Geomechanics and Engineering, *Vol. 26, No. 1 (2021) 13-25*
https://doi.org/10.12989/gae.2021.26.1.013

Pile-soil interaction determined by laterally loaded fixed head pile group

Aysan Poorjafar[1a], Mahzad Esmaeili-Falak[2b] and Hooshang Katebi[*1]

[1]*Faculty of Civil Engineering, Department of Geotechnical Engineering, University of Tabriz, Tabriz, 5166616471, Iran*
[2]*Department of Civil Engineering, Tehran North Branch, Islamic Azad University, Tehran, 1468763785, Iran*

(Received August 13, 2020, Revised May 14, 2021, Accepted June 23, 2021)

Abstract. This paper summarizes the results of small-scale laboratory modelling of pile behavior under lateral loading, considering the parameters such as short or long, single or group, spacing and rigidity or flexibility of piles. The head of piles was fixedly connected to the cap. In addition, the PIV method has been used to examine the effect of the mentioned parameters on the failure mechanism and pile-soil interaction more accurately. The results show that the short piles have a rigid movement, the displacement of the surrounding soil has occurred along the total length of the pile and the piles rotate around a point but the long piles have a flexible movement at the part of the pile length. It seems that the group effect be more obvious for long piles than short piles. Also, the effective depth of total soil displacement vectors around the trail pile is more than the lead one in long pile group, while this depth for trail pile is less than the lead pile in short pile group. Due to the sharper angles of total displacement vectors around the trail pile, the intensity of soil shear strains around the trail pile is greater than the lead pile.

Keywords: deflection and rotation point; laterally loaded piles; physical modelling; pile group; pile-soil interaction

1. Introduction

For supporting various structures constructed on poor soils from lateral and vertical loads, pile foundations are used widely, where shallow foundations have remarkable problem from the point of view of low bearing capacity and unacceptable settlement. The piles are used to support whether vertical load, lateral load or sometime combination of these (Poulos and Davis, 1980). Moreover, a pile-soil interaction issue is complicated as this phenomenon is a function of pile and geometry properties, interaction friction between soil and pile, type of loading as well as soil specification (Maghsoodi *et al.* 2013, Aksoy *et al.* 2016). For designing piles, pre-failure conditions derived from pile-soil interaction are of paramount importance and must exactly be considered.

A single pile may behave substantially different from pile within a group. In addition, depending on the position of the pile in a group, the behavior of the pile may be different (McVay *et al.* 1995, Keawsawasvong and Ukritchon 2016). To research around geotechnical engineering, experimental studies and physical modelling have been widely used within the researchers (Esmaeili-Falak 2012, Esmaeili-Falak *et al.* 2018, 2020). The vertical and lateral responses of piles would be better to be considered simultaneously with their interactions. This approach could be acceptable just for small lateral loads (Brown *et al.* 1988), but, for pile groups, the lateral loads are not negligible and they are about 10 to 20% of the vertical loads.

Large laterally loaded pile groups in loose and medium dense sand have been studied by McVay *et al.* (1998). They measured bending moment and shear forces of the pile head. They investigated pile group interaction effects, and found that the p-y concept was independent from the soil density and is only a function of the pile group geometry.

The behavior of pile group multi-layered model was studied in order to determine the pile-soil-pile interaction effects (Rollins *et al.* 1998; Esmaeili-Falak, 2013). During same load conditions, the single pile was deflected half times less than pile group. Moreover, bearing capacity of the trail piles are less than that of the lead ones. Rollins *et al.* (2006) did another study on laterally loaded pile group in stiff clay. They showed that, increase in pile spacing from 3.3D to 5.65D leads to considerable decrease on the interaction effects of the group. In the pile group, considering the location into a row, lateral bearing is a function of location of row within the group. In pile group, the largest bearing corresponds to the front pile rows, while the next pile rows (second ones) have lower load capacity. Al-abboodi *et al.* (2020) studied sandy soil behavior around the pile group under lateral loading. They attempted to examine the influence of soil density, the depth of moving layer and pile spacing on the behavior pile group subjected to a uniform profile of lateral soil movement. They indicated that the effect of pile spacing were related to the soil-structure interaction caused by the transferring process of forces between pile rows with the existing of the rigid pile cap.

Laterally loaded single and pile group in soft clay has been investigated in physical modelling tests (Bauer *et al.*

∗Corresponding author, Professor
E-mail: Katebi@tabrizu.ac.ir
[a]M.Sc.
E-mail: apg.civil@gmail.com
[b]Assistant Professor
E-mail: Mahzad.ef@tabrizu.ac.ir

http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

2016, Shen *et al.* 2017). Soil displacement around piles was calculated experimentally and analytically. The soil mass displacement pattern around the piles leads to increase in lateral force at pile sides in very soft soils. On the contrary, soil mass accumulated in front of the pile in case of stiff soils. For comparing the behaviors of piled raft foundations with free-standing pile groups, Lemnitzer (2008) conducted a series of physical model tests on single rigid pile, group pile, un-piled raft, free-standing pile group and piled raft foundation in sand. The results showed that adding single pile to a group would lead to an increase in bearing capacity and soil mass stiffness. Finally, it is proved that, as the number of piles increases, it considerably reduces the piled raft settlement.

Using Particle Image Velocimetry to conceive the deformation mechanism widely increased in the recent years (Esmaeili-Falak 2017). Similarly, in order to analyze deformations and displacement vectors, an optical method using image processing was used. White *et al.* (2003, 2004) studied the resistance offered by sand to penetration of a pile by carrying out model studies using PIV technique. After that, various researchers used this method, especially to evaluate soil behavior around pile in single and group piles.

If the ratio of applied lateral forces to the vertical piles were low, lateral forces could be neglected. Otherwise, the influence of lateral forces should be considered in analysis and design of the piles. Numerical studies were done by Meyerhof (1976), Poulos and Davis (1980), Kraft (1991) and Sarkhani Benemaran *et al.* (2020) focusing on the performance of axial capacity of piles. Investigators like Chore *et al.* (2009), Khodair and Abdel-Mohti (2014) utilized finite element method on models with piles embedded in both sand and clay. Boominathan *et al.* (2010) carried out the lateral load tests on different arranging pile groups embedded in soft clay. It was concluded that the lateral capacity of piles in group at three diameters spacing was 40% less than that of the single pile.

Many investigators have studied of laterally loaded pile group using three dimensional (3D) finite element or finite differences method (Kimura *et al.* 1995, Hazzar *et al.* 2014). Hussien *et al.* (2012, 2014), using two dimensional finite element model, reported a little the lateral capacity increment of free-head group pile installed in sandy soil because of the presence of vertical loads, and this increase is due to the increase in the confining pressures in the sand surrounding the upper part of the pile. Achmus and Thieken (2010) used the 3D FEM to investigate the behavior of single pile through combination of lateral and vertical loading in sandy soil, and they reported that the loading on piles causes interaction effects due to passive earth pressure derive from lateral loads and pile skin friction mobilized vertical loads. Hazzar *et al.* (2016) performed a series of 3D FD analyses to study the influence of vertical loads on the lateral performance of pile. Numerical consequences showed that in sandy soil, the lateral resistance of the piles does not vary considerably with the vertical load. Many researchers investigated laterally loaded piles.

In the past studies, the effect of the fixed head pile and its soil-pile-soil interaction less attention has been paid. The purpose of the present study is experimental and laboratory investigation of the effect of the fixed head pile and its soil-pile-soil interaction on a single pile and 1x2 pile groups. Eventually, pile-bearing capacity and displacement of pile length and soil-pile-soil interaction have been studied in this paper. The outstanding and distinct work done in this research is experimental measurement of the depth of deflection and rotation point in pile groups.

2. Material and methods

2.1 Test set-up and procedure

Sensitivity analysis with finite element software was used to select the box dimensions and boundary conditions. To conduct physical modelling tests and to investigate the effects of the parametric studying, a 300 × 800 × 700 mm3 box (in width, length and height, respectively) has been used. Three sides and the bottom of the box were made of steel with a thickness of 4 mm. In order to provide the box rigidity, some stiffeners were prepared. Eventually, in front of the box, a transparent Plexiglas sheet was used.

In all tests, the lateral force was applied from the right side to the left side by an electric motor at a constant strain rate of 0.7 mm/min. Strain was applied statically. The applied force and lateral displacement of the pile cap at intervals of 10 seconds was recorded using a load-cell and a LVDT in the DASYLAB code, respectively. The displacement of 0.3B (10 mm) at the load position considered as the end of the test. Fig. 1 shows the perspective view of the test set-up and equipment, schematically.

2.2 Dimensional analysis

Physical modelling has a fundamental role in development of geotechnical understandings. In comparison to the full-scale modelling, small-scale modelling may be preferred because of more tests, low costs and rapid results. In small-scale physical models, it is crucial to find out the dimensional analysis and scaling laws. The pile can be supposed as a beam under a given load by tip and head. The loads can be in vertical or horizontal directions that the

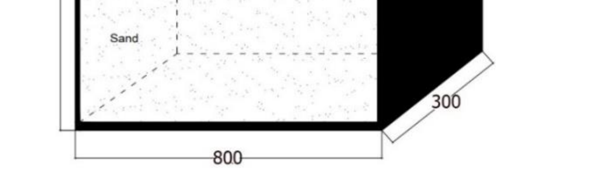


Fig. 1 Perspective view of model and equipment

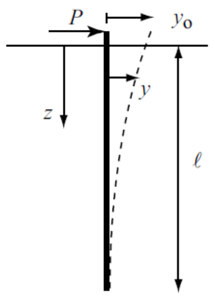


Fig. 2 Pile under lateral loading

Table 1 description of parameters

Description	Parameter
EI	flexural rigidity of the pile
$K = \beta G$	coefficient of subgrade reaction
y	the horizontal deflection of the pile
y_0	the lateral deflection of the pile at its top
z	the distance measured along the pile length
l	the length of the pile
$\lambda = y / y_0$	normalized pile deflection
$\xi = z/l$	normalized depth

Table 2 The properties of the model and the prototype for long and short pile

Parameter	Model		Prototype	
Pile type	long	short	long	short
Metal type	Aluminum	Aluminum	Steel	Steel
E (GPa)	71.4	71.4	190	210
Dimension (mm)	width 30	width 30	diameter 400	diameter 870
	thickness 2	thickness 5	wall thickness 10	wall thickness 15
I (m^4)	2×10^{-11}	3.125×10^{-10}	2.5×10^{-4}	3.8×10^{-3}
EI ($N.m^2$)	1.428	22.3	4.8×10^{7}	7.4×10^{8}
Length	300 mm	200 mm	22.8 m	15.2 m

horizontal loading is considered in the present study (Wood 2004). Pile under lateral loading is shown in Fig. 2 and the equation governing the deformation of the pile is as Eq. (1). Table 1 describes the used parameters. Eq. (1) can be normalized as Eq. (2).

$$EI\frac{d^4y}{dz^4} = -ky \qquad (1)$$

$$\frac{EI}{l^4}\frac{d^4\lambda}{d\xi^4} = -ky \qquad (2)$$

A pile model with scale factor n=1/76 with 30 mm, 2 mm and 300 mm width, thickness and length was selected, respectively to simulate a long prototype tube pile with 400 mm, 10 mm and 22.8 m in diameter, thickness and length, respectively. Also, for modelling a short prototype tube pile with 870 mm diameter, 15 mm thickness and 15.2 m length, a model with scale factor n=1/76 with 30 mm width, 5 mm thickness and 200 mm length has been selected. Table 2 shows the properties of long and short piles for both prototype and model piles. Single pile and trail piles of groups are located at 300 mm from the right edge of the test box. In addition, the pile cap is placed at the level of 30 mm above the soil surface and the length of the pile embedded in the soil is considered as the length of the pile. The first step for studying laterally loaded piles is determining the rigidity or flexibility of the piles. This can be determined by calculating the stiffness coefficients of the pile and soil. The used piles in this research are long and short. The used soil is sand. For sandy soils, the length factor (T) is as Eq. (3). Flexibility and rigidity of the long and short piles validated by Eqs. (4) and (5), respectively (Prakash & Sharma 1989). Where L, T, EI and n_h are the pile length embedded in the soil, the length factor, the flexural rigidity of the pile and the reaction modulus of the horizontal subgrade ($k = n_h.z$), respectively. Also, n_h was calculated by Eq (6) (Terzaghi, 1955).

$\phi_1 = \frac{Gl^4}{EI}$ is an appropriate dimensionless group to describe relative pile-soil stiffness. Then, the correct physical modelling will be obtained when the dimensionless ratio ϕ_1 is maintaining identical in the model and the prototype. Assuming the scale factors n_E and n_I for Young's modulus E and second moment of area I of the pile, respectively, consequently it can be concluded $n_E n_I = n_G n_l^4$. A length scale $n_l=1/n$ leads to $n_E n_I = 1/n^{4+\alpha}$ for single gravity testing and $n_E n_I = 1/n^4$ for modelling with an acceleration factor of n_G.

$$T = \sqrt[5]{\frac{EI}{n_h}} \qquad (3)$$

$$L \geq 4T \qquad (4)$$

$$L \leq 2T \qquad (5)$$

$$n_h = \frac{A.\gamma}{1.35} \qquad (6)$$

2.3 Piles specifications

Rectangular cross-section considered for the model piles in which, to have plane strain behaviour, the thickness (t) of the pile selected considerably less than that of the pile width (B). The piles are loaded laterally at the direction of weak axis in which they have less flexural rigidity so that they have more significant deformation. In the present study, the effect of pile length and centre by centre spacing of the piles on the behavior of the piles and the interaction of the piles on each other have been investigated in a pile group. The tests programming is listed as Table 3 for long and short piles.

The pile cap is typically used to connect the piles to each other in the pile group. For this purpose, in the present study a rigid element is used to locate the piles in the fixed

Table 3 Tests programming for long and short piles

Test number	Test definition	symbol
1	Single long pile	SL
2	Long pile group at spacing 1B	GL1B
3	Long pile group at spacing 2B	GL2B
4	Long pile group at spacing 3B	GL3B
5	Long pile group at spacing 4B	GL4B
6	Single short pile	SSH
7	Short pile group at spacing 1B	GSH1B
8	Short pile group at spacing 2B	GSH2B
9	Short pile group at spacing 3B	GSH3B
10	Short pile group at spacing 4B	GSH4B

determined positions. The circumstance of fixed joint of piles to the cap has been shown in Fig. 3. To investigate the displacement of different points of the pile length, the face of the pile, which is located on the Plexiglas of the box, is covered by calibrated paper. Fig. 3 shows the model piles before embedding into the physical model box.

2.4 Sand

In constructing the physical models, circumstance of the soil filling has a great importance from the viewpoint of sand density uniformity and the tests repeatability, so that the density of the sand is the same in all parts of the physical model box. For this purpose, the sand-rainer of the geotechnical laboratory of the University of Tabriz has been used. For more certainty before each test, density of the sand in different levels was monitored carefully. Fine dry sand was used from the Sofian region in the northwest of Iran, which is classified as SP in unified soil classification system (USCS) and the friction angle of the sand is determined by direct shear test. The soil was placed in the box using a sand raining system in order to obtain a uniform and homogeneous medium. The average unit weight and relative density of soil in the box were 14.8 kN/m3 and 24%, respectively. Note that, the used sand, due to different colour of the particles, creates a light and shadow between adjacent particles, which increases the accuracy of the results form PIV analysis. Grain size distribution of the mentioned soil is demonstrated in Fig. 4 and physical properties of that is as Table 4.

2.5 Particle image velocimetry (PIV)

The particle image velocimetry (PIV) is used to measure deformation patterns in a plane strain continuum. White *et al.* (2002, 2003) has used and developed this method for geotechnical physical models. Using PIV, the movements of the fine mesh of the soil patches is measured with high precision. The displacement vectors are obtained by using a photogrammetric transformation of the image space to the object space. All experiments were carried out in dark surrounding to prevent the occurrence of errors due to light changes and reflections in the laboratory environment, which could lead to wild vectors in the PIV analysis. A 14.1 MP high-speed digital camera facilitated the shooting of the soil displacement during testing. The camera was positioned in front of the test box, which consisted of Plexiglas. All shooting controls were automatically on the viewing window facilitated by PS-Remote software. Two projectors positioned on both sides of the camera at appropriate angles beside the camera axis to enhance the quality of shootings. The precision of PIV is function of the patch size and the grid spacing and the selecting of optimum patch size in the PIV technique requires a balance between patch size and grid spacing. Therefore, analysis was conducted using patches of 64 * 32 pixels, spaced at 64-pixel centre to centre, and a search area of 32 pixels.

In this study, the effect of pile rigidity and axe-to-axe distance of piles were investigated on the pile-soil-pile interaction and the behavior of the pile group under lateral loading. In order to compare single pile behavior with the pile group behavior and to investigate the effect of the pile-soil-pile interaction, several tests were performed. For this purpose, the piles were tested separately in single condition and in 2x1 group condition with an axe-to-axe distance equal to 1 to 4 times of the pile width. These experiments were repeated also on long and short piles similarly. The lateral force was applied statically by an electromotor to the piles cap horizontally. The closest and the farthest pile to the force location are called “trial pile” and “lead pile, respectively”. The following results were obtained from 12 physical modelling experiments.

3. Test results and discussion

3.1 Lateral bearing capacity of piles

3.1.1 Long pile

Fig. 5 shows the lateral load-displacement curves for long piles per each 1 mm displacement. As shown in this figure, it is found that due to overcoming in significant resistance induced by the strain-hardening of the loose soil, slopes of curves at the beginning are relatively higher. The load-displacement curve of the single pile is lower than the curves of the groups of long pile. Due to the interaction between the piles in a group, the stiffness of the pile group has increased compared with a single pile. As a result, for the same displacement, the lateral bearing capacity (F_L) of the pile group increases more than the single pile. Also, according to Table 5, about long piles, it can be stated that with increasing the distance between the piles from 1B to 4B, the bearing capacity of the long pile group has increased by about 12.7%. In fact, with increasing the equivalent stiffness of the soil-pile system and the strain stiffening of soil, the bearing capacity has increased for same displacement. Also, due to the expansion of the arching effects, the stress around the pile increases, and as a result, the ultimate bearing capacity of the pile increases. In the case of the long pile group, the values of F_L increased by 5.5%, 4.7%, and 2.1% from the GL1B test to GL4B test, respectively, indicating the decreased increasing rate of F_L with increasing the distance between piles of a group.

3.1.2 Short pile

Fig. 5 shows the lateral load-displacement curves for

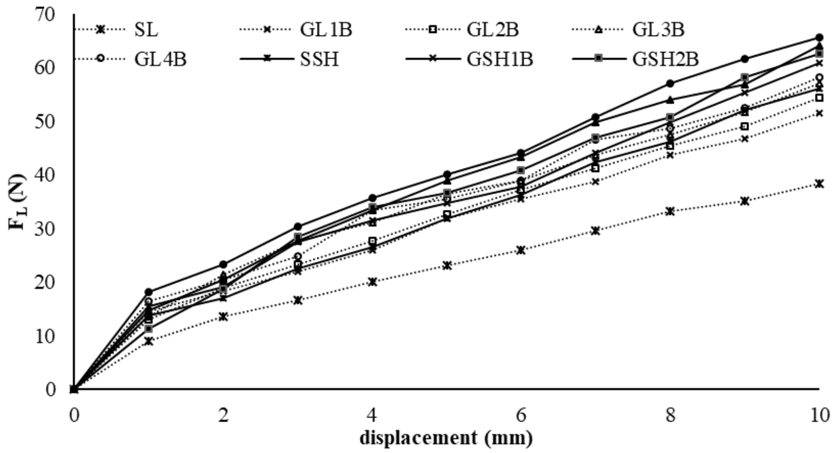


Fig. 5 Variation of lateral load with pile head deflection for long and short piles

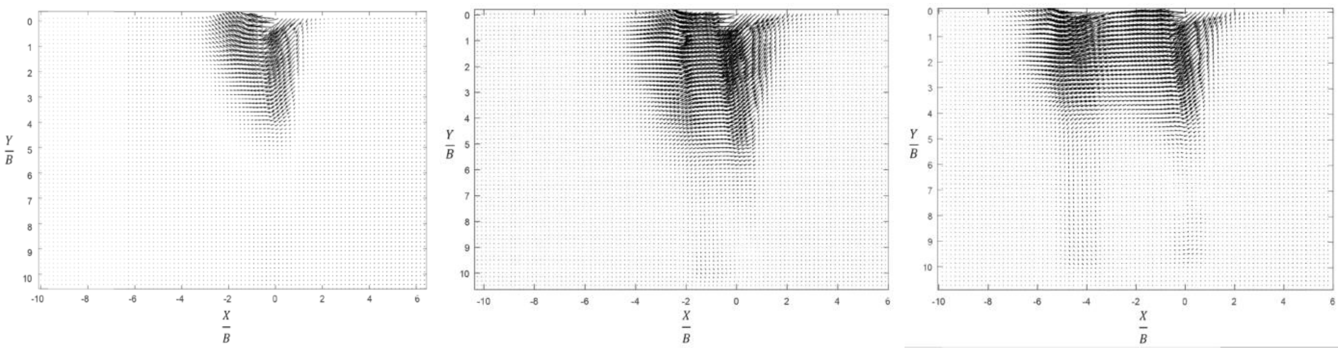
Table 5 Tests programming for long and short piles

Test number	The properties of test	Model pile Lateral load capacity of pile head for 10 mm displacement (N)	Difference with single pile	Increased percentage respect to single pile
1	SL	39.1	0	----
2	GL1B	52.6	13.5	34.5%
3	GL2B	55.5	16.4	41.9%
4	GL3B	58.1	19.0	48.6%
5	GL4B	59.3	20.2	51.7%
6	SSH	57.2	0	----
7	GSH1B	62.0	4.8	8.4%
8	GSH2B	63.8	6.6	11.5%
9	GSH3B	65.4	8.2	14.3%
10	GSH4B	67.0	9.8	17.1%

short piles. As shown in this figure, it is found that relatively greater slopes at the beginning of the curves are due to the strain stiffening of soil. For the same displacement, the lateral bearing capacity of the pile group increases more than the single pile. Due to the effect of each pile on the behavior of the pile group, the stiffness and lateral bearing capacity of the pile group have increased more than the single pile, leading to greater lateral bearing capacity for the same displacement. Moreover, about short piles, according to Fig. 5, it can be concluded that with increasing the distance between the piles in a group from 1B to 4B, the bearing capacity has increased by about 8.1%. In fact, with increasing the equivalent stiffness of the soil-pile system and the strain stiffening of soil, the lateral force required for applying same displacement has increased. Also, due to the expansion of the arching effects, the stress around the pile increases, so, the ultimate bearing capacity of the pile increases.

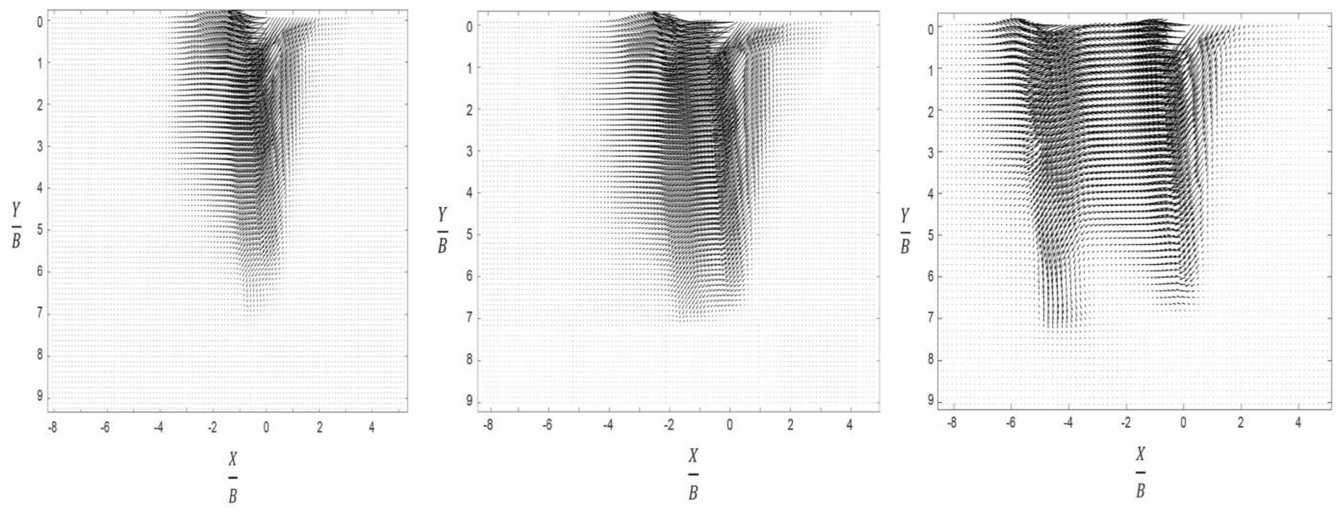
In the case of the short pile group, the values of F_L increased by 2.9%, 2.5%, and 2.4% from the GSH1B to GSH4B test, respectively, indicating the decreased increasing rate of F_L with increasing the distance between the piles of a group. By comparing the lateral load-displacement curves of short and long piles in Fig. 5 and investigating their lateral bearing capacities, it is observed that due to the increased rigidity of the constant-width pile, the greater amount of load is required to apply the same displacement in short piles compared with long piles under same conditions. For the same displacement, the increase in the lateral bearing capacity of the pile group compared with the single pile is greater in long piles than in short piles. Also, for the same displacement, with increasing the distance between piles from 1B to 4B, the increase in lateral bearing capacity of the pile group is greater in long piles than in short piles. As a result, it seems that about lateral bearing capacity, the group effect for long piles is more obvious than short piles.

In short piles, the embedded part in the soil remains rigid under load and is essentially displaced by the rigid rotation. Also, its capacity is determined by the passive resistance of the surrounding soil. The lateral capacity of the long pile is not governed by soil resistance. It is governed by the stresses and moments of the pile. The distinction between short and long piles, depending on the function of the pile, is influenced not only by the pile geometry but also by the stress-strain characteristics of the pile as well as the soil around the pile. The role of piles is determined by the modulus of elasticity and the role of soil by stress-strain characteristics, which are usually expressed as the horizontal reaction modulus of the ground or as a P-Y curve.



(a) Single long pile (SL) (b) Long pile group at spacing 1B (GL1B) (c) Long pile group at spacing 4B (GL4B)

Fig. 6 Total soil displacement vectors around



(a) Single short pile (SSH) (b) Short pile group at spacing 1B (GSH1B) (c) Short pile group at spacing 4B (GSH4B)

Fig. 7 Total soil displacement vectors around

3.1 Total displacement vectors of soil around the pile and angle of total displacement vectors created on the soil surface

Figs. 6 and 7 show the total displacement vectors of soil around the long and short piles, respectively. To show the deformation pattern of soil around the pile, total displacement vectors related to the center of the meshes have been used. In all these diagrams, the horizontal axis shows the distance between the piles and the origin of the horizontal axis, i.e. X/B=0 point, is the location of the single pile, and the location of the trail pile in the case of the pile group. The vertical axis shows the depth of soil, Y/B=0 point, i.e. the origin of the vertical axis is the soil surface. Both horizontal and vertical axes are normalized with respect to pile width (B).

Figs. 8 and 9 show the angles of the total displacement vectors of soil surface in the experiments on long and short piles, respectively. These diagrams are plotted for vectors with values equal to or greater than 0.5mm, and descending vectors are shown with negative values and ascending vectors with positive values. In these diagrams, the horizontal axis shows the distance between the piles, and X/B=0 point is the location of the single pile, and the location of the trail pile in the case of the pile group. The vertical axis shows the angle of total displacement vectors of soil relative to the horizon (in degree).

3.2.1 Long pile

Fig. 6 shows the total displacement vector of soil around the pile for models with long piles. It can be seen when the long pile is subjected to lateral load, the largest values of total displacement vectors are obtained around the pile head and then, they gradually decrease along the pile length. When a single pile is subjected to a lateral load, forming a gap behind the pile makes the soil mass of this part move downwards and according to Fig. 8, since the angles of the vectors behind the trail pile are greater than 45 degrees relative to the horizontal axis, the vertical displacement of soil mass is greater than its horizontal displacement. Due to the formation of a passive area in front of a single pile, the soil mass of this part moves upwards. Created vectors in front of the pile, by moving away from the pile, have larger angles and smaller values, which is due to the presence of a passive wedge in front of the pile. In general, the area influenced by total displacement vectors is approximately

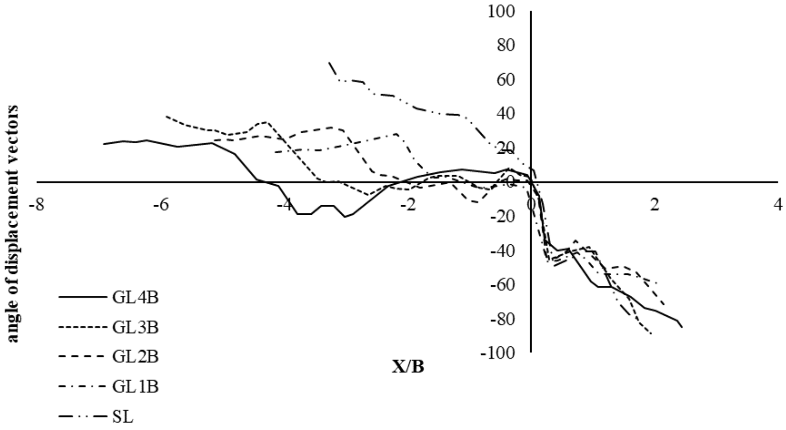


Fig. 8 Angle of soil displacement vectors for long piles

equal to 2B behind the pile and 3.5B in the front of the single pile.

For the pile group models, it is observed that due to the formation of a gap behind the trail pile and angles greater than 45 degrees relative to the horizontal axis, the downward vertical displacement of the soil mass is greater than its horizontal displacement. In front of the lead pile, a passive area is formed, and the angle of vectors is smaller than 45 degrees relative to the horizontal axis, i.e. the horizontal displacement of soil is greater than its vertical upward displacement.

In general, the area affected by total displacement vectors of soil around the pile group is approximately from the distance of 2B behind the trail pile to the distance of 3B in front of the lead pile. The behaviour of the soil between the two piles varies depending on the distance between the piles and the interaction effect among them. When the distance between piles is 1B to 3B in the group, the angles of the total soil displacement vectors between the two piles are almost zero, meaning that the soil mass between the two piles moves almost horizontally in the direction of loading. This indicates the piles in a group behave like a block. In fact, due to the location of the lead pile, the resistance of soil in front of the trail pile decreased compared with the soil in front of the single pile. However, when the distance between the long piles is 4B in the group, it is possible for the soil mass in front of the trail pile to move upwards and also for the soil mass behind the lead pile to move downwards, meaning that each pile behaves like a single pile, and the effect of interaction among piles is reduced.

It can be concluded that the spacing range of 3B is an optimal distance for the pile group under lateral load not to behave like a single pile and also it can be seen no interaction effect and no decrease in lateral bearing capacity. The total displacement vectors of soil behind the single pile and behind the trail pile in the pile group are almost aligned along the pile length, but the values of vectors gradually decrease with increasing the depth.

Fig. 8 shows that at the location of piles, a sudden jump occurred in curves due to a change in the direction of displacement vectors (conversion of descending vectors to ascending vectors). In the pile group, this sudden jump is more noticeable because the angles of displacement vectors of soil behind the trail pile are greater than the lead pile. By increasing the spacing between piles from 1B to 3B in pile groups, the value of the ascending angle in front of the lead pile becomes larger, indicating that the dimensions of the passive wedge have become larger. However, when the spacing between piles is 4B, the angles of vectors in front of the lead pile become smaller, and the dimensions of the passive wedge decrease. Therefore, in general, it is recommended to choose the spacing of 3B for the piles in a group to mobilize the maximum bearing capacity of soil in the long pile group under lateral load.

3.2.2 Short pile

Fig. 7 shows the total displacement vector of soil around the pile for models with short piles. According to this figure, it can be seen that soil masses away from the pile do not move and the total displacement vectors of soil become larger by approaching the pile. Applying lateral load to a single pile forms a gap behind the pile and the soil mass behind the pile moves downwards. According to the vectors in Fig. 9, the vertical soil displacement is greater than its horizontal displacement. Also, the formation of a passive wedge in front of the pile makes the soil mass in front of the pile move upwards. By examining the components of the total displacement vectors, it is observed that the horizontal displacement of the soil mass in front of the pile is greater than its vertical displacement. The change in the directions of vectors at the pile location has caused a sudden jump in the angles of vectors, as clearly seen in Fig. 9. The area affected by total displacement vectors is approximately equal to 2B behind the pile and 3.5B in the front of the single pile.

In short pile groups with the spacing ranging 1B to 4B between piles, due to the gap behind the piles, the total displacement vectors of soil move downwards, but the angles of total displacement vectors relative to the horizontal axis, are greater behind the trail piles than the lead piles and the vertical displacement is greater than the horizontal displacement. The soil mass in front of the trail pile moves almost horizontally, meaning that with the performance of the lead pile in the pile group, the resistance of the soil in front of the trail pile decreases compared with the soil in front of the single pile. By increasing the spacing

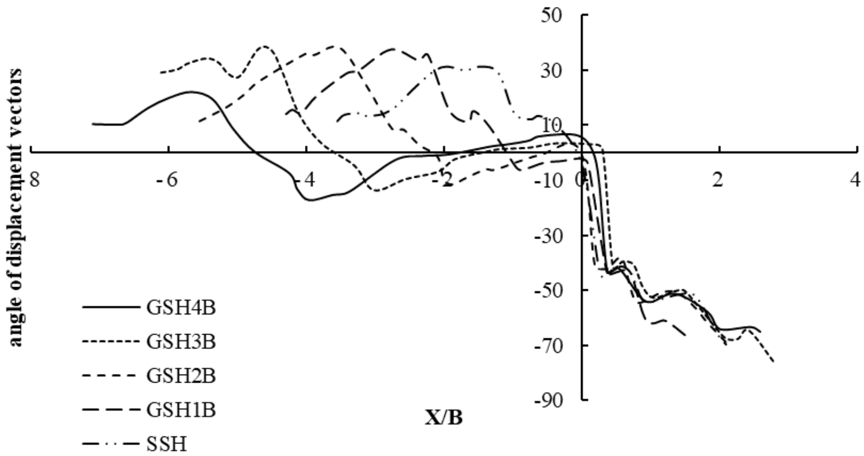
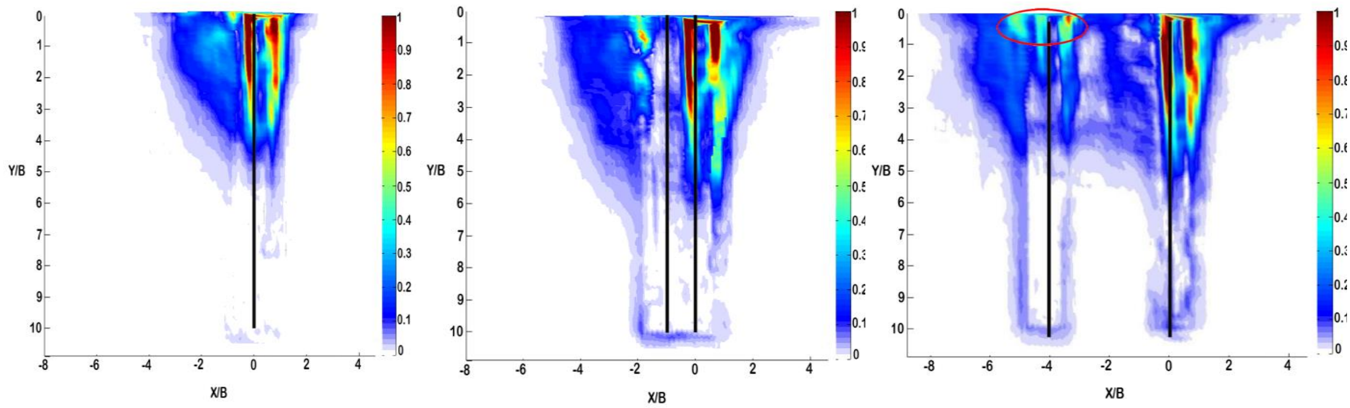


Fig. 9 Angle of Soil displacement vectors for short piles



(a) Single long pile (SL)

(b) Long pile group at spacing 1B (GL1B)

(c) Long pile group at spacing 4B (GL4B)

Fig. 10 Soil shear strain around

between piles in groups, it is possible for the soil mass behind the lead pile to more move downwards, and the angles of vectors behind the lead piles relative to the horizontal axis, become greater, and eventually the overlapping of total displacement vectors of soil around the piles decreases. However, the interaction effect among piles is still seen in the behaviour of the pile group. The formation of a passive area in front of the lead pile makes the soil in this part move upwards, and by increasing the spacing between piles from 1B to 3B, the angles of total displacement vectors of soil in front of the lead pile become greater slightly, which is due to the increased passive wedge dimensions. However, with the increase in the spacing between piles to 4B, due to the reduction of the group effect, the angles of total displacement vectors of soil in front of the lead pile decreased, indicating the reduced dimensions of the passive wedge. As a result, the spacing of 3B is the optimal spacing for the short pile group to mobilize the maximum soil bearing capacity and make it possible for the group to have the greatest effect. The value of the total displacement vectors of soil behind the single pile and behind the trail pile in the pile group has been reduced along the pile length, but their angles are almost aligned.

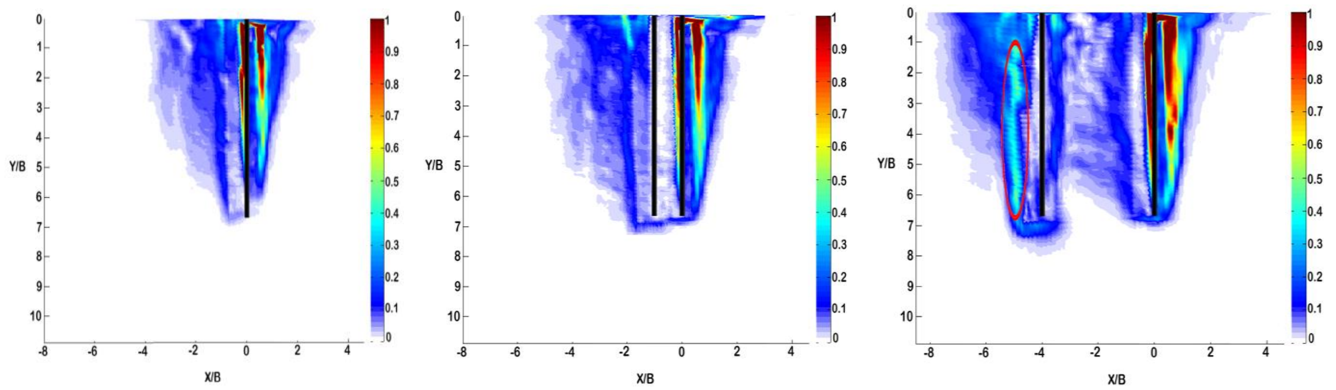
As seen in Fig. 9, at the location of the piles, a sudden jump occurred in curves due to a change in the direction of displacement vectors. In the pile group, this sudden jump is more noticeable because the angles of displacement vectors of soil behind the trail pile are greater than the lead pile.

Comparing the graphs plotted for long and short piles, it can be concluded that the displacement of soil around the long piles occurs only along a part of the pile length, while the displacement of soil around the short piles occurs along the entire pile length. This is due to the rigid rotation of the short pile and the structural bending of the long pile. The depth along the pile length at which the total displacement vectors are formed is called the effective depth of the total displacement vector. According to Figs. 6 and 7, it can be concluded that for the short pile group, the effective depth of the total displacement vectors of soil around the trail pile is lower than the lead pile, while in long pile groups, this effective depth is higher for the trail pile than the lead pile.

3.3 The shear strain of soil around the pile

3.3.1 Long pile

Fig. 10(a) for the SL model shows that the maximum soil shear strain occurs near the single pile, at the top (near the soil surface) and decreases by moving away from the pile. Those lengths of the horizontal and vertical axes where



(a) Single short pile (SSH)
(b) Short pile group at spacing 1B (GSH1B)
(c) Short pile group at spacing 4B (GSH4B)

Fig. 11 Soil shear strain around

the shear strain is created are called the effective length and the effective depth of the shear strain, respectively. It can be almost said that the effective depth of shear strain is 6B from the ground level and the effective length of shear strain is 2.5B behind the pile and 3.7B in front of the pile. There is also a passive area in front of the pile under lateral loading. Due to the right-to-left direction of the applied load, the shear strain area does not have a symmetrical shape with respect to the position of the pile and tends to the left. Besides, since the size and angle of the total displacements vectors of soil behind the pile are greater than those in front of the pile, the shear strain created behind the pile is greater than that in front of the pile. In the curves related to the long pile group (Figs. 10(b) and 10(c)), it can be seen that, unlike the curves of the long single pile, at the deeper points of the soil mass, there is a very small (close to zero) shear strain. With the rotation of the pile cap, the piles in a group are displaced vertically, and consequently, shear strain is created in the soil around the piles at deeper points, too. In the pile group, total displacement vectors of soil between the piles are formed up to a certain depth, so there is no shear strain at deeper points. According to Fig. 10(c), as the spacing between piles increases, total displacement vectors of soil between the piles are formed up to lower depth and zero shear strain is created in a larger area between the piles, due to the reduction in the depth of the deflection point. Also, since the angles of total displacement vectors of soil around the trail pile is larger than the lead pile (Fig. 8), the shear strains created in the soil around the trail pile are greater than the lead pile.

3.3.2 Short pile

According to Fig. 11(a) for single short piles, it is observed that the soil shear strain occurs along the entire pile length. At the level of soil surface, approximately the effective width of the shear strain is 2.5B behind the pile and 3.7B in front of the pile, and the shear strain zone tends to the left due to the loading direction. Considering the value and angle of the total displacement vectors of soil, it is obvious that the shear strain created behind the pile is greater than that in front of the pile, but due to the rigid rotation of the pile (relative to the pile tip) and the movement of soil mass in front of the pile, the effective depth of the shear strain in front of the pile is greater compared with behind the pile.

In the short pile group, since the angles of total displacement vectors of soil around the trail pile are greater compared with the lead pile (Fig. 9), the shear strain created in the soil around the trail pile is greater than the lead pile. Also, due to the counter clockwise rotation of the cap, the displacement of the soil under the tip of the lead pile occurs at deeper points than the trail pile, so the effective depth of the lead pile is greater than that of the trail pile, which becomes greater and more noticeable as the spacing between piles increases. The effective width range of the lead pile is approximately up to -5B, -6B, -7B, -8B in GSH1B, GSH2B, GSH3B, GSH4B groups, respectively, i.e. 4B from the location of the lead pile. In the short pile group, with a spacing of 1B (according to Fig. 11(b)), since the total displacement vectors of soil between the piles are horizontal, the shear strain is zero. By increasing the spacing between piles (according to Fig. 11(c)), the angles of total displacement vectors of soil between the piles become greater than zero in relative to the horizontal axis, and consequently, the area of the shear strain of zero between the two piles decreases.

In the SL model, it is observed that the effective depth of shear strain in front of the pile decreases, while in the SSH model, due to the rotation in the entire length of the pile, the effective depth of shear strain in front of the pile increases. In the GL4B group (area marked in Fig. 10(c)), since the piles behave as a single pile, the shear strain is greater at the upper part, due to the formation of a gap and passive wedge at the upper part of the lead pile. In the GSH4B group (area marked in Fig. 11(c)), the shear strain is greater at the lower part due to the rotation and displacement of the lead pile. It can be seen that for the long pile, the shear strain around the lead pile is greater at the upper part and for the short part, this is seen at the lower part.

3.4 Pile displacement curve

3.4.1 Long pile

Fig. 12 shows the displacement curves of the single long

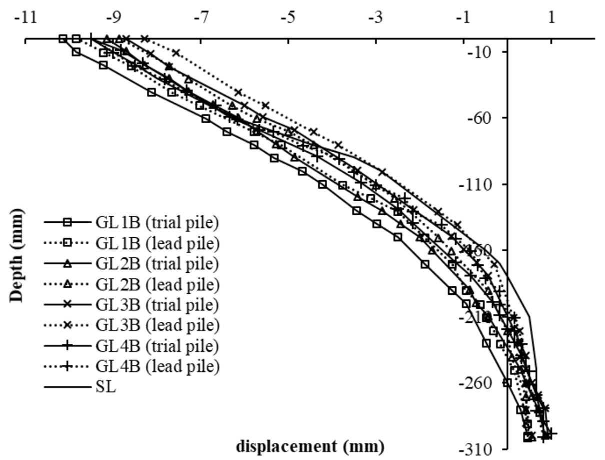


Fig. 12 Displacement curve of long piles

Table 6 The depth of deflection point for long piles

Test number	The properties of test		The depth of deflection point	
			Model pile(mm)	Prototype pile(m)
1	SL		-180	-13.680
2	GL1B	Trail pile	-253	-19.228
		Lead pile	-245	-18.620
3	GL2B	Trail pile	-230	-17.480
		Lead pile	-220	-16.720
4	GL3B	Trail pile	-215	-16.340
		Lead pile	-205	-15.580
5	GL4B	Trail pile	-219	-15.960
		Lead pile	-206	-15.580

pile and the long pile groups relative to their initial coordinates at the end of the experiment. Similar to the results of studies by Ukritchon *et al.* (2016), Liu (2013) and Hazzar (2017), in the long pile under lateral load, the greatest horizontal displacement occurred in the pile head and its value decreased along the pile length until the point of deflection (the horizontal displacement of zero), and after this point, the displacement of the pile is very small and negligible, which is due to the distribution of overhead pressure along the pile length. For none of the long piles, the rigid rotation around a single point has occurred.

In the case of long piles, according to Table 6, it can be concluded that the depth of the deflection point of the pile group is greater than the single pile, which is due to the placement of the lead pile and the pile-soil-pile interaction in the group. With the increase in the spacing between piles from 1B to 3B in group models, the depth of the deflection point of piles has decreased because the pile group behaved as a block. In other words, increasing the spacing between piles in a group has increased the dimensions of the block, leading to an increase of moment of inertia and thereby the increase of flexural rigidity of the group. However, in the GL4B model, the deflection point depth becomes greater than the GL3B model, indicating the reduced effect of the group due to the increased spacing between piles. Also, due to the effect of the stiffness of the lead pile on the group and the pile-soil-pile interaction, the depth of the deflection point for the trail pile is greater than the lead pile. The minimum deflection point depth of the pile group is associated with 3B, due to the reduction of the effective length of the pile, this case seems an optimal and economical option for the same displacement of the pile head. Although the flexible behaviour of the long pile is governed by the effective deflected length, the pile did not reach the plastic yielding point and no permanent bending was observed in piles after the experiment, confirming that the pile did not reach the yielding point.

3.4.2 Short pile

Fig. 13 shows the displacement curve of single short pile and the short pile groups under lateral load, relative to their initial coordinates, at the end of the experiment. In agreement with the results of the study by Taheri (2015), rotation occurred in all curves and the greatest horizontal displacement occurred in the pile head. Due to the effect of the lead pile in the pile group and the pile-soil-pile interaction, Fig. 13 shows that the displacement curve of the trail pile is in front of the displacement curve of the lead pile, meaning that the horizontal and vertical displacements of the trail pile are greater compared with the lead pile. Examining the coordinate of the trail pile in the place of the pile head, it can be seen that in the GSH1B model, there is a downward displacement, in the GSH2B model, there is no vertical displacement and in the GSH3B and GSH4B models, there are upward displacements. The coordinate of the lead pile in the place of the pile head shows a downward displacement in all group models. Finally, it is observed that the pile cap is rotated counter clockwise in all cases, and the angle of rotation of the pile cap for the GSH1B, GSH2B, GSH3B, GSH4B group models is 1.54º, 1.78°, 1.86°and 1.92°, respectively, indicating that as the spacing between piles of a group and the angle of rotation of the pile cap increase, the difference between the levels of the lead and trail pile heads increases, which is of great importance in design issues.

The quantitative results of the short pile displacement curve are listed in Table 7. In cases where the rotation has occurred around a point of the pile length, the greatest horizontal displacement occurred at the pile head, up to the rotation point, the displacement along the pile length decreased and it occurred in the opposite direction below the rotation point. For cases where the rotation has occurred around a point below the pile tip, this depth has been calculated approximately, and in addition to the rotational motion, a translational motion has also occurred in the direction of the load along the entire pile length. Due to the effect of the stiffness of the lead pile and the pile-soil-pile interaction in the pile group, increasing the spacing between pile leads to the increased depth of the rotation point of the trail pile. However, as the spacing between piles increases, due to the greater rotation and displacement of the pile cap in the place of the lead pile, a slight decrease is observed in the depth of the rotation point of the lead pile.

By comparing the displacement curves of long and short piles under lateral load, it is observed that long piles behave quite flexibly, while in short piles, the whole mass of piles

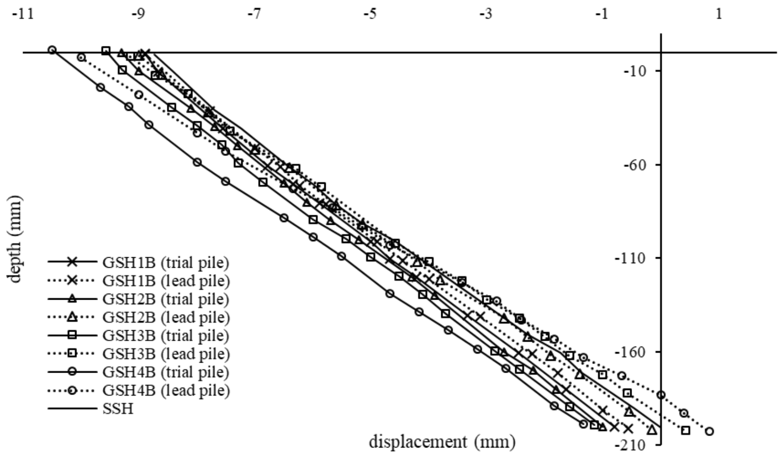


Fig. 13 Displacement curve of short piles

Table 7 The depth of rotation point for short piles

Test number	The properties of test		The depth of rotation point		Transform
			Model pile(mm)	Prototype pile(m)	
6	SSH		-200	-15.200	No
7	GSH1B	Trail pile	-220	Below -15.200	Yes
		Lead pile	-213	Below -15.200	Yes
8	GSH2B	Trail pile	-223	Below -15.200	Yes
		Lead pile	-205	Below -15.200	Yes
9	GSH3B	Trail pile	-225	Below -15.200	Yes
		Lead pile	-190	-14.440	No
10	GSH4B	Trail pile	-226	Below -15.200	Yes
		Lead pile	-180	-13.680	No

rotates around one point and the piles behave quite rigidly. Compared to piles with pin connections, the deflection point depth of the long pile and the rotation point depth of the short pile in the fixed connection are transferred to a deeper point

4. Conclusions

In this study, the behavior of the fixed head pile group under lateral load has been investigated. The overall results of the present study show that:

- In the models of the pile group, with increasing the distance between the piles from 1B to 4B, the lateral load capacity of the long pile group has increased about 12.7% and for short one about 8.1%.
- For the same displacement, the lateral load capacity of the pile group compared with the single pile has increased due to increasing equivalent stiffness of the pile-soil-pile composition, arching effects and increasing of stress around the pile.
- The increase in the lateral load capacity of the pile group compared with the single pile is greater in long piles than short piles. Because of this study, it seems that the group effect for long piles is more obvious than short piles.
- For a single long pile, the soil mass behind the pile moves sharply downwards. However, when the pile spacing in group is from 1B to 3B, pile group acts as block and the soil mass between the two piles moves almost horizontally and in the same direction of loading. In addition, the displacement of soil around the long piles has occurred only along a part of the pile length, while the displacement of soil around the short piles, unlike the long piles, occurs along the entire of pile length.
- For the group of short piles, the effective depth of total soil displacement vectors around the trail pile is less than the lead pile, while for the group of long piles, the effective depth of total soil displacement vectors around the trail pile is greater.
- Because the angles of total displacement vectors of soil around the trail pile are larger than the lead pile, the shear strains created in the soil around the trail pile are greater than the lead pile.
- Comparison between the displacement curves of long and short piles shows that long piles are quite flexible, but in short piles, the whole mass of pile rotate around one point and the behavior of the pile is quite rigid. With the effect of the stiffness of the lead pile in the group and the effects of pile-soil-pile interaction, the depth of these points for the trail pile is more than the lead pile.

• In the long pile group, due to the increase in moment of inertia, because of increasing the dimensions of the pile block and subsequently increasing the flexural rigidity of the pile group, by increasing the spacing between the piles from 1B to 3B, the depth of the deflection point of the piles decreases.

References

Achmus, M. and Thieken, K. (2010), "On the behavior of piles in non-cohesive soil under combined horizontal and vertical loading", *Acta Geotechnica*, **5**(3), 199-210. https://doi.org/10.1007/s11440-010-0124-1.

Aksoy, H., Gör, M. and İnal, E. (2016), "A new design chart for estimating friction angle between soil and pile materials", *Geomech. Eng.*, **10**(3), 315-324. https://doi.org/10.12989/gae.2016.10.3.315.

Al-abboodi, I., Sabbagh, T.T. and Al-salih, O. (2020), "Response of passively loaded pile groups – an experimental study", *Geomech. Eng.*, **20**(4), 333-343. https://doi.org/10.12989/gae.2020.20.4.333.

Bauer, J., Kempfert, H.G. and Reul, O. (2016), "Lateral pressure on piles due to horizontal soil movement", *Int. J. Phys. Model. Geotech.*, **16**(4), 173-184. https://doi.org/10.1680/jphmg.15.00005.

Brown, D.A., Morrison, C., and Reese, L.C. (1988), "Lateral load behavior of pile group in sand", *J. Geotech. Eng.*, **114**(11), 1261-1276. https://doi.org/10.1061/(ASCE)0733-9410(1988)114:11(1261).

Chandrasekaran, S.S., Boominathan, A., and Dodagoudar, G.R. (2010), "Group interaction effects on laterally loaded piles in clay", *J. Geotech. Geoenviron. Eng.*, **136**(4), 573-582. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000245.

Chore, H.S., Ingle, R.K. and Sawant, V.A. (2009), "Building frame-pile foundation-soil interactive analysis", *Interact. Multiscale Mech.*, **2**(4), 397-411. https://doi.org/10.12989/imm.2009.2.4.397.

Esmaeili-Falak, M. (2012), "Study of displacement potential of landslides in Yamchi dam's abutments and Slopes Lake", Ph.D. Dissertation, Islamic Azad university of Science and research branch, Tabriz, East Azerbaijan, Iran.

Esmaeili-Falak, M. (2013), "Two-dimensional finite element analysis of influence of plasticity on the seismic soil-micropiles-structure interaction", *Tech. J. Eng. Appl. Sc.*, **3**(13), 1301-1305.

Esmaeili-Falak, M. (2017), "Effect of system's geometry on the stability of frozen wall in excavation of saturated granular soils", Ph.D. Dissertation, University of Tabriz, Tabriz.

Esmaeili-Falak, M., Katebi, H. and Javadi, A. (2018), "Experimental study of the mechanical behavior of frozen soils- A case study of Tabriz subway", *Period. Polytech. Civ. Eng.*, **62**(1), 117-125. https://doi.org/10.3311/PPci.10960.

Esmaeili-Falak, M., Katebi, H. and Javadi, A. (2020), "Effect of freezing on stress-strain characteristics of granular and cohesive soils", *J. Cold Reg. Eng.*, **34**(2), 05020001. https://doi.org/10.1061/(ASCE)CR.1943-5495.0000205.

Hazzar, L. (2014), "Analyse numérique de la réponse des pieux sous sollicitations latérales [Numerical analysis of the response of piles under lateral loads]", Ph.D. Dissertation, University of Sherbrooke, Sherbrooke, Quebec, Canada.

Hazzar, L., Hussien, M.N. and Karray, M. (2016), "Investigation of the influence of vertical loads on the lateral response of pile foundations in sands and clays 2", *J. Rock Mech. Geotech. Eng.* http://doi.org/10.1016/j.jrmge.2016.09.002.

Hazzar, L., Hussien, M.N. and Karray, M. (2017), "On the behaviour of pile groups under combined lateral and vertical loading", *Ocean Eng.*, **131**, 174-185. https://doi.org/10.1016/j.oceaneng.2017.01.006.

Hussien, M.N., Tobita, T., Iai, S. and Rollins, K.M. (2012), "Vertical loads effect on the lateral pile group resistance in sand", *Geomech. Geoeng.*, **7**(4), 263-282. https://doi.org/10.1080/17486025.2011.598571.

Hussien, M.N., Tobita, T., Iai, S., and Karray, M. (2014), "On the influence of vertical loads on the lateral response of pile foundation", *Comput. Geotech.*, **55**, 392-403. https://doi.org/10.1016/j.compgeo.2013.09.022.

Keawsawasvong, S. and Ukritchon, B. (2016), "Ultimate lateral capacity of two dimensional plane strain rectangular pile in clay", *Geomech. Eng.*, **11**(2), 235-252. http://doi.org/10.12989/gae.2016.11.2.235.

Khodair, Y. and Abdel-Mohti, A. (2014), "Numerical analysis of pile-soil interaction under axial and lateral loads", *Int. J. Concrete Struct. Mater.*, **8**(3), 239-249. https://doi.org/10.1007/s40069-014-0075-2.

Kimura, M., Adachi, T., Kamei, H. and Zhang, F. (1995*), 3-D Finite Element Analyses of the Ultimate Behaviour of Laterally Loaded Cast-in-Place Concrete Piles*, in *Numerical Models in Geomechanics*, A.A. Balkema, Brookfield, The Netherlands, 589-594.

Kraft Jr, L. M. (1990), "Computing axial pile capacity in sands for offshore conditions", *Mar. Georesour. Geotec.*, **9**(1), 61-92. https://doi.org/10.1080/10641199009388230.

Lemnitzer, A., Ahlberg, E.R., Khalili-Tehrani, P., Rha, C., Taciroglu, E., Stewart, J.P. and Wallace, J.W. (2008), "Experimental testing of a full-scale pile group under lateral loading", *Proceedings of the 14th World Conference on Earthquake Engineering*, Beijing, China, October.

Liu, H.L., Kong, G.Q., Ding, X.M. and Chen, Y.M. (2013), "Performances of large-diameter cast-in-place concrete pipe piles and pile groups under lateral loads", *J. Perform. Constr. Fac.*, **27**(2), 191-202. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000304.

Maghsoodi, V., Atermoghaddam, F. and Esmaeili-Falak, M. (2013), "Parametric and two dimensional study of seismic behavior of micro pile group in sandy soil", *Int. Res. J. Appl. Basic Sci.*, **6**(7), 901-909.

Mayerhof, G.G. (1976), "Bearing capacity and settlemtn of pile foundations", *J. Geotech. Geoenviron. Eng.*, **102**(3), 197-228. https://doi.org/10.1061/AJGEB6.0000243.

McVay, M., Casper, R. and Shang, T.I. (1995), "Lateral response of three-row groups in loose to dense sands at 3D and 5D pile spacing", *J. Geotech. Eng.*, **121**(5), 436-441. https://doi.org/10.1061/(ASCE)0733-9410(1995)121:5(436).

Poulos, H.G. and Davis, E.H. (1980), *Pile Foundation Analysis and Design*, Wiley, New York, USA.

Prakash, S. and Sharma, H.D. (1989), *Pile Foundations in Engineering Practice*, Wiley, London, UK.

Rollins, K.M., Olsen, R.J., Egbert, J.J., Jensen, D.H., Olsen, K.G. and Garrett, B.H. (2006), "Pile spacing effects on lateral pile group behavior: load tests", *J. Geotech. Geoenviron. Eng.*, **132**(10), 1262-1271. https://doi.org/10.1061/(ASCE)1090-0241(2006)132:10(1262).

Rollins, K.M., Peterson, K.T. and Weaver, T.J. (1998), "Lateral load behavior of full-scale pile group in clay", *J. Geotech. Geoenviron. Eng.*, **124**(6), 468-478. https://doi.org/10.1061/(ASCE)1090-0241(1998)124:6(468).

Sarkhani Benemaran, R., Esmaeili-Falak, M., & Katebi, H. (2020), "Physical and numerical modelling of pile-stabilised saturated layered slopes", *Proc. Inst. Civ. Eng. Geotech. Eng.* 1-16. https://doi.org/10.1680/jgeen.20.00152.

Shen, Y., Wu, Z., Xiang, Z. and Yang, M. (2017), "Physical test study on double-row long-short composite anti-sliding piles", *Geomech. Eng.*, **13**(4), 621-640.

http://doi.org/10.12989/gae.2017.13.4.621.
Terzaghi, K. (1955), "Evalution of conefficients of subgrade reaction", *Geotechnique*, **5**(4), 297-326. https://doi.org/10.1680/geot.1955.5.4.297.
Ukritchon, B., Faustino, J.C. and Keawsawasvong, S. (2016), "Numerical investigations of pile load distribution in pile group foundation subjected to vertical load and large moment", *Geomech*. *Eng*., **10**(5), 577-598. http://doi.org/10.12989/gae.2016.10.5.577.
White, D.J. and Bolton, M.D. (2004), "Displacement and strain paths during plane-strain model pile installation in sand", *Géotechnique*, **54**(6), 375-397. https://doi.org/10.1680/geot.2004.54.6.375.
White, D.J. and Take, W.A. (2002), "GeoPIV: Particle Image Velocimetry (PIV) software for use in geotechnical testing", Technical Report, Cambridge University, Cambridge, U.K.
White, D.J., Take, W.A. and Bolton, M.D. (2003), "Soil deformation measurement using particle image velocimetry (PIV) and photogrammetry", *Geotechnique*, **53**(7), 619-631. https://doi.org/10.1680/geot.2003.53.7.619.
Wood, D.M. (2003). *Geotechnical Modelling*, Wiley, London, U.K.

JS