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Group effect on ultimate lateral resistance of piles against uniform ground movement

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Abstract

In earthquake engineering, pile foundations are designed to withstand the lateral loading that results from large displacements due to ground movement caused by strong earthquakes. The distress and failure of superstructures occurs when the lateral load exceeds the ultimate lateral resistance of the piles. The aim of this study is to estimate the ultimate lateral resistance of piles especially in terms of the group effect induced by the pile arrangement. Several experimental and numerical analyses have been conducted on pile groups to investigate the group effect when the groups are subjected to uniform large horizontal ground movement. However, the ultimate lateral resistance of the pile groups in these studies was calculated by applying load to the piles. The present study directly assesses the ultimate lateral resistance of pile groups against ground movement by systematically varying the direction of the ground movement. Although the load bearing ratio of each pile in a pile group, defined as the ratio of the ultimate lateral resistance of each pile in a pile group to that of a single pile, is an important design criterion, it was difficult to assess in past works. This study focuses on the load bearing ratio of each pile against ground movement in various directions. The use of the finite element method (FEM) provides options for simulating the pile-soil system with complex pile arrangements by taking the complicated geometry of the problem into account. The ultimate lateral resistance is examined here for pile groups consisting of a 2×2 arrangement of four piles, as well as two piles, three piles, four piles, and an infinite number of piles arranged in a row through case studies in which the pile spacing is changed by applying the two-dimensional rigid plastic finite element method (RPFEM). The RPFEM was extended in this work to calculate not only the total ultimate lateral resistance of pile groups, but also the load bearing ratio of the piles in the group. The obtained results indicate that the load bearing ratio generally increases with an increase in pile spacing and converges to almost unity at a pile spacing ratio of 3.0 with respect to the pile diameter. Moreover, the group effect was further investigated by considering the failure mode of the ground around the piles.

Keywords: Ultimate lateral resistance; Pile group; Load bearing ratio; Horizontal ground movement; Two-dimensional analysis

1. Introduction

When an earthquake occurs, piles installed in the ground are laterally loaded due to the ground displacement caused by the earthquake's vibrations. Thus, it is important to design piles in such a way that they will remain safe during earthquakes. For this purpose, it is necessary to assess

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the magnitude of the load that will be applied to the piles during an earthquake. This load is usually assessed by a spring model using the lateral ground displacement recorded during past earthquakes. Recently, however, due to the development of highly sensitive sensors and systems to measure an earthquake's vibrations, the measured maximum acceleration is becoming larger every year and earthquake records must be updated to reflect these changes. This situation causes an increase in the cost of constructing pile foundations; and thus, more economical and suitable design methods are being intensively sought. When the ground displacement is large, rather than occuring together with the piles, the deformation of the ground leads the ground movement to pass around the piles. Therefore, it is natural that a bi-linear spring model is introduced to assess the load applied to the piles. The ultimate load applied to the piles is computed for the limit state where the ground displacement passes through the piles. In this study, the ultimate load is described as the ultimate lateral resistance of the piles. For most pile problems, the lateral resistance of the piles is usually assessed along the longitudinal direction of the piles. This study, however, concentrates on the cross section of the piles so that a two-dimensional analysis can be conducted. Since earthquakes take place in short periods of time, the ground deforms under an undrained condition. Thus, the ground is usually modeled by cohesive material. In this study, focus is placed on clayey soils, since the displacement of clayey soils is generally observed to be greater during an earthquake. However, focus is sometimes placed on sandy soils when the ground has been liquefied by an earthquake. It is widely known that liquefied sandy soil causes great lateral deformation. The physical properties of liquefied sandy soil are not clear; and therefore, the material is often assumed cohesive in the design.

In pile-soil systems, the ultimate lateral resistance of the piles depends exclusively on the pile-soil adhesion. Although the pile-soil adhesion depends on the pile material (concrete, steel or wood), it has been modeled under two extreme conditions, namely, either perfectly smooth or perfectly rough. This study models the adhesion under the perfectly rough condition from the conservative viewpoint. To investigate the resistance of laterally loaded single piles, several empirical and theoretical investigations have been performed to analyze the ultimate lateral resistance of single piles, such as those by Broms (1964) and Randolph and Houlsby (1984). In these works, the ultimate lateral resistance of the piles was compared to the prescribed load applied to the piles. Broms (1964) studied the slip line method to calculate the ultimate lateral resistance of single piles driven into cohesive soil. They reported lateral resistance in the range of 8.28 c_u–12.56 c_u for various piles with circular and rectangular shapes and with smooth and rough surfaces, in which c_u was the undrained shear strength of the ground. A solution was provided for all pile surface conditions, and the shapes of the slip lines around the piles were predicted. Randolph and Houlsby (1984) used two-dimensional lower-bound and upper-bound limit analyses to provide the collapse load for circular piles in cohesive soil. The ultimate lateral resistance of the piles was in the range of 9.14 c_u for perfectly smooth piles to 11.94 c_u for perfectly rough piles. However, more complex problems arise for pile groups because the ultimate lateral resistance of each pile is different among all the piles in a pile group due to the pile-soil interaction effect. The group effect on the ultimate lateral resistance has been investigated by several researchers using numerical analyses and model tests. Stewart (1992), Chen (1994), Chen and Poulos (1997), and Goh et al. (1997) used numerical analyses to calculate the ultimate lateral resistance of pile groups against horizontal ground movement. The analyses showed that the ultimate lateral resistance of a pile in a pile group was generally lower than that of a single pile due to the pile-soil interaction. The same results were also obtained in model tests conducted by Cox et al. (1984), Chen et al. (1997), Pan (1998), Pan et al. (2002), Llyas et al. (2004), Miao (2005), Miao et al. (2008), and Bauer et al. (2016). In recent years, several researchers have reported the group effect on the ultimate lateral resistance using numerical analyses, such as Georgiadis et al. (2013a, 2013b, 2013c) and Zhao et al. (2017a, 2017b). However, most of the studies involved the analysis of the limit load for the prescribed load applied to the piles. That is, since the load being applied to each pile in a pile group was not known prior to analysis, the past works were focused on the ultimate lateral resistance of single piles. The ultimate lateral resistance of a pile group is affected by many factors, such as the pile spacing, the number of piles, and the direction of the ground movement against the pile arrangement.

In this study, the pile-soil system is simulated by employing a rigid plastic finite element analysis based on the upper bound theorem. The rigid plastic finite element method (RPFEM) has been applied in geotechnical engineering by Tamura et al. (1984, 1990) and was further developed by Tamura et al. (1987) for frictional material. In this method, the limit load is computed without the assumption of the potential failure mechanism. The method is effective for computing the ultimate lateral resistance of pile groups against horizontal ground movement in clayey soils. The RPFEM was originally developed based on the upper bound theorem in the limit analysis, but was shown to have been derived directly from the rigid plastic constitutive equation by Tamura et al. (1984). The advantage of the rigid plastic constitutive equation is that it can be extended and then applied to soils with more complicated material properties for the non-associated flow rule. In this study, the rigid plastic constitutive equation for the Drucker-Prager yield function is employed by the application of the penalty method. Hoshina et al. (2011), Komura et al. (2016), and Nguyen et al. (2016) developed the rigid plastic constitutive equation by introducing the dilatancy condition that is explicitly modeled through the use of the penalty method. The limit load is obtained by introducing the constraint condition for external work into the equilibrium equation using the penalty method in the same way. Since the penalty method incorporates the constraint condition directly into the governing equation, high computational efficiency can be achieved.

Only a few studies have considered the effect of the loading direction on the ultimate lateral resistance of pile groups, such as the numerical analyses of Georgiadis et al. (2013b), Zhao et al. (2017a, 2017b) and the model tests of Kashiwa et al. (2007) and Su and Zhou (2015). However, Georgiadis et al. (2013a, 2013b, 2013c) and Zhao et al. (2017a, 2017b) provided the total ultimate resistance of the pile group, rather than the ultimate reaction of each pile in the group subjected to horizontal ground movement. In this study, the effect of the direction of the ground movement and the pile arrangement on the ultimate lateral resistance of pile groups and the load bearing ratio of each pile is investigated. Pile groups consisting of a 2×2 arrangement of four piles, as well as two piles, three piles, four piles, and an infinite number of piles arranged in a row are intensively investigated by changing the pile spacing.

2. Constitutive equation for rigid plastic finite element method

Tamura et al. (1987) developed the rigid plastic constitutive equation for frictional material. The Drucker-Prager yield function is expressed as follows:

$$f(\sigma) = \alpha I_1 + \sqrt{J_2} - k = 0 \tag{1}$$

where I_1 is the first invariant of stress σ_{ij}, and $I_1 = \mathrm{tr}(\sigma_{\mathrm{ij}})$ in which the extension stress is defined as positive.

J_2 is the second invariant of deviator stress s_{ij}, defined as $J_2 = \frac{1}{2} s_{ij} s_{ij}$, and coefficients $\alpha = \frac{\tan\phi}{\sqrt{9+12\tan^2\phi}}$ and $k = \frac{3c}{\sqrt{9+12\tan^2\phi}}$ are the material constants corresponding to the shear resistance angle and cohesion, respectively, under the plane strain condition. The volumetric strain rate is expressed as follows:

$$\dot{\varepsilon}_v = tr(\dot{\boldsymbol{\varepsilon}}) = tr\left(\lambda \frac{\partial f(\boldsymbol{\sigma})}{\partial \sigma}\right) = tr\left(\lambda\left(\alpha \boldsymbol{I} + \frac{\boldsymbol{s}}{2\sqrt{J_2}}\right)\right) = \frac{3\alpha}{\sqrt{3\alpha^2 + 1/2}} \dot{e} \tag{2}$$

where λ is an indeterminate multiplier and $\mathbf{I}$ is the unit tensor. Strain rate $\dot{\varepsilon}$, which is a purely plastic component, should satisfy the volumetric constraint condition, as follows:

$$h(\dot{\varepsilon}) = \dot{\varepsilon}_v - \frac{3\alpha}{\sqrt{3\alpha^2 + 1/2}} \dot{e} = \dot{\varepsilon}_v - \eta \dot{e} = 0 \tag{3}$$

in which $\dot{\varepsilon}_v$ and $\dot{e}$ indicate the volumetric strain rate and the norm of the strain rate, respectively. Parameter η is defined in Eq. (3). The rigid plastic constitutive equation is expressed by the Lagrangian method after Tamura et al. (1987), as follows:

$$\boldsymbol{\sigma} = \frac{k}{\sqrt{3\alpha^2 + 1/2}} \frac{\dot{\boldsymbol{\varepsilon}}}{\dot{e}} + \beta\left(\boldsymbol{I} - \eta \frac{\dot{\boldsymbol{\varepsilon}}}{\dot{e}}\right) \tag{4}$$

where β represents a Lagrangian multiplier which indicates the equilibrating stress satisfying the yield function expressed by Eq. (1). Moreover, the constraint condition on the strain rate is directly introduced into the constitutive equation with the use of the penalty method (Hoshina et al., 2011; Nguyen et al., 2016). The stress-strain rate relation for the Drucker-Prager yield function is expressed as follows:

$$\boldsymbol{\sigma} = \frac{k}{\sqrt{3\alpha^2 + 1/2}} \frac{\dot{\varepsilon}}{\dot{e}} + \kappa(\dot{\varepsilon}_v - \eta \dot{e})\left(\boldsymbol{I} - \eta \frac{\dot{\varepsilon}}{\dot{e}}\right) \tag{5}$$

where κ is a penalty constant. The FEM, together with this constitutive equation, provides an equivalent equation for the upper bound theorem in plasticity; the method is called the RPFEM in this study. It is a noted property of this constitutive equation that the relationship between stress and the strain rate is specified. The norm of the strain rate is substantially indeterminate since focus is placed on the limit state of the structure. Stress is determined for the normalized strain rate using its norm in order to determine the limit load coefficient for the prescribed load. Hoshina et al. (2011) introduced the constraint condition on external work into the equilibrium equation by using the penalty method. They reported that more rational results were obtained by the developed method than by methods in previous works. The use of the penalty method is advantageous in that it can shorten the computation time and lead to stable computational results. Since this study focuses on cohesive soils, as mentioned above, the constitutive equation is limited to the von Mises yield function where the soil composing the ground exhibits plastically incompressible deformations. The rigid plastic constitutive equation is simple and effective for assessing the limit state of the ground due to the advantage of not using an uncertain elastic modulus for the ground.

3. Analysis of boundary conditions of model under plane strain condition

As was mentioned as the object of this study in the Introduction, although the lateral resistance of the pile is exerted along the longitudinal direction of the pile which increases with depth from a minimum value at the ground surface to a maximum value at a certain critical depth and remains constant up to the bottom part of the pile. This study introduces a two-dimensional model to analyze the behavior of the ground surrounding the pile. It treats the pile-soil interaction below the critical depth which indicates the threshold value where the failure mode of the ground changes from three-dimensional to two-dimensional behavior. The study newly defines the boundary conditions for the assessment of the ultimate lateral resistance of pile groups. Fig. 1(a) and (b) show two ways to simulate the pile-soil system with different boundary conditions. One way is to assess the reaction force at the limit state by applying a uniform velocity field to the pile, while the other way is to assess the ultimate lateral resistance by applying a load to the pile. To survey the ultimate lateral resistance of a pile group, the model in Fig. 1(a) is necessary for the computation in consideration of the piles-soil interaction which is unknown prior to the analysis. Fig. 1(a) shows the typical finite element mesh and the first boundary condition of the single piles used in the analysis. A mesh with approximately 4000 four-node iso-parametric rectangular elements was used to model the piles and the soil surrounding the piles. A finer density mesh was employed around the piles. Each pile was modeled as a solid element and the strength of the pile was set to be higher than that of the soil in order to simulate a rigid pile. The soil and the piles were modeled as rigid perfectly plastic material with the following properties: the undrained shear strength of the soil was $c_u = 100$ kPa and the internal friction angle of the soil was $\phi = 0$ deg, while the shear strength of the pile material was $c_p = 50{,}000$ kPa and the internal friction angle of the piles was $\phi = 0$ deg. Analyses were performed for a pile diameter of $D = 0.6$ m. In particular, higher strength elements were employed for the outer boundary elements in order to simulate the homogeneous ground movement at the boundary elements. A uniform distributed load was applied at all nodes of the rigid outer boundary elements to define the prescribed load and the load coefficient. The ultimate lateral resistance was assessed by computing the limit value for this load coefficient. The center of each pile was set as the fixed velocity boundary condition and the reaction of the piles was computed to analyze the load bearing ratio. The two boundary surfaces, parallel to the direction of the ground movement, were set as the slider condition. The distance from the center of a pile to all four boundary surfaces was basically set to be far away in order to avoid the effect of the boundary conditions on the failure mode of the ground around the pile; it was set at more than 10.0 D in all analyses. Fig. 1(b) shows the second boundary condition for directly applying the load on the pile, as was seen in past works. While the center of each pile was set to be under the free condition, the four boundary surfaces were set to be under the fixed condition. The analysis was performed by applying a uniformly distributed load on all nodes of the pile diameter.

The ultimate lateral resistance of the pile was generally obtained as a value close to 12.27 c_u for model (a) and 12.30 c_u for model (b), in which the total resistance is normalized by the length of the pile diameter. As a result, since the setting of the shear strength and the pile diameter does not affect the ultimate lateral resistance, the ultimate lateral resistance is shown irrespective of them. The results obtained for the strain rate distribution for a single pile are shown in Fig. 2. The norm of the strain rate presented contour lines in the range of $\dot{e}_{\max} \sim \dot{e}_{\min} (= 0)$. The distribution of $\dot{e}$ shows the failure mode of the ground and reflects the pile-soil interaction effect. Fig. 2 shows the failure modes of a single pile under both boundary conditions. The failure zone of the ground around the pile is observed in the range of 1.5 D–2.0 D from the center of the pile and is the same as the slip line described in Broms (1964), Georgiadis et al. (2013a, 2013b, 2013c) and Zhao et al. (2017a, 2017b). The obtained ultimate lateral resistance of a single pile against the horizontal ground movement was 12.27 c_u for the perfectly rough pile condition, which is similar to the value of 11.95 c_u reported by Georgiadis et al. (2013a, 2013b, 2013c). The difference may be caused by the fact that they employed different models, namely, the soil and the pile were modeled as linear elastic-perfectly plastic and linear elastic materials in their work.

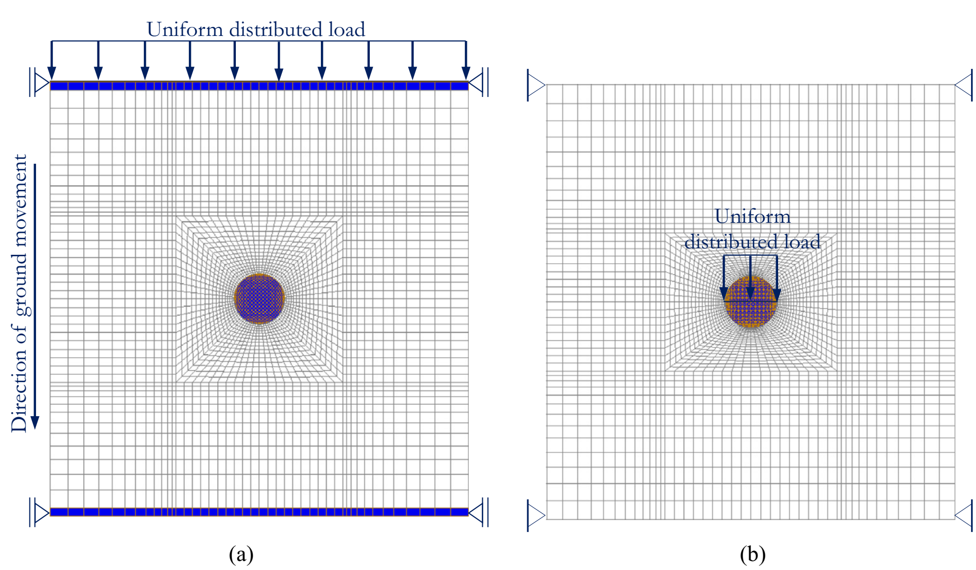


Fig. 1. Typical finite element mesh and two boundary conditions of single pile for RPFEM.

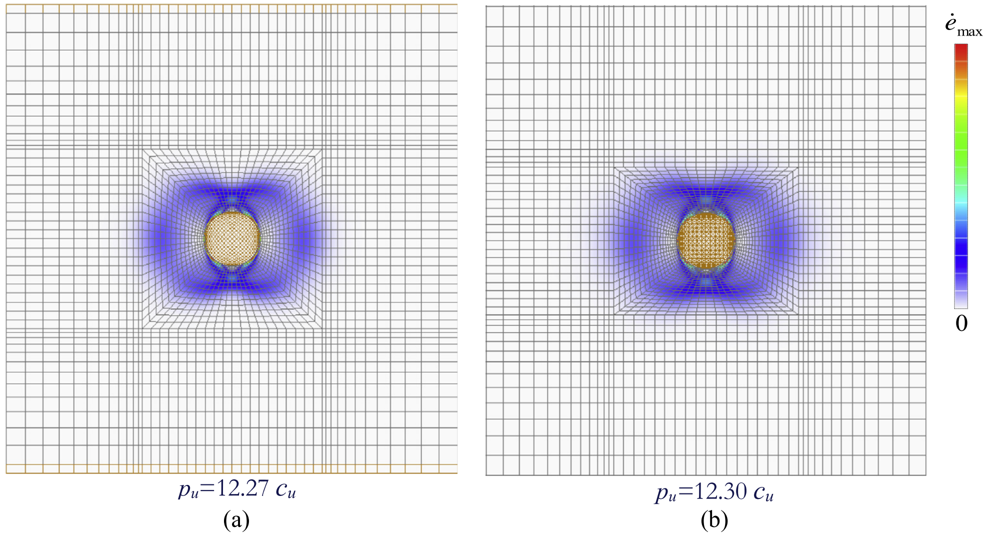


Fig. 2. Failure modes of single pile in two models.

The ultimate lateral resistance of a single pile was also computed by the RPFEM in the same way as in past works in which the pull-out force was directly applied to the pile, as shown in Fig. 2(b). The obtained value was found to coincide with that of the problem defined in Fig. 1(a). This indicates that the method proposed for assessing the ultimate lateral resistance of piles is rational and accurate. In addition, the method provides a load bearing ratio for each pile in the pile group against the homogenous ground movement. The upper bound method tends to overestimate the limit value even though an optimization is conducted. Basically, it is difficult to judge the magnitude of an exact solution; however, the results obtained here have apparently proven it to be almost the same as that in past works.

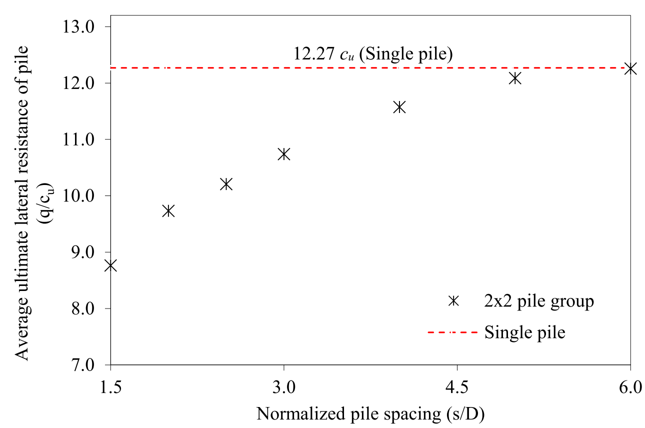


Fig. 3. Average ultimate lateral resistance of pile in 2 × 2 pile group.

4. Ultimate lateral resistance of 2 × 2 pile group

4.1. Group effect on ultimate lateral resistance

In practice, piles are often employed in a group and the performance of the piles is influenced by the pile-soil interaction. Therefore, to survey the group effect, the ultimate lateral resistance of a 2 × 2 pile group in clayey soil was investigated in this study. The ultimate lateral resistance was systematically computed for changes in the pile spacing where the spacing, s, is the distance between the centers of two piles. When the four piles and the intermediate ground between the piles form a rigid body, the ultimate lateral resistance of the 2 × 2 pile group can be compared with that of a square pile. A numerical simulation was conducted for horizontal ground movement by fixing the pile spacing from 1.5 D to 6.0 D, in which D is the outside diameter of a single pile. The size of the square pile L was adjusted to have the same outer perimeter as a pile group and $L = s + D$.

Fig. 3 shows the variation of the average ultimate lateral resistance of pile in 2 × 2 pile group with the normalized pile spacing s/D, in which the average ultimate lateral resistance (q/c_u) of piles is expressed as q/c_u to indicate the normalized value by the undrained shear strength of clay c_u. The average ultimate lateral resistance q (kN/m^2) is subsequently calculated by dividing the total ultimate lateral reaction force Q (kN/m) by the pile diameter and the number of piles. The average ultimate lateral resistance of pile tends to increase with an increasing pile spacing and coincides with the ultimate lateral resistance of 12.27 c_u the isolated single pile at a sufficiently large pile spacing. This trend was found to have been caused by the difference in the failure modes of the ground peripheral of the piles, as seen in Fig. 4. The failure mode of the ground around the piles apparently changed as the pile spacing increased from 1.5 D to 6.0 D.

The results obtained for the strain rate distribution of the two models with a normalized pile spacing s/D = 1.5 and a normalized pile width L/D = 2.5 are shown in Fig. 5. The figure expresses the failure modes of both the pile group in case of s/D = 1.5 and the square pile corresponding to pile group. The total ultimate lateral reaction

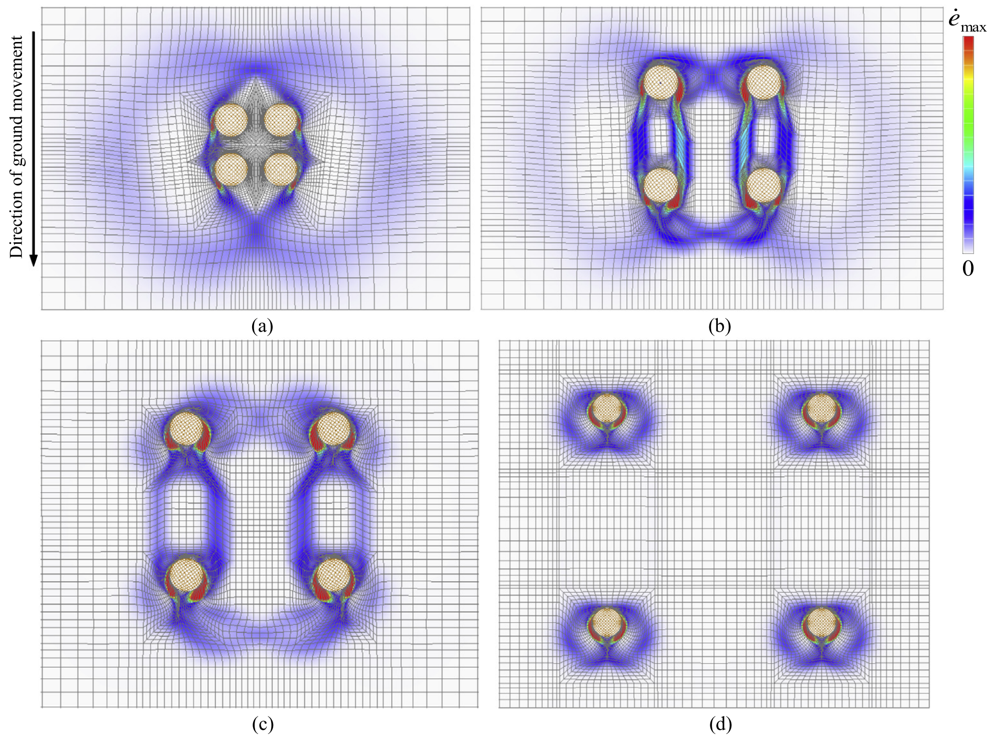


Fig. 4. Deformation diagrams of 2 × 2 pile group: (a) s/D = 1.5, (b) s/D = 3.0, (c) s/D = 4.5, and (d) s/D = 6.0 in direction of 90 deg.

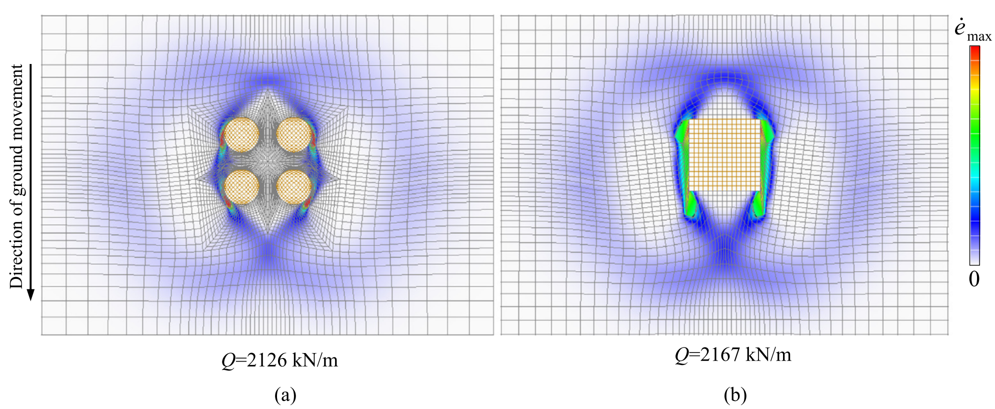


Fig. 5. (a) Deformation diagrams of 2 × 2 pile group with normalized pile spacing s/D = 1.5 in direction of 90 deg. (b) Deformation diagram of square pile with normalized pile width L/D = 2.5 (In computation D = 0.6 m was employed).

force of two models was obtained to almost coincide each other, namely, 2126 (kN/m) and 2167 (kN/m), respectively. This is because in the case of a normalized pile spacing s/D = 1.5, the ground between the piles did not undergo any plastic deformation due to the support of the piles, as shown in Fig. 5(a). Four different failure modes of the ground around the 2 × 2 pile group are indicated in Fig. 4(a)–(d) for normalized pile spacing s/D = 1.5, 3.0, 4.5, and 6.0, respectively. It is noted that all figures only present the ground around the piles in order to focus the failure mode of the ground, despite the wider ground area was analyzed to avoid the effect of the boundary condition. They express the deformation of the ground by multiplying the arbitrary time by the obtained nodal velocity in order to clearly indicate each failure mode. The illustrated deformation expresses the failure mode at the limit state. With an increase in pile spacing, the failure mode of the ground is found to change. At a smaller pile spacing, two pile lines form a rigid block and the intermediate ground between the two pile lines passes through the piles along the two pile lines. The detailed failure mode of the intermediate ground reflects the pile spacing even though the failure modes seem similar. Finally, when the pile spacing reaches 6.0 D, no group effect can be observed, as shown in Fig. 4(d).

4.2. Effect of direction of ground movement on ultimate lateral resistance

Georgiadis et al. (2013b) and Zhao et al. (2017a, 2017b) investigated the effect of the loading direction on the ultimate lateral resistance of two-pile groups, with a tetrapod jacket foundation and a tripod foundation, for the prescribed load applied to piles. They demonstrated the change in the ultimate lateral resistance of pile group and the failure mode of the ground around the piles. The present study investigates the effect of the direction of the ground movement on the ultimate lateral resistance of a 2×2 pile group for various horizontal directions. The horizontal direction angle is defined as being the angle between the direction of the ground movement and the pile to pile axis, and the angle varies from 0 to 90 deg. The load applied to the piles is basically unknown and must be determined through computation.

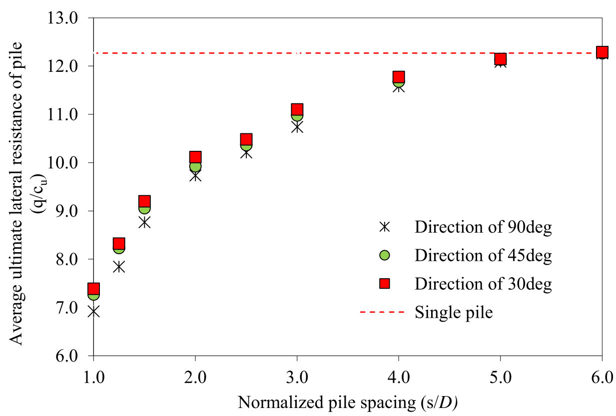


Fig. 6. Effect of the direction of ground movement on average ultimate lateral resistance of 2×2 pile group.

The effect of the direction of the ground movement on the average ultimate lateral resistance (q/c_u) is presented in Fig. 6. It indicates that the average ultimate lateral resistance increased with the increase in pile spacing for all cases of direction angles. It was the lowest at 90 deg; however, the greatest difference in ultimate lateral resistance among the various direction angles did not exceed 7% at any pile spacing and little effect of the direction was observed. These results are preferable from the design viewpoint because the resistance performance of a pile group can be expected to be sufficient for any direction of ground movement. In all cases of ground movement direction, the difference was maximum at a small pile spacing. However, it is noticeable that the effect of the direction of the ground movement on the failure mode of the ground around the piles was different, as shown in Figs. 4 and 7. At the small pile spacing of 1.5 D, although the average ultimate lateral resistance of pile was similar for any direction of ground movement, the change in the failure mode of the ground peripheral of the piles was clearly observed in Figs. 4(a), 7(a), and 7(c). It is noted that the intermediate ground surrounding the four piles deformed in the cases of 30 and 45 deg, whereas no plastic deformation was observed in the case of 90 deg, as seen in Fig. 4(a). For the pile spacing of 6.0 D, the failure mode of the ground was obtained as being almost the same as that in Figs. 4 (d), 7(b), and 7(d) regardless of the direction of the ground movement.

Moreover, to compare the performance of each pile in a group with that of a single pile, the lateral resistance of

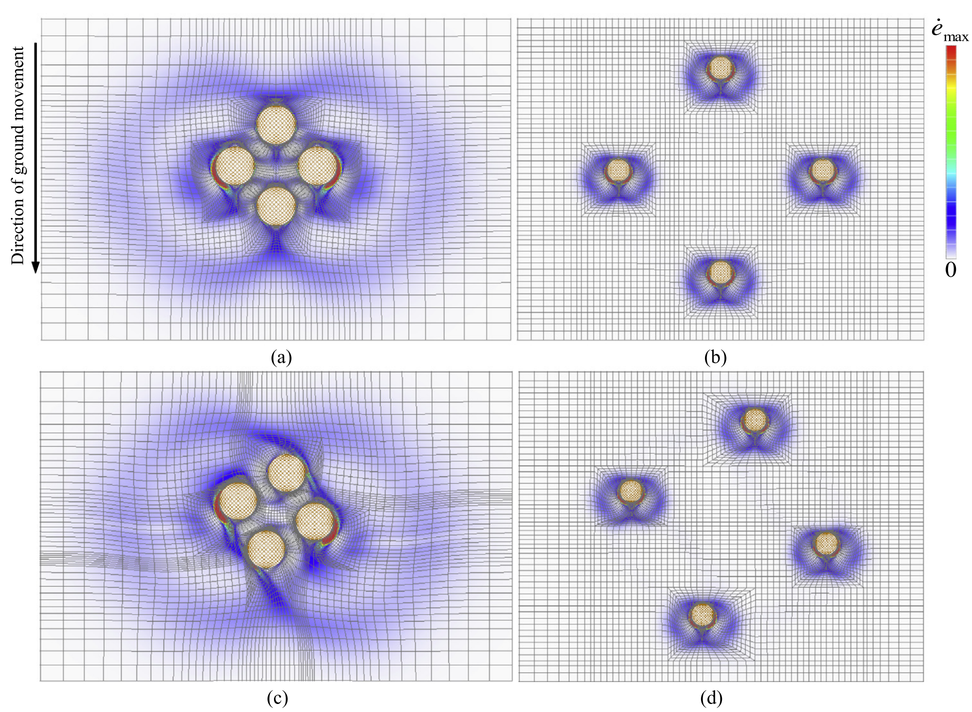


Fig. 7. Deformation diagrams of 2×2 pile group: (a) s/D = 1.5 and (b) s/D = 6.0 in case of 45 deg; (c) s/D = 1.5 and (d) s/D = 6.0 in case of 30 deg.

each pile in a group is calculated. The ratio of the lateral resistance of each pile to that of a single pile is defined as the load bearing ratio in this study. The ultimate lateral resistance of each pile was assessed by computing the reaction force at the center of each pile, where the fixed velocity boundary condition is imposed. The results given in Table 1 show that the load bearing ratio of each pile possessed two components of reaction, in which x and y components express the perpendicular and the parallel components to the direction of ground movement, respectively. The table indicates that the x component of reaction was generally very small in comparison to the y component of reaction, and that the total load bearing ratio of the pile almost coincided with that of the y component of reaction. The load bearing ratio of each pile tends to increase with the increase in pile spacing. In the case of 90 deg, the load bearing ratio of the front pile was greater than that of the back pile in all cases of pile spacing. While the load bearing ratio of the front pile was slightly less than 1.0, a significant reduction in the load bearing ratio of the back pile was observed to be nearly 37% at a small pile spacing ($s = 1.5\ D$). When the pile spacing was about 6.0 D, the load bearing ratio of each pile was 1.0, which is identical to that of an isolated single pile. The failure mode was obtained as the single-pile mode, and the failure area of the ground around the pile reached 1.5 D–2.0 D from the pile center. In the case of 45 deg, the load bearing ratios of the two side piles were significantly greater than those of the two middle piles at a small pile spacing. However, there was not much difference between the load bearing ratios of each pile for a pile spacing in the range of 4.0–6.0 D. In the two middle piles, the back pile may have been supported by the front pile and the two side piles so that the load bearing ratio of the back pile had the smallest value among them. The results showed that the effect of the direction of the ground movement on the load bearing ratio is considerable.

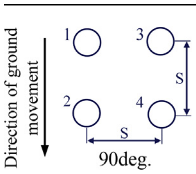
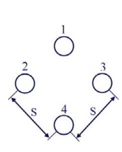
5. Ultimate lateral resistance of line alignment pile groups

5.1. Effect of direction of ground movement in case of pile group with few piles

This study considered groups of two, three, and four piles arranged in a row. The effect of the direction of the ground movement on the ultimate lateral resistance of the pile groups was widely investigated. Georgiadis et al. (2013b) reported a calculation for the ultimate lateral resistance of two piles in clay for various loading directions. Their results show that the ultimate lateral resistance of the pile group was changed significantly by the loading direction. However, the effect of the number of piles arranged in a row was not considered. In this study, the effect of the direction of the ground movement on the ultimate lateral resistance by an increase in the number of piles is addressed. The ultimate lateral resistance and the ground failure mechanism were found to depend on both the pile spacing and the pile number. An examination was conducted on two to four piles for the direction angle of the ground movement in the range of 0–90 deg, in which the direction angle was defined as the angle between the direction of ground movement and the pile to pile axis. To discuss the effect of the direction of the ground movement for various numbers of piles, the average ultimate lateral resistance of pile in the pile group was computed by considering the pile number.

Fig. 8 shows the relationship between the average ultimate lateral resistance and the normalized pile spacing for an increase in pile number. Despite the number of piles, a similar trend was found in the computed relationship in the figure. In the case of two piles, the average ultimate lateral resistance decreased almost proportionally to the decrease in the direction angle of the ground movement in the range of 1.0 D–3.0 D spacing, and it coincided with

Table 1
Summary of load bearing ratios in 2 × 2 pile groups in case of 90 and 45 deg.

Group size	s/D	Load bearing ratio							
		1st pile		2nd pile		3rd pile		4th pile	
		x	y	x	y	x	y	x	y
	1.5	0.04	0.80	0.07	0.63	0.04	0.80	0.07	0.63
	2.0	0.02	0.86	0.05	0.73	0.02	0.86	0.05	0.73
	3.0	0.01	0.93	0.04	0.83	0.01	0.93	0.04	0.83
	4.0	0.01	0.98	0.03	0.91	0.01	0.98	0.03	0.91
	5.0	0	0.99	0.01	0.98	0	0.99	0.01	0.98
	6.0	0	1.00	0	1.00	0	1.00	0	1.00
	1.5	0	0.72	0.12	0.91	0.12	0.91	0	0.42
	2.0	0	0.79	0.07	0.95	0.07	0.95	0	0.54
	3.0	0	0.92	0.04	0.96	0.04	0.96	0	0.71
	4.0	0	0.96	0.01	0.97	0.01	0.97	0	0.90
	5.0	0	0.98	0	1.00	0	1.00	0	0.97
	6.0	0	1.00	0	1.00	0	1.00	0	1.00

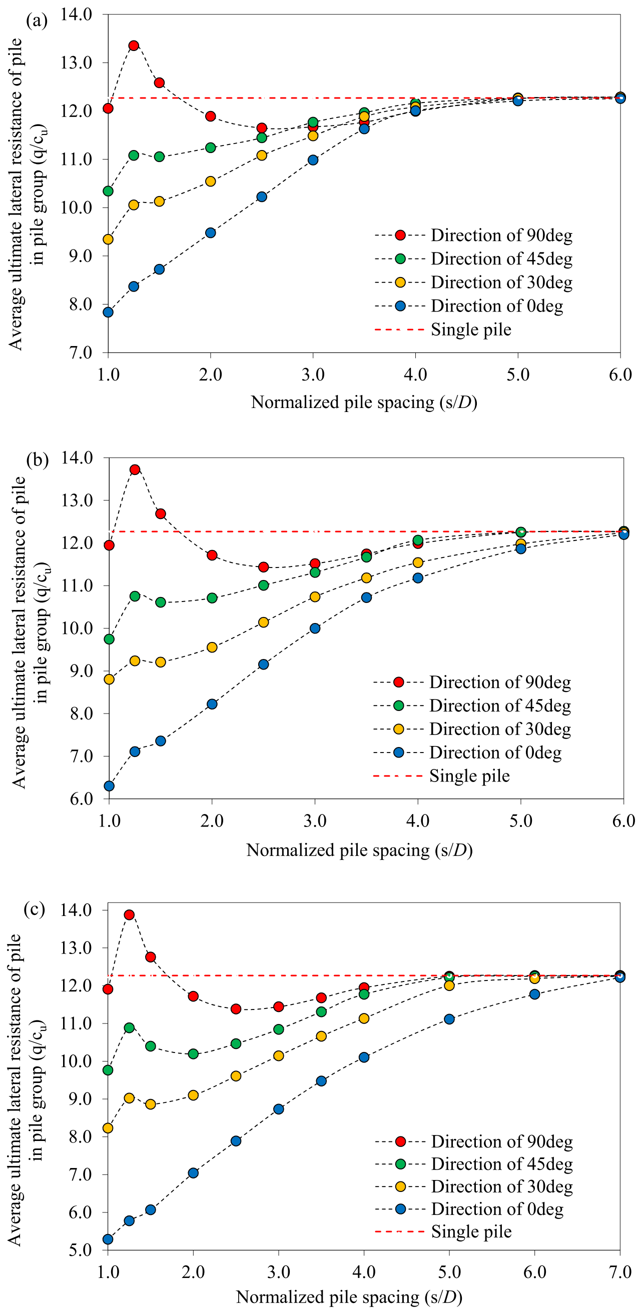


Fig. 8. Average ultimate lateral resistance of pile in case (a) two-pile, (b) three-pile, and (c) four-pile groups.

that of a single pile with a range in pile spacing of 4.0 *D*–6.0 *D*, while the average ultimate lateral resistance increased non-linearly with an increase in pile spacing for all directions. In the case of 90 deg, the average ultimate lateral resistance was slightly higher than that of a single pile in the range of nearly 1.0 *D*–1.75 *D*. This is because the two piles and the intermediate soil behaved as a rigid block, as shown in Fig. 9(a) of 90 deg. Similar results can be found in the computational results in Georgiadis et al. (2013). However, the authors cannot find experimental data to verify them. It seems appropriate that the average ultimate lateral resistance was the greatest in the case of 90 deg, since the substantial distance of the pile spacing projected to the perpendicular plane against the ground movement was the largest even if the pile spacing was the same. However, as the failure mode of the pile-soil system varied depending on the pile spacing, the peak value for the average ultimate lateral resistance was obtained at a pile spacing of around 1.25 *D*. The trend to locally form the peak value was observed for other inclination angles at a pile spacing of around 1.25 *D*. In the cases of three-pile and four-pile groups, the obtained results also show a similar trend to that of the two-pile group in Fig. 8(b) and (c). However, the difference in the average ultimate lateral resistance between the case of 90 deg and that of 0 deg increased with an increase in the number of piles. In the case of 90 deg, the average ultimate lateral resistance of the pile group was the same for the pile spacing despite the number of piles. However, in the case of 0 deg, the average ultimate lateral resistance was shown to vary with the number of piles and to decrease with an increase in the number of piles. The effect of the pile number on the trend in the ultimate lateral resistance against the pile spacing changed with the number of piles, where the range in pile spacing to vary the ultimate lateral resistance became wider. The other cases, varying from 0 to 90 deg, were found to be in between those of 0 and 90 deg.

As the preliminary analysis, discussed above, the effect of the direction of the ground movement was caused by changes in the failure mechanism of the ground around the piles. The typical failure modes of the two-pile, three-pile, and four-pile groups were influenced by the direction of the ground movement with a normalized pile spacing of $s/D = 1.25$, as shown in Fig. 9. In the cases of 0 and 90 deg, the intermediate ground of the piles did not yield any plastic deformation, whereas it clearly yielded plastic deformation in the case of 45 deg. This indicates that shearing of the intermediate ground took place despite the same pile spacing in the cases of 0 and 90 deg. It is interesting that the failure mode changed due to the direction of the ground movement in spite of the smaller pile spacing, and that the average ultimate lateral resistance continuously varied between the values of 0 and 90 deg. It can be observed from Fig. 9(a)–(c) that the area of the failed ground became wider as the number of piles became greater due to the group effect. The failure zone of the ground around the piles was about 3.0 *D*–3.5 *D* from the centers of the piles for the two-pile group, 4.5 *D*–5.0 *D* for the three-pile group, and 5.5 *D*–6.0 *D* for the four-pile group.

5.2. Effect of direction of ground movement in case of infinitely long row of piles

In practice, an infinite number of piles in a long row is sometimes employed to support structures. Chen (1994) and Bransby and Springman (1999) used a finite element analysis to evaluate the group effect of rows of closely spaced piles under lateral loading from ground movement. Georgiadis et al. (2013c) employed analytical upper bound plasticity methods to investigate the undrained limiting lat-

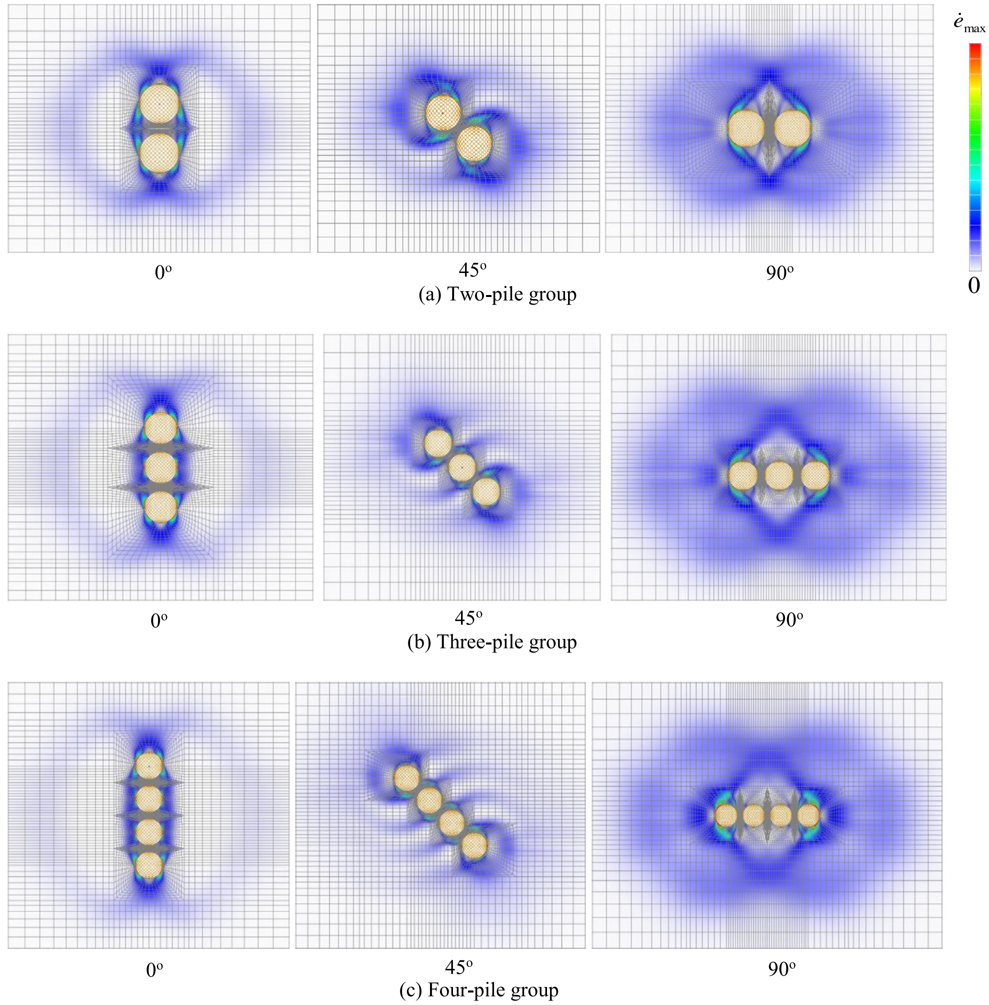


Fig. 9. Failure modes of pile groups with normalized pile spacing $s/D = 1.25$ in cases of 0, 45, and 90 deg, respectively.

eral resistance of piles in a row. However, no reports on the effect of the direction of the ground movement on an infinitely long row of piles can be found in the literature. Therefore, it is necessary to search for solutions that will give insight into this problem and to predict the effect in practice. In this study, an analysis was conducted for a unit cell by considering the symmetric property of the problem. It is noted that the width of the unit cell is dependent on the pile spacing and that the average ultimate lateral resistance of the piles is determined by the pile number per length. The ultimate lateral resistance of piles was computed against the horizontal movement in the same way as before. The typical finite mesh element and boundary condition of a unit cell on an infinitely long row of piles are shown in Fig. 10(a). As seen in this figure, the unit cell is defined due to the symmetry of the geometry to consider the behavior of the infinitely long row of piles. The figure expresses the model of the half piles and the intermediate ground for the direction angle of 45 and 90 deg between the direction of ground movement and the pile to pile axis. The setting of the boundary condition of the unit cell is similar to that of pile groups. The results of the failure modes for the intermediate ground between the piles varied significantly depending on the range in normalized pile spacing of 1.5–6.0, as shown in Fig. 10(b). The calculated results for the ultimate lateral resistance of the unit cell are shown in Fig. 11(a). The ultimate lateral resistance was the same as that of Georgiadis et al. (2013c). It is interesting to survey the failure mode of the ground when the ultimate lateral resistance of each pile is identical with that of a single pile at the pile spacing around 1.5 D. However, it is difficult to directly discuss since this numerical method cannot assess the ultimate lateral resistance in succession for the change in pile spacing. The relationship between the ultimate lateral resistance and the failure mode has not been made clear, but it is apparent that the failure mode changed from the combined mode of two failure modes for piles to the isolated two single failure mode.

Here, the ultimate lateral resistance of two and three rows of an infinite number of piles was also analyzed. However, the pile arrangement was limited to the lattice arrangement where the unit cell can be defined. It can be seen in Fig. 11 that both the group effect and the effect of the direction of the ground movement on the average ultimate lateral resistance of the piles were the same as those of the one row of an infinite number of piles. In the case of 90 deg, the average

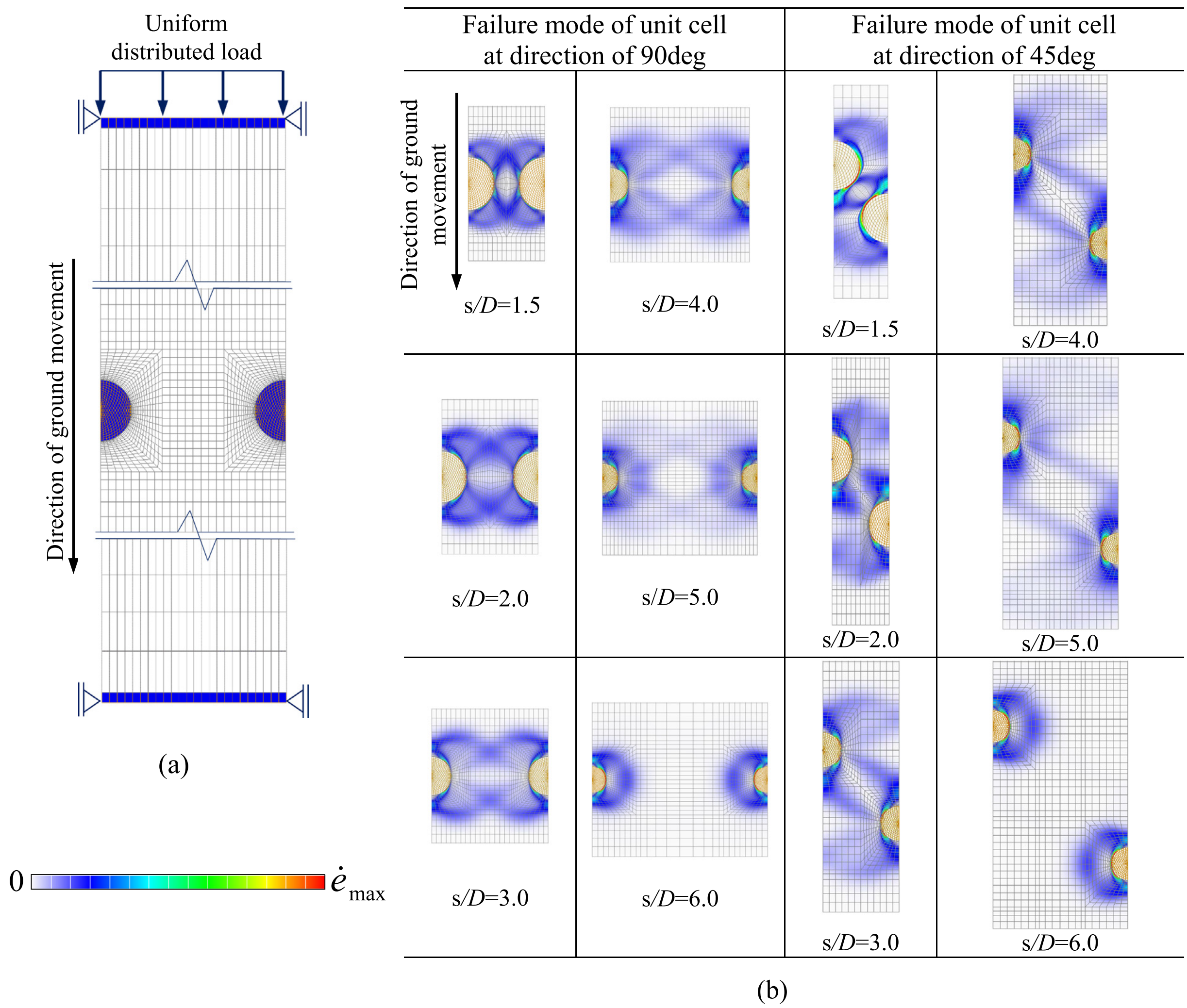


Fig. 10. (a) Typical finite element mesh and boundary conditions of unit cell in case of 90 deg. (b) Failure modes of unit cell for one row of infinite number of piles in case of 90 deg and 45 deg.

ultimate lateral resistance of the row of piles was found to decrease with an increase in the number of rows. The same trend can be seen in the case of 45 deg. On the other hand, the difference in average ultimate lateral resistance between the cases of 90 and 45 deg decreased with an increase in the number of rows. It was found that the difference became almost zero in the case of the three rows of piles.

It is noted that the ultimate lateral resistance of multiple rows of piles was almost the same for various directions of ground movement. Since the staggered arrangement of piles is often employed in practice, it needs to be surveyed in the same way. However, it is difficult to set the unit cell to represent the resistance mechanism of a staggered arrangement of piles. Therefore, this problem will be addressed in a future study. The ultimate lateral resistance of piles in a staggered arrangement is thought to be higher than that in a lattice arrangement. However, the effect of the direction of the ground movement can be predicted as being the same for the staggered arrangement of piles as for the lattice arrangement of piles.

6. Load bearing ratio of piles in pile groups

Significant differences in the piles were seen in the results for two piles, three piles, and an infinite number of piles in a row due to the group effect. Tables 2 and 3 present summaries of the obtained results for the load bearing ratios of piles for a variety of spacing. The difference in load bearing ratios can be seen clearly for directions in ground movement. However, the load bearing ratios were generally less than 1.0 at a small pile spacing and increased with an increase in pile spacing to finally converge to 1.0.

In the case of a direction angle of 0 deg, the two-pile and three-pile cases were compared. The load bearing ratio was greater for the front pile and less for the back pile. The difference in the load bearing ratios of the piles were comparatively large. However, this trend was greatly seen at a small pile spacing and was seen less with an increase in the pile spacing. It is noted that the load bearing ratio of the middle pile was the smallest for the three-pile case as the pile spacing was small.

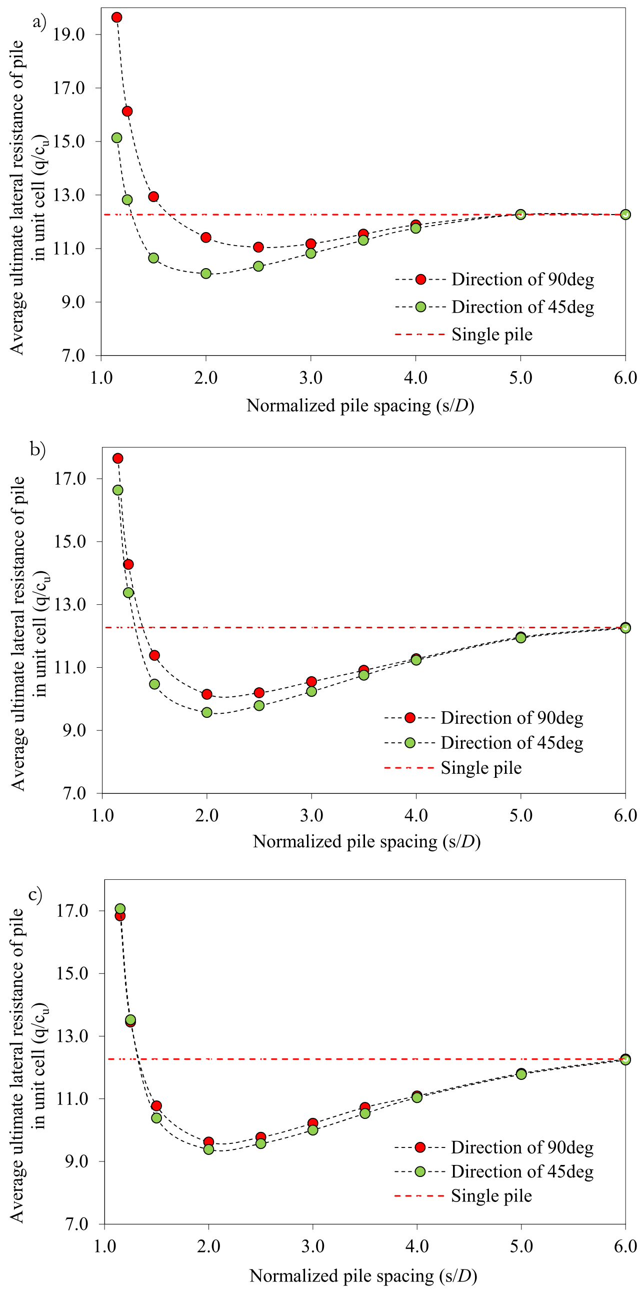


Fig. 11. Average ultimate lateral resistance of pile in unit cell in case (a) one row; (b) two rows, and (c) three rows of piles.

In the case of a direction angle of 90 deg, the cases of two piles, three piles, and an infinite number of piles were analyzed. The variance in the load bearing ratios was comparatively small among the piles despite the pile spacing. The general property of the load bearing ratios can be seen typically for the case of an infinite number of piles. It was greater than unity at a smaller pile spacing, but it decreased with an increase in pile spacing and became less than 1.0 around 2.0 *D* and 3.0 *D*. Beyond the pile spacing of 3.0 *D*, the load bearing ratio of the piles increased with the pile spacing and approached 1.0.

In the case of a direction angle of 45 deg, the cases of two piles, three piles, and an infinite number of piles were analyzed. The same trend in load bearing ratios was obtained as in the case of 90 deg, but the uniqueness of this case was that two orthogonal components existed in the reaction force. The component of the reaction force in the same direction as the ground movement was large, while that of the orthogonal direction was found to be comparatively small. Hence, the load applied to the piles almost coincided with the reaction component for the same direction of ground movement.

7. Conclusions

This study has investigated the ultimate lateral resistance of pile groups against the horizontal ground movement of clayey soils using the rigid plastic finite element method. The group effect of the piles and the effect of the direction of the ground movement on the ultimate lateral resistance were analyzed for changes in pile spacing.

The conclusions of this study are as follows:

1. The ultimate lateral resistance of piles was analyzed against the horizontal ground movement by defining the displacement boundary value problem. The ultimate lateral resistance was obtained by computing the resultant reaction force of the piles. The advantage of this method is that it can assess the load bearing ratio of piles in a pile group at the limit state. The RPFEM provided the ultimate lateral resistance of an isolated single pile as 12.27 c_u for a perfectly rough pile in clayey soils where c_u is the undrained shear strength of clayey soil. The failure zone of the ground around the pile was found to be in the range of 1.5 *D*–2.0 *D* from the center of the pile. It was similar to the result reported by Broms (1964).
2. The group effect in the ultimate lateral resistance of piles was clarified by varying the pile spacing. Regarding the 2 × 2 arrangement of four piles, as well as the two, three, four, and infinite number of piles arranged in a row, the group effect was assessed by changing the direction of the ground movement. For each case, the load bearing ratio of the pile was examined.
3. The effect of the pile spacing on the ultimate lateral resistance was found to reflect the failure mode of the pile-soil system. When the pile spacing was large, the failure mode of the ground around each pile coincided with that of a single pile, but as the pile spacing decreased, the failure modes of the ground for the piles interfered with each other. The group effect on the ultimate lateral resistance appeared at this stage. The intermediate ground between the piles formed a rigid block in the failure mode of piles and a ground system when the pile spacing was even smaller.
4. In the case of the 2 × 2 piles, the ultimate lateral resistance of each pile was shown to be equal to that of a single pile when the pile spacing was large, and to decrease monotonically as the pile spacing decreased. Almost no difference was found in the average ultimate lateral resistance of pile for changes in the direction of the ground

Table 2
Summary of load bearing ratios in case of 0 and 90 deg.

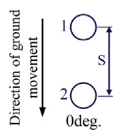
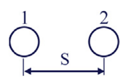
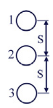
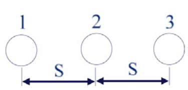
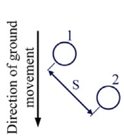
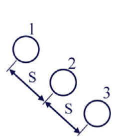
Group size	s/D	Load bearing ratio		
		1st pile	2nd pile	3rd pile
 0deg.	1.5	0.76	0.67	
	2.0	0.81	0.73	
	3.0	0.93	0.86	
	4.0	0.99	0.96	
	5.0	1.00	0.99	
 90deg.	1.5	1.03	1.03	
	2.0	0.97	0.97	
	3.0	0.95	0.95	
	4.0	0.98	0.98	
	5.0	1.00	1.00	
 0deg.	1.5	0.72	0.52	0.57
	2.0	0.86	0.54	0.61
	3.0	0.94	0.75	0.76
	4.0	0.97	0.91	0.85
	5.0	1.00	0.98	0.92
 90deg.	1.5	1.04	1.02	1.04
	2.0	0.98	0.90	0.98
	3.0	0.98	0.85	0.98
	4.0	1.00	0.94	1.00
	5.0	1.00	1.00	1.00
One row of infinite number of piles 90deg.	1.15	1.60		
	1.5	1.05		
	2.0	0.93		
	3.0	0.91		
	4.0	0.97		
	5.0	1.00		

Table 3
Summary of load bearing ratios in case of 45 deg.

Group size	s/D	Load bearing ratio					
		1st pile		2nd pile		3rd pile	
		x	*y*	*x*	*y*	*x*	*y*
	1.5	0.04	0.93	0.05	0.87		
	2.0	0.03	0.94	0.04	0.90		
	3.0	0.03	0.97	0.03	0.95		
	4.0	0.02	1.00	0.03	0.99		
	5.0	0	1.00	0	1.00		
	1.5	0.02	0.92	0.07	0.79	0.03	0.89
	2.0	0.02	0.93	0.06	0.80	0.03	0.91
	3.0	0.01	0.96	0.04	0.87	0.01	0.93
	4.0	0	1.00	0.03	0.98	0	0.99
	5.0	0	1.00	0	1.00	0	1.00
One row of infinite number of piles	1.15	0.07	1.23				
	1.5	0.05	0.87				
	2.0	0.03	0.82				
	3.0	0.02	0.88				
	4.0	0	0.96				
	5.0	0	1.00				

movement. However, the load bearing ratio of the piles varied among the piles, and it was seen to be larger in the front pile with respect to the ground movement and smaller in the back pile. It varied with the direction of the ground movement.
5. In the case of the piles in a row, the ultimate lateral resistance was equal to that of a single pile when the pile spacing was large. It was obtained to vary greatly depending on the pile spacing and the direction of the ground movement. With the decrease in pile spacing, the ultimate lateral resistance of the piles decreased due to the group effect. However, when the pile spacing was less than about 2.0 *D*, the ultimate lateral resistance was found to increase greatly regardless of the direction of the ground movement. For the piles in a row orthogonal to the ground movement, the ultimate lateral resistance of each pile was larger than that of a single pile when the pile spacing was small. On the contrary, for the piles in a row in the same direction as the ground movement, the ultimate lateral resistance of each pile decreased monotonously as the pile spacing decreased. As for the group effect, the load bearing ratio of each pile was computed in detail with respect to the changes in the direction of the ground movement.

Acknowledgements

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