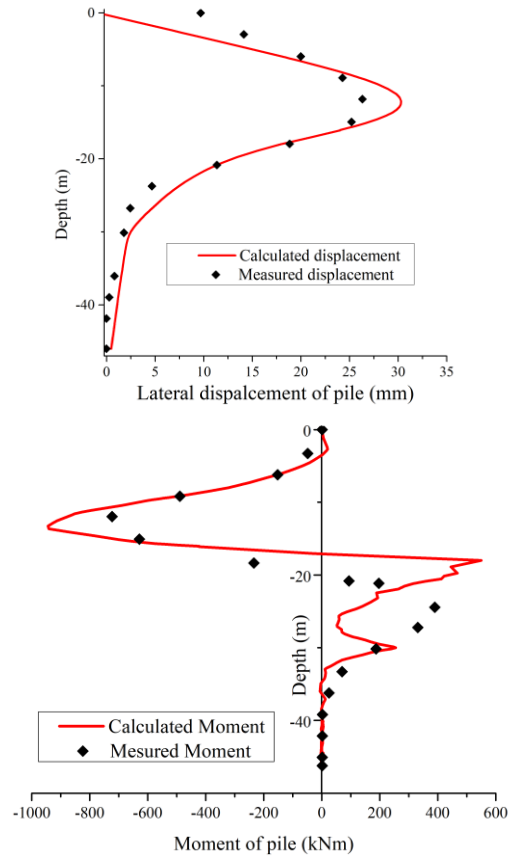


Figure 2. Comparison of calculated and measured lateral pile deflection and bending moment profiles.

2. 2. Parametric sensitivity analysis

Figure 3 shows the plan layout of the pile group and the diaphragm wall. The s_v is spacing in the direction of soil movement, and the s_h is the spacing in the perpendicular direction of soil movement. The one-row pile group is at the same location as the front row of the two-row pile group. Table 3 lists the ranges of the s_v , s_h , d , N_p (the number of piles in one case).

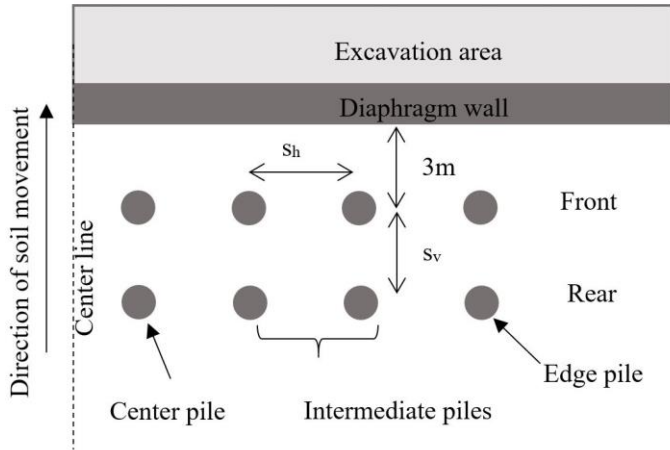


Figure 3. Plan layout of the pile group and diaphragm wall.

Table 3. The parameters and ranges.

Parameters	Ranges	Units
s_h	$2d, 3d$	m
s_v	$2d, 3d$	m
d	0.4, 1.0	m
N_p^*	1, 4, 8, 16	-

*The number of piles in one case.

Figure 4 plots the comparison of the bending moments between the pile group (8×2 group with $s_v=3d$, $s_h=2d$) and a single isolated pile. The bending moments of piles in the pile group are significantly reduced, especially for the front row piles. Moreover, the group effect on the center piles is less significant than the edge piles.

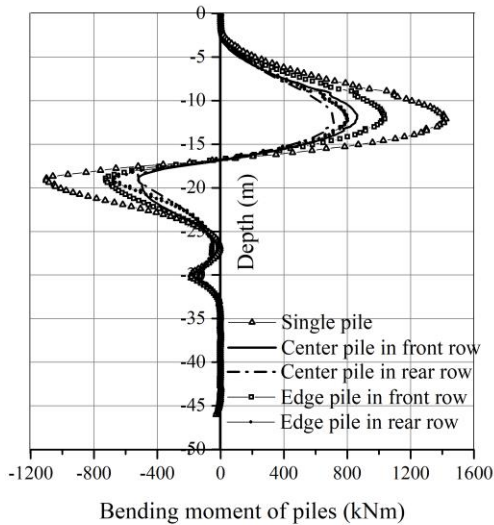


Figure 4. Bending moment of single pile and 8×2 pile group with $s_v=3d$, $s_h=2d$.

3. Assessment of different types of group factor

Group effects on the lateral response of vertical piles subjected to lateral soil movements have been studied numerically by previous researchers. However, the assessment of different types of group factors has not been systematically discussed, and a suitable comparison method is desired to investigate the group effects on the lateral pile response. [21] suggested assessing the group effects in terms of loadings or head deflections for laterally loaded piles. [22] used the pile bending moment for evaluating the group effect on the lateral pile response in analyzing the slope/pile system subjected to lateral soil movements. [23] also studied the braced excavation induced pile group factors using the maximum pile bending moment. The expression is as follows:

$$F_{p,m} = M_{\max,g}/M_{\max,s} \quad (1)$$

in which $M_{\max,g}$ is the maximum pile bending moment for the pile in a group while $M_{\max,s}$ is the maximum pile bending moment for a single isolated pile.

In [17], the group factor F_p , which was calculated in terms of the limiting pile-soil contact pressure, was based on plane-strain FE analysis of piles in an infinitely long row. [24-25] used the ultimate soil pressure as the criteria. The group effect was assessed by a group factor $F_{p,p}$, based on the measured ultimate soil pressure p_u :

$$F_{p,p} = p_{uc}/p_{us} \quad (2)$$

where p_{uc} =ultimate soil pressure of a pile from a coupled pile test, and p_{us} =ultimate soil pressure of a pile from a single pile test.

In general, p-y curves are complicated to calculate from either field instrumentation or model tests. Pile pressure is generally determined by double differentiation of a curve-fit to the pile bending moment distribution, which is measured by strain gauging several locations downwards the pile. This procedure is complicated for passive lateral loading because of the varied load reversals downwards the pile [3]. Moreover, the group factors calculated by p_{uc} were consistent with those calculated by the M_{\max} , according to [24]. For simplicity, this study adopts the group factor $F_{p,m}$ in terms of the maximum bending moment.

4. Effect of pile spacing on the group factors

Figure 5 shows the influence of the pile spacing on the $F_{p,m}$ for 4×1 and 8×1 pile group. The pile spacing produces a more significant influence on the center piles than the edge piles in the cases of 4×1 and 8×1 pile group. Moreover, the pile number in a row also has a significant influence on the pile group factors.

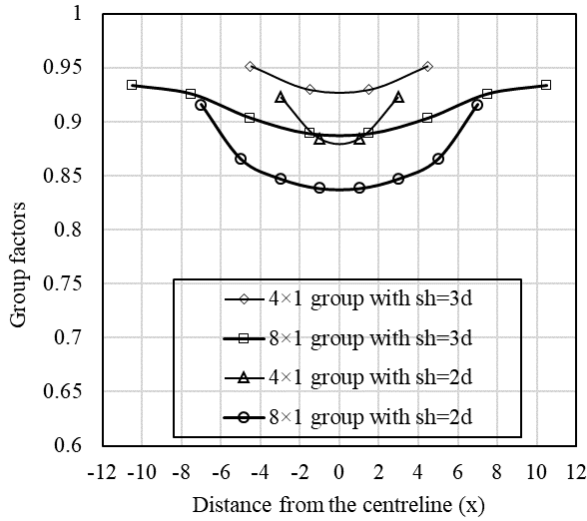
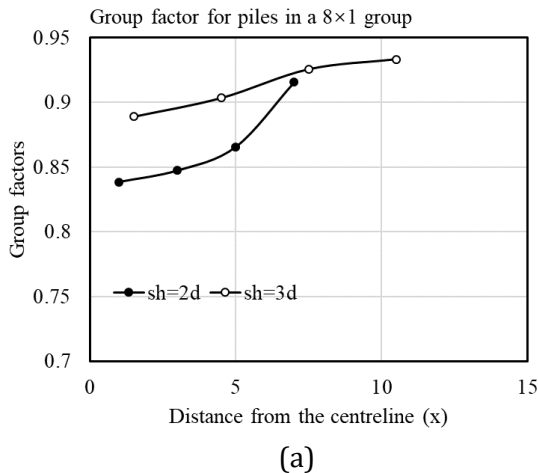
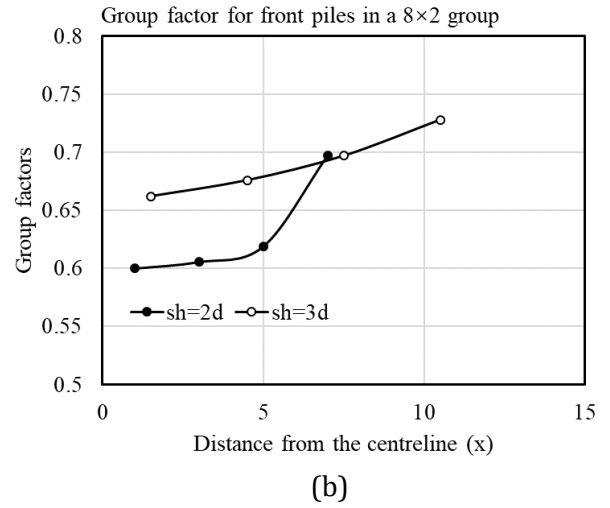


Figure 5. Influence of the pile spacing on $F_{p,m}$ for 4 and 8 piles in one row.

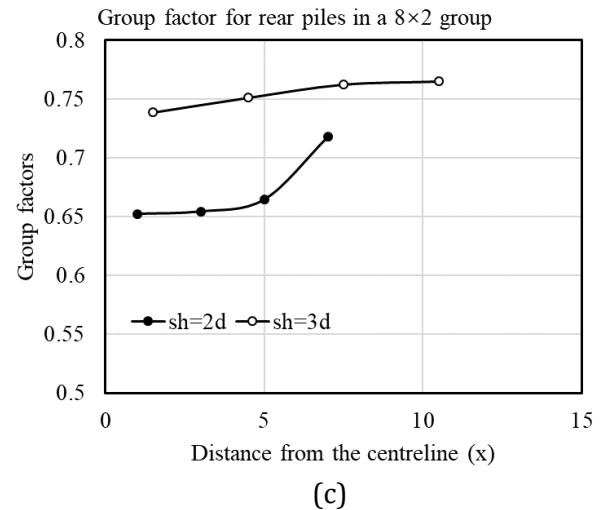
Figure 6 plots the $F_{p,m}$ for piles in an 8×1 pile group and 8×2 pile group with $s_v = 2d$. As shown in Figure 6(a), the edge effect is more significant for the pile groups with $s_h = 2d$ than $s_h = 3d$. Figure 6(b) and 6(c) indicates that the reduction of pile spacing has more significant influence on the rear piles, since when reducing the s_h from $3d$ to $2d$, $F_{p,m}$ of the center pile in the rear row decreases by 12%, while 9% for center pile in the front row; and the same trend for the edge piles.



(a)



(b)



(c)

Figure 6. Influence of s_h on $F_{p,m}$ for piles in (a) 8×1 group and (b) front row (c) rear row of 8×2 group.

5. Effect of pile diameter

The effect of the pile diameter on the group factor is investigated by analyzing the pile groups with pile diameters of 1.0 m and 0.4 m. The pile spacings of $s_v = 2m$ and $s_h = 3m$, $s_v = 2m$ and $s_h = 2m$ are considered. When comparing Figure 7(a) and 7(b), for the center piles, the effect of the pile diameter is more significant with a greater s_h . For example, in Figure 7(a) with $s_h = 3m$, the $F_{p,m}$ decreases by 0.11 (from 0.85 to 0.74) for center pile in the rear row when the pile diameter changes from 0.4 m to 1.0 m; while in Figure 7(b), for the same pile, the $F_{p,m}$ decreases by 0.15 (from 0.80 to 0.65) when $s_h = 2m$. A similar trend can be observed for center piles in the front row. However, the trend is not decisive for the edge piles.

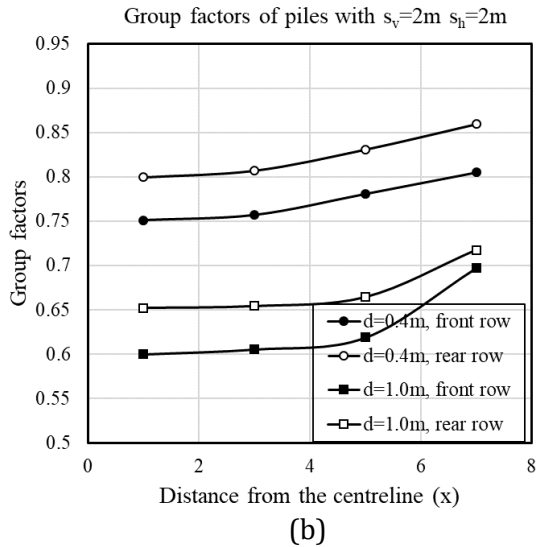
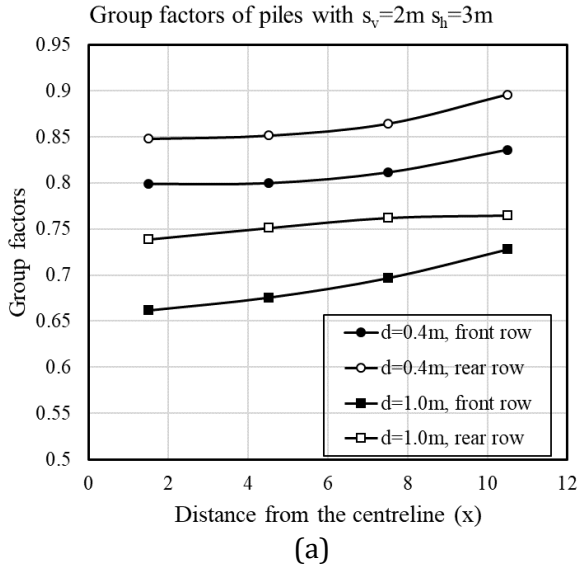


Figure 7. Influence of pile diameter on the $F_{p,m}$ for piles spacing (a) $s_v=2m$ $s_h=3m$ and (b) $s_v=2m$ $s_h=2m$.

6. Shielding effect of piles

[26] investigated the shielding effect of free-head pile groups adjacent to excavations by numerical simulations and centrifuge tests and concluded that the shielding effect is only significant when the excavation is deep. In this section, the shielding effect of $d = 1.0m$ piles with $s_v = 2d$, $s_h = 2d$ and $3d$ is analyzed. As shown in Figure 8, the shielding effect of the front piles on the rear piles is very significant. For example, the group factor of the center pile in the rear row with $s_h = 2d$ decreases to 0.65. Simultaneously, the group factor of the center pile in the front row with $s_h = 2d$ decreases from 0.84 to 0.60,

comparing to the one-row pile. Furthermore, the tendency is similar for edge piles. The results are consistent with the conclusion of [30] that the shielding effect of the front piles along beside the retaining wall reduces the adverse effects of soil movement on rear piles. Moreover, the results are also similar to [31] that the induced bending moments on the peripheral piles in a group have higher bending moments when compared to internal piles that benefit from a stronger pile-soil interaction.

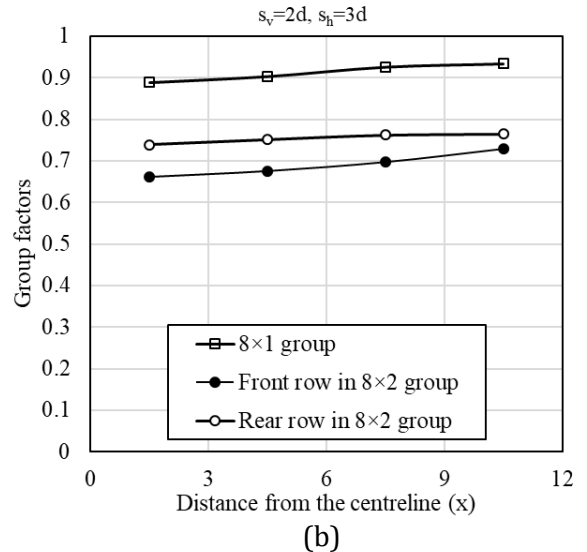
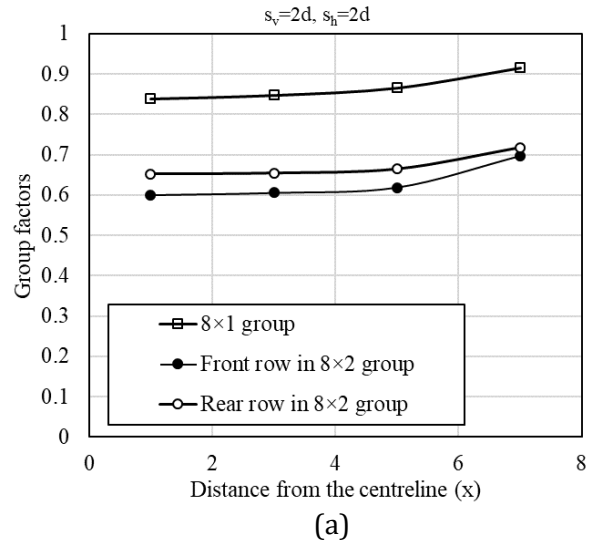


Figure 8. Shielding effect of $d = 1.0m$ piles with $s_v = 2d$, $s_h = 2d$ and $3d$.

7. Conclusions

This paper analyses a series of responses of pile groups adjacent to deep braced excavation in soft marine clay by 3D finite element method, based on field instrumented case history. This study numerically investigated The effects of pile diameter, pile spacing, and pile number on the group factors. The group factor for the center piles and edge piles, as well as the front piles and rear piles in a two-row pile group, are compared.

The pile diameter, pile spacing, and pile number have significant influences on pile groups subjected to braced excavation in soft marine clay. The group effect on the maximum bending moment for center piles is less significant than the edge piles, and the edge piles contribute more to a greater group factor than the central piles, which indicating a marginal effect of the pile groups.

For edge piles in one single row, a greater s_h value results in a higher p_u value; on the contrary, for the center piles, a larger s_h value lead to a lower p_u value. The reduction of pile spacing has a more significant influence on the rear piles than the front piles. The effect of the pile diameter is more significant with a larger s_h for the center piles but not for the edge piles. The shielding effect of the front piles on the rear piles is considerable.

Acknowledgments

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