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Load-Displacement behavior of passive piles in cohesive soils

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ABSTRACT: In this paper, the load transfer mechanism; especially the processes leading to formation of an arching zone around the passive pile groups in purely cohesive soils is investigated with plane strain model simulations. Lateral loads acting on piles in a row are analyzed considering different pile spacing. Furthermore, various numerical simulations are performed to investigate the effects of pile rigidity and pile arrangement on the load displacement behavior of passive piles in double rows.

It is observed that the loads acting on piles increase with a decrease in pile spacing due to soil arching which is not effective if pile spacing is greater than 7.5 times pile diameter. When the relative movement between the pile and the soil reaches a certain value, the loads reach a maximum value and remain constant as the soil movement continues to increase. This indicates that the excess soil movement after soil failure has no further influence on the load transfer mechanism. In the case of piles in two rows, pile rigidity really affects the loads carried by front and rear piles. For piles with low rigidity, it was determined that the loads carried by the front and the rear rows are approximately the same. When the pile stiffness is increased, the loads carried by front piles are increased to 4 times that carried by rear piles.

1 INTRODUCTION

Installing piles with sufficient length in a stable soil or rock stratum and adequate pile spacing is an effective measure for slope stabilization (Wang & Yen, 1974; Ito et al, 1975; Viggiani, 1981; Reese et al, 1992; Poulos, 1995, 1999; Zeng & Liang, 2002). Stabilizing effect is provided by the passive resistance of the pile below the slip surface and load transfer from the sliding mass to the underlying stationary soil or rock formation through the piles due to soil arching mechanism (Chen et al, 1997; Chen & Martin, 2002; Liang & Zeng, 2002; Kahyaoğlu et al, 2009).

In the analysis of a slope reinforced with piles, the forces acting on piles or the lateral force reactions to the sliding mass must be known. Investigations of the performance of piles on sliding slopes (Chen & Poulos, 1993; Chow, 1996; Bransby & Springman, 1999; Chen & Martin, 2002; Liang & Zeng, 2002) made it possible to provide a quantitative estimate of the ultimate lateral soil pressure against these piles.

Chen & Poulos (1993) presented a numerical analysis which combines the infinite and finite element method to gain a better understanding of pile-soil interaction under passive loading. Researches are focused on the group effect on ultimate lateral soil resistance. It is shown that the group effect tends to reduce pile capacity when the spacings between piles are within the practical ranges. Chow (1996) presented an approach to analysis piles for slope stabilization, where piles are modeled using the modulus of subgrade reaction and the pile-soil-pile interaction considered using the theory of elasticity. A finite element study was carried out by Bransby & Springman (1999) to determine the pile–soil–pile interaction behavior for pile groups. Interaction between piles increased both with reduction of pile spacing and the fineness of mesh in the pile vicinity.

Chen & Martin (2002) investigated the existence of an arching zone around pile groups for granular and fine-grained soils using the finite difference method. The results reveal that the formation of the arching zone is functions of pile arrangement, relative pile/soil displacement, pile shape, interface roughness, and soil dilation angle. Liang & Zeng (2002) investigated the soil arching mechanism in slope stabilizing piles using a two dimensional finite element (FE) approach assuming rigid-plastic soil behavior, plane strain conditions, and uniform soil movement with respect to pile length. The formation of soil arching was simulated by applying a triangular displacement field occurring in the soil between the piles. It was found that soil arching is strongly dependent on the magnitude of soil movement, soil strength properties and pile spacing. Based on this analysis, it is concluded that the finite element method appears to be effective to analyze this difficult problem.

The ratio of ultimate load to the product of pile diameter and the cohesion of soil (P_u/c_ud) was determined to be in the range from 2.8 to 16.56 (Brinch Hansen, 1961; Broms, 1964; Ito & Matsui, 1975; DeBeer & Carpentier, 1977; Viggiani, 1981; Randolph & Houlsby, 1984; Maugeri & Motta, 1992). In analytical investigations, the results depended on the selection of the model simulating the interaction of the soil-pile system. The arch shape of the zone of plastic deformations, which has been adopted by many researchers, does not reflect the actual pattern of interaction between pile rows and the slide soil, since the sliding pressure frequently exceeds the strength of the soil.

The main objective of this paper is to model the soil-structure interaction associated with stabilizing piles and to estimate loads acting on rigid piles rigorously. The load transfer mechanism; especially the processes leading to formation of an arching zone within rigid pile groups in a row for purely cohesive soils was examined with 2-D plane strain model, utilizing the finite element program, PLAXIS (version 8.2) (Brinkgreve & Vermeer, 2001). Furthermore, various numerical simulations were performed to investigate the effects of pile rigidity and pile arrangement on the load displacement behavior of flexible passive piles in two rows. Both objectives have not been dealt with in the existing literature. It is observed that the loads acting on piles increase parallel to a decrease in pile spacing due to soil arching. The results also show that load transfer mechanism is not only a function of soil properties and pile spacing, but also a function of relative pile/soil movement and the rigidity of the pile. It is also shown that the relative movement of the front and rear pile rows has a significant influence on load share.

2 PLANE STRAIN FINITE ELEMENT MODELING

The representative finite element model for the analysis in this study, consists of four main elements namely, rigid box, cohesive soil, model piles, and fixed end anchors. The rigid box filled with clay has the dimensions of 300x300 mm in plan. 10 mm diameter (d) circular piles with anchors having adjustable rigidity were placed into the center of this box. The model dimensions were decided upon several FEM trials until boundary effects, which depends on the relative size of the pile and the box, became negligible. It was found that thirty times the diameter of the pile was satisfactory for one side of the square working plane. The results verified that the difference was sufficiently small from a model with 60dx60d square dimensions and that the calculations of the model with 30dx30d square dimensions gave enough accuracy in this case.

The soil movement due to the box movement is simulated by the prescribed displacements imposed on the top and bottom boundary of the box with only vertical movement allowed along the sides. The box is able to move when the anchor rigidity of the pile is zero. This simulates the situation of slope failure and causes soil to flow through the space between piles. The load required to achieve the prescribed displacement of the box occurs due to the relative displacement and is equal to the load carried by the pile. In the rigid pile analyses, the pile was restrained from moving and rotating in any direction with a rigid anchor to act as a rigid pile. Whereas in the case of flexible piles, the piles were allowed to move with anchors having different elastic stiffnesses (EA). Numerical studies with different numbers of elements in the mesh around the pile were performed to investigate the model including mesh refinement near the pile–soil interface and became coarser further from the pile. The piles and the surrounding soil were discretized using a mesh consisting of 1679 six-node triangular elements. A typical model with the FEM mesh is shown in Figure 1. The constitutive soil model in FEM analyses was the Mohr-Coulomb model. Soil elements are assumed to be homogeneous and isotropic. Piles were modeled as linear elastic non porous soil elements.

Based on Coulomb's frictional law, interface elements are used along the outside surfaces of the piles to simulate pile–soil interaction in terms of slippage and gapping at pile–soil interface (Desai et al, 1984; Yan, 1986; Trochianis et al, 1988; Wang & Richwien, 2002). These elements are specified with an interface reduction factor (R_{inter}) to model a reduced strength between piles and soil. The soil-pile interface strength parameter is set to two-thirds of the corresponding soil strength parameter according to the recommendations from program manual so that strength reduction due to slippage of the soil around the pile is taken into consideration. In Plaxis, the undrained behavior can be simulated by selecting the non-porous option while directly entering the undrained elastic properties $E = E_u$ and $\nu = \nu_u = 0.495$ in combination with the undrained strength properties $c = c_u$ and $\phi = \phi_u = 0°$. The material properties used in numerical studies are given in Table 1.

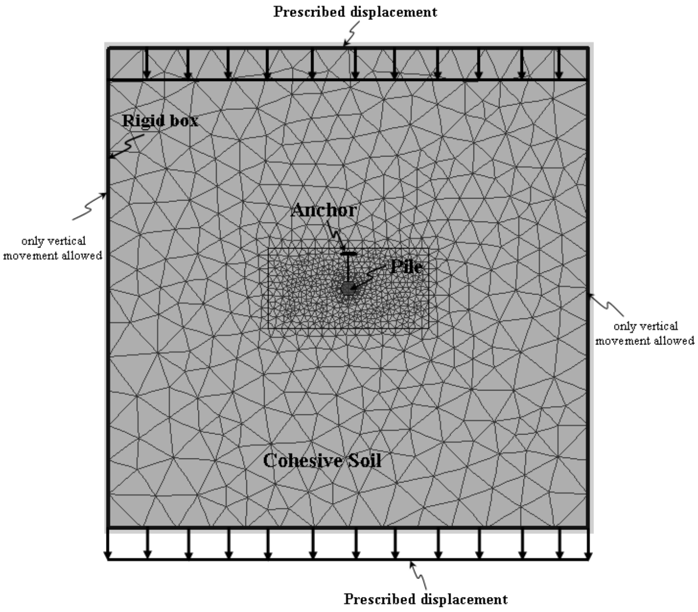

Figure1. Plan view of FEM mesh in numerical study

3 DETERMINATIONS FROM NUMERICAL RESULTS

Firstly, normalized pressures acting on rigid piles against various soil movements up to soil failure are determined. Furthermore, a parametric study is performed to determine the effects of the ratio of pile spacing to pile diameter (s/d) on the load transfer behavior. The numerical analyses were then extended to two rows of pile groups. Numerical simulations were conducted on two different arrangements for investigating the effect of pile spacing on load transfer mechanism on both rigid and flexible piles.

3.1 Effect of Relative Pile/Soil Displacement

The measured load-displacement relationships of the box indicate the contribution of the pile to the resistance of the system. The anchor load determined via FE simulation reflects the load carried by the pile. It should be noted that the loads on the piles varied depending on the relative displacement between pile and soil. The ratio of the difference between the displacements of pile head and the soil adjacent to the pile to pile diameter is defined as the relative pile–soil displacement (δ/d). The response of the passive pile for various soil movements (y) up to soil failure is also compared. The normalized pressures against the relative pile-soil displacement are plotted in Figure 2.

Table 1. Material property of the soil, pile, anchor and rigid model box

	Parameter	Name	Value	Unit
Clay	Material Model	Model	Mohr-Coulomb	-
	Type of Material behavior	Type	Non-porous	-
	Unit weight of soil	γ	0	kN/m^3
	Young's modulus (constant)	E_{ref}	2500	kN/m^2
	Poisson's ratio	ν	0.495	-
	Undrained cohesion (constant)	c_u	12	kN/m^2
	Effective friction angle	ϕ	0	°
	Dilatancy angle	ψ	0	°
	Interface Roughness	R_{inter}	0.67	-
Pile	Material Model	Model	Linear Elastic	-
	Type of Material behavior	Type	Non-porous	-
	Unit weight of soil	γ	0	kN/m^3
	Young's modulus (constant)	E_{ref}	$1x10^7$	kN/m^2
	Poisson's ratio	ν	0.2	-
Anchor	Material Type	Type	Linear Elastic	-
	Axial Stiffness	EA	Adjustable	kN/m
Box	Material Type	Type	Linear Elastic	-
	Axial Stiffness	EA	$4.03x10^6$	kN/m
	Flexural Rigidity	EI	800	kNm^2/m
	Poisson's ratio	ν	0.15	-

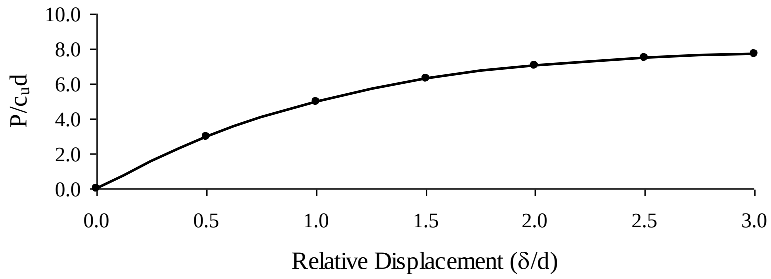

Figure 2. Calculated normalized load per length against relative displacement

As seen from Figure 2, when relative displacement (δ/d) increases, the loads acting on the pile increase rapidly as a result of elastic pile-soil interaction induced stress transfer. When relative displacement reaches a certain value, $\delta/d \cong 3$, the loads reach the maximum value and remain constant as the relative displacement continues to increase. This indicates that the maximum load corresponds to soil yield around the pile and the additional soil movement has no more influence on the stress re-distribution.

3.3 Effect of Pile Spacing

Furthermore, a parametric study was performed to determine the effects of the ratio of pile spacing to pile diameter (s/d) on the load transfer behavior due to soil arching. The rigidity of the anchor as well as the pile diameter and the Young's modulus of the soil were kept constant throughout the analysis, while only the pile spacing was changed in order to determine the effect of pile spacing on the pile response. Eight model simulations with different pile spacing ranging from s = 2.5d to s = 30d were carried out. The pile spacing and the number of piles used in simulation series are summarized in Table 2.

Interpretations are carried out with different pile spacing ratio (s/d) for ultimate state analyses, in which enough soil movement occurs to cause soil plastic flow. By varying the spacing and increasing the relative displacement up to ultimate state, the load acting on the piles was calculated. The values of $P_u/c_u d$ for different pile spacing in the simulation series are summarized in Figure 3.

Table 2. Pile Configurations

Simulation No	Pile Spacing s/d	Number of Piles
1	30	1
2	15	2
3	10	3
4	7.5	4
5	6	5
6	5	6
7	3	10
8	2.5	12

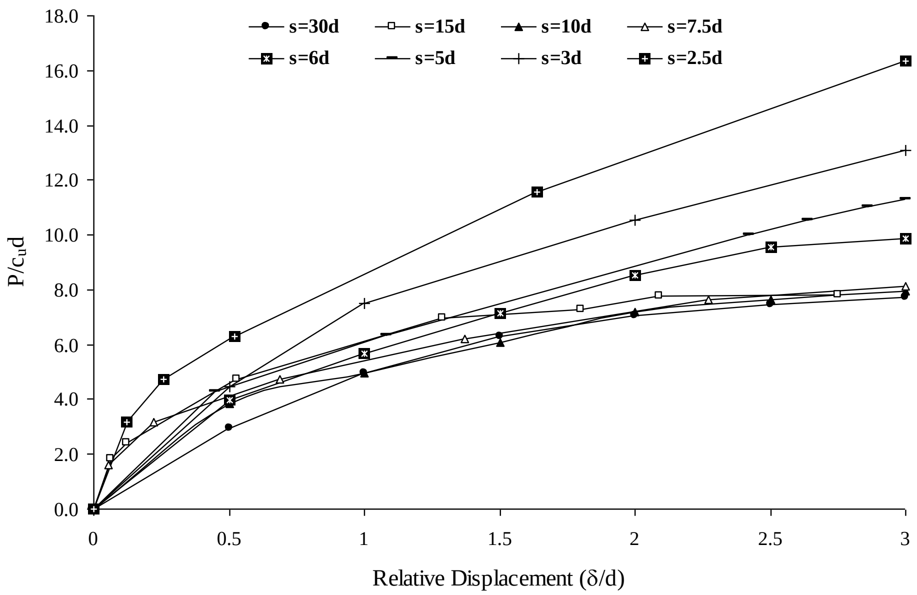

Figure 3. Calculated pile loads for different pile spacing

It can clearly be seen in Figure 3, the initial slopes of the curves are not the same. Load transfer in pile groups with closer spacing starts more rapidly than discrete piles in the initial displacements. The slopes of the curves decrease up to 2.0 ≈ 2.5 then become constant. The value of 2.5 for relative displacement is sufficient for the development of group effects.

It is apparent that the load acting on the piles decreases, as the spacing increases. However the rate of this increment gradually decreases and arching is not as effective at large spacing as at small spacing. Once the pile spacing becomes larger than 7.5d, there would be no arching effect such that each pile behaves like a single pile.

3.4 Effect of Pile Arrangement and Pile Rigidity

Piles in a single row arrangements was considered a relatively standard approach, therefore the numerical analyses were then extended to two rows of pile groups. It was decided that a series of pile group numerical simulations were conducted on two different arrangements. In the first arrangement, piles in two rows in parallel arrangement; in the second arrangement, piles in two rows in zigzag arrangement, for investigating the effect of pile spacing on load transfer mechanism on both rigid and flexible piles. The piles were set up in two rows at 6d intervals, and the interval between rows was 3d. The rigidity of the anchors was changed and the loads acting on piles were determined in the case of ultimate state. For the rigid pile analyses, the pile was restrained from moving and rotating in any direction with a rigid anchor to act as a rigid pile.

For the case of flexible piles, the piles were allowed to move in the direction of movement of the box with anchors having different EA to act as flexible piles. The analyses for different plan views along the pile length were performed with the same rigidity of the anchors for both the first and the second row of pile. Parallel and zigzag arrangements of pile groups were examined and shown in Figures 4 and 5, respectively.

The loads acting on piles are determined after the completion of the FEM analyses with different pile rigidity. The values of pile loads which are representative for the presentation of load transfer in the case of both parallel and zigzag arrangement are given in Table 4.

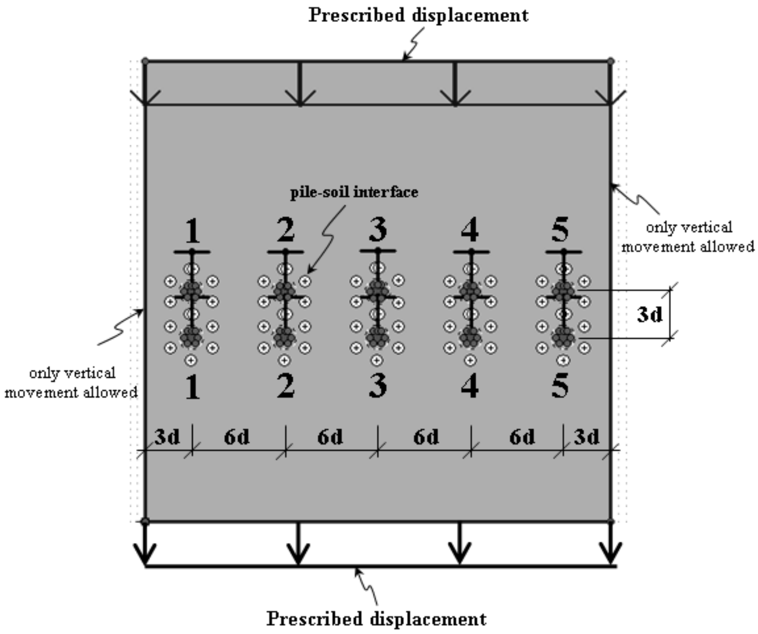

Figure 4. Simulation of two rows of piles in parallel arrangement

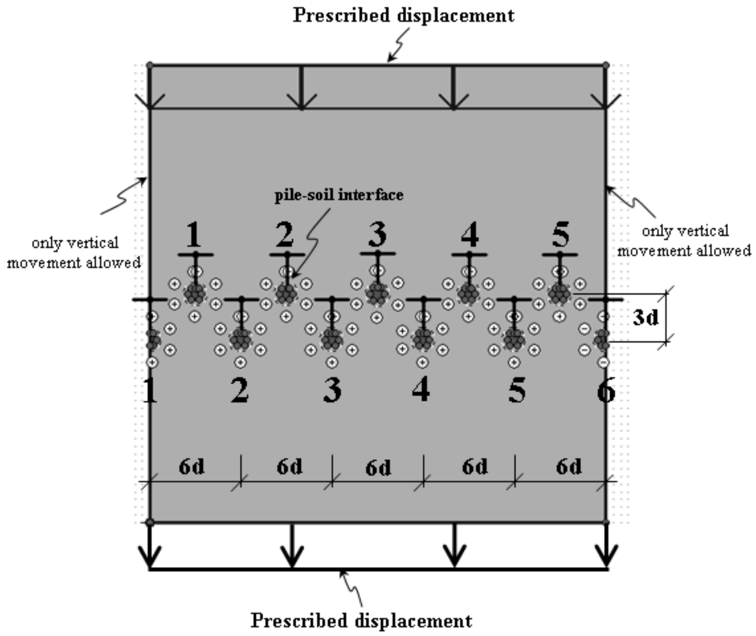

Figure 5. Simulation of two rows of piles in zigzag arrangement

For flexible piles with low rigidity, it was determined that the forces carried by the front piles and the forces carried by the rear piles were approximately the same. When the pile stiffness was increased, the load carried by front piles was increased up to 4 times of load carried by rear piles. Pile loads determined in the parallel arrangement are approximately 5% in excess of loads in zigzag arrangement. However, for a zigzag arrangement of piles provide piles more restraint to soil movement.

Table 4. Normalized pressures in parallel and zigzag arrangements

NORMALIZED PILE PRESSURE (P/c_ud)				
		Parallel Arrangement / Zigzag Arrangement		
s=6d	Pile No	EA=20 (kN/m)	EA=200 (kN/m)	EA=2000 (kN/m)
Front row	2	6.00 / 6.32	7.08 / 7.21	8.88 / 9.28
	3	6.00 / 6.32	7.06 / 7.20	8.85 / 9.44
Rear row	2	5.94 / 6.29	2.63 / 2.98	2.18 / 2.32
	3	5.96 / 6.29	2.73 / 2.95	2.21 / 2.27

In order to investigate the effect of pile rigidity, the response of each individual pile in the first row was compared with that in second row. Pile rigidity effect was assessed in terms of loads. In using pile loads for evaluating the pile rigidity, the group load ratio is primarily based on the loads which compares the maximum load of a pile from front piles with that of back piles at the same amount of relative displacement, and is expressed in Figure 6 with different pile configurations. It can be seen from the figure that group load ratio is the same for flexible piles in a parallel or zigzag arrangement.

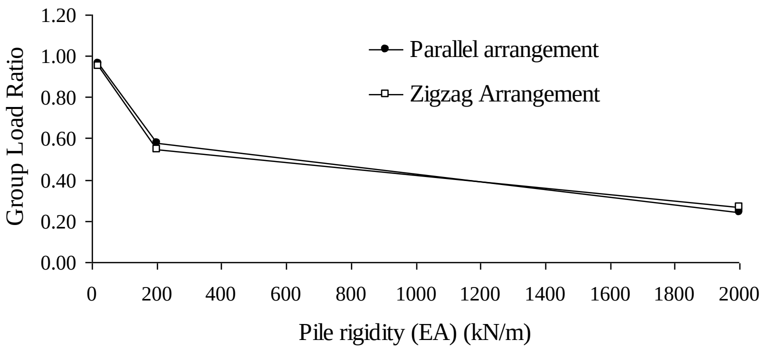

Figure 6. Group load ratio variations with pile rigidity

3 CONCLUSION

Firstly, a parametric study utilizing 2D FEM is carried out in order to investigate the effect of pile spacing on the rigid piles. Furthermore, a series of numerical simulations are conducted on double rows of flexible piles with two different arrangements for investigating the effect of pile rigidity on load transfer mechanism. Some conclusions from the results are as follows:

- As relative displacement (δ) increases, the loads acting on the piles increase rapidly. When the soil movement reaches a certain value, the acting loads reach a maximum value and remain constant as the soil movement continues to increase. This indicates that the additional soil movement has no more influence on the load transfer mechanism.
- With an increase of the pile spacing, s, the loads acting on the piles decrease. However, each pile behaves like a single pile without any arching effect when pile spacing is greater than 7.5 times pile diameter.
- The normalized lateral load per length (P/c_ud) was determined to be in the range from 7.74 to 16.36 for rigid pile groups in a row, which is similar to theoretical values based on classical plasticity.

- For flexible piles in two rows, it was determined that the loads acting on the front and rear piles are approximately the same. When the pile rigidity is increased, the load on front piles was increased up to 4 times of load on rear piles. Pile loads determined in the zigzag arrangement are approximately 5% higher than loads in parallel arrangement. Therefore, multi soil arching effects for a zigzag arrangement of piles provide piles more restraint to soil movement.

There are some limitations associated with plane-strain analyses (2-D) of passive piles. For cases when an assumed soil movement is applied only in a horizontal plane with uniform initial stress and boundary conditions, factor such as ground heave which have significant influence on the behavior of lateral loaded piles are not taken into account. 3-D analyses are more reliable to model the complex soil-structure interaction associated with stabilizing piles in slopes, and to predict the limit loads on piles.

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