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Experimental Study of Axially Loaded Pile Group Near a Sloping Ground

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Abstract

Understanding the axial loading response of pile group located near the crest of the slope is of practical value to structural design. In this paper, a large-scale test setup (1.8 m × 0.90 m × 0.90 m) has been developed to investigate the response of pile group (2 × 2) located near the crest of the slope under axial loading. This paper presents a series of physical modelling tests performed to investigate the effects of slope angles, distance of the pile group from the slope crest, embedment length of the pile group and pile diameter on the axial loading response of pile groups. The results show that the response of pile group located near the crest of the slope approaches to the level ground condition with increasing edge distance from slope crest. In addition, the horizontal displacement of pile group towards the slope face increases with decreasing distance of pile group from the slope crest or embedded length of piles or with increasing slope angle. Furthermore, increasing pile diameter results in a low increase in the horizontal displacement for edge distances less than 3 dp (dp = pile diameter). However, the horizontal displacement is almost independent of pile diameter at edge distances greater than 3 dp. Higher embedded length results in the response of pile group approaches to the response of pile group located on the level ground at a shorter edge distance from the slope crest.

Keywords

pile group, slope, sand, physical modeling, axial load

1 Introduction

The pile is commonly adopted to transfer a part of the building and civil engineering structural loads into deeper layers with higher stiffness and thereby allow the reduction of total settlement and differential settlement of structures in a very economical way. Piles are often used in groups and the load transfer mechanism in group piles is generally different from that of a single pile due to the pile-soil and pile-pile interaction effects which has been described by previous researchers [1–7]. Previous studies indicated that the interaction between soil and structure has a significant effect on the responses of foundation and structure [8–11]. The pile-soil-pile interaction is a complicated phenomenon which can be significantly influenced by many factors, such as the load-deformation properties and the shear strength characteristics of both pile and surrounding soils. Pile group foundations which are commonly employed in many geotechnical projects to support various structures are often subjected to large amount of vertical and horizontal loads which are often studied separately without considering their possible interactions [12].

So far, many studies have been conducted to investigate the behavior of laterally or axially loaded single or group of piles installed in the horizontal [13–17]. However, the response of axially loaded single or group of piles near a cut or slope are still not fully understood. Piled raft foundations embedded in a loose soil material near a sloping ground are composite structures and susceptible to large ground displacement where the applied load is either transferred through the raft or the piles alone. The use of pile groups to stabilize active slopes or to improve slope stability, as a preventive measure in stable slopes has been suggested and studied by previous research which is a widely accepted and successful method [18–21]. Lateral movement of slopes results in large lateral force on piles used in slope stabilization such as the support of bridge abutments and transmission towers, so that they are considered as passive piles [22].

A lateral or axial-load test of full-scale pile or pile group is the most reliable technique to determine the response of a single pile or piles group in the field [23–25]. However,

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the high cost and time consuming of the full-scale pile tests and the inherently high variability of the soil layers and test conditions make them impractical for researchers [26]. Therefore, physical model tests are usually conducted to study the behavior of single or group of piles which is a powerful tool used for understanding physical process in soil-pile interaction and in determining the important factors controlling the load-settlement response of piles [27]. So far, several studies have been done on the effects of sloping ground conditions on lateral capacity of single piles or pile groups using physical model and finite element methods [28–35]. However, the response of axially loaded pile groups near a sloping ground are still not fully understood.

Sales et al. [36] stated that the response of a single pile can be used to predict the response of pile groups. Choi et al. [37] studied the behavior of pile groups subjected to combined vertical and lateral loads using large scale physical modeling. The results showed that the presence of the axial load resulted in an increase of the bending moment and lateral deflection of the pile head. In general, the influence of axial loads on the response of laterally loaded pile groups subjected to combined axial and lateral loads was important and should be considered in the design of laterally loaded pile groups. Jesmani et al. [38] studied the behavior of piles located near slopes with different angles under vertical loading using three-dimensional numerical analyses. The results indicated that the lateral movement of soils increased with decreasing edge distance and the lack of soils on the slope side of the pile resulted in decreasing the bearing capacity. Furthermore, the pile lateral deflection and eccentricity of the axial load on the pile significantly increased due to increasing the slope angle. Sharafkhah and Shooshpasha [39] carried out a series of physical modelling tests on single pile and pile groups. The results showed that the axial bearing capacity of the piled raft foundation was significantly higher than that of the free-standing pile group for a given condition and a number of piles. Also, the settlement of the piled raft decreased with increasing the number of piles. Chen et al. [40] studied the failure mechanism of pile groups installed in sand under different pile spacing by means of laboratory experimental model tests. They stated that the narrow pile spacing was a key factor to the development of the pile tip resistance which may be useful to improve the bearing performance of the pile group at the initial stage of settlement.

The above review of the previous studies indicates that research on the effects of slope inclination on the response of axial loaded pile groups is scanty. Therefore, the understanding of the axial response of pile groups near a slope is one of major interest in design of pile foundations located on sloping grounds. The objective of the current study is to evaluate the effect of sloping ground on the response of axial loaded pile groups. The physical model tests are carried out to investigate the effect of diameter and embedment length of piles, slope angle, and location of pile groups relative to the slope crest.

2 Materials and methods

2.1 Soil properties

In this work, sand sample was collected from Ramhormoz city located in the Khuzestan province, Iran. The dry sand sample was used in constructing the slopes. Fig. 1 shows the grain-size distribution curve of the sand used in the experimental program which was determined using the dry sieving method. The sand physical and geotechnical characteristics are presented in Table 1, which is classified as poorly graded sand (SP) as per Unified Soil Classification System (USCS). Noting that the angle of internal friction of the sand was determined using direct shear test apparatus in according to ASTM D3080 [41].

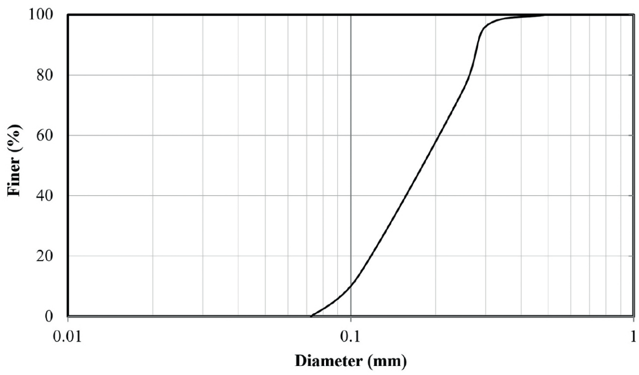


Fig. 1 Grain size distribution curve for sand

Table 1 Physical and geotechnical characteristics of soil

Characteristics	Value
γ_{max} (KN/m^2)	16.90
γ_{min} (KN/m^2)	13.88
G_s	2.65
Φ (°)	35
D_{10}	0.10
D_{50}	0.18
C_u	2.05
C_c	0.82
Passing 200 sieve (%)	0
Soil type: USCS	SP

2.2 Experimental setup and testing program

As shown in Fig. 2, a large-scale experimental setup was developed to study the response of axially loaded group of piles located on sloping ground. A box of inner dimensions 1.80 m × 0.90 m × 0.90 m (length × width × height) were prepared for the present study. The model dimensions were chosen to minimize boundary effects and the interference between the walls of the sand. Polythene sheets were also attached to the inner side walls of the steel box to reduce friction between the slope material and the model box. One side of the model box made of glass so that the proposed testing geometry of the slope was first marked on transparent glass wall reference and allow the observation of the sand deformations if any. Figs. 3(a) and (b) show a schematic view and laboratory photograph of the experimental apparatus used in the current study, respectively which consists of steel box, sand, pile group, cap, screw jack, dial gauges, and load cell. As shown from Fig. 3, the vertical displacements of piles subjected to vertical loads were measured using two 50 mm dial gauges with the accuracy of 0.01 mm mounted on the either side of the cap. The vertical displacements were calculated as the average of two dial gauges. The lateral displacements of piles were also measured using a 50 mm dial gauge with the accuracy of 0.01 mm. Axial load was applied through a screw jack coupled to a steel rod attached to the loading frame. A steel box was used to attach the piles cap to the screw jack and force measurement was carried out using a load cell placed between the steel box and the pile cap. The axial load was applied at the center of the piles cap with a constant strain ratio of 1.5 mm/min. During the free-standing pile group tests, the loading was continued up to displacements exceeding 20 mm.

A pile group configurations included 2 × 2 square model pile groups in all tests. Steel rods with an outer diameter of 16 mm or 18 mm were used as end-closed piles. The pile groups subjected to axial loads using a steel pile cap of size 16 cm × 16 cm and thickness of 2 cm which can be regarded as rigid. The upper 2 cm of the piles were fixed in the rigid steel cap. In order to study the free-standing pile group and better compact the soil around the piles, the piles head is elevated about 15 cm from the surrounding soil.

Pile driving changes the relative density of sand. Pre-installation process (positioning of the pile before the sand is fully prepared) was used to install the piles which involved first pouring and tamping a sand bed, then the piles were temporarily fixed on the sand bed at its designed location by mounting the pile cap firmly to a support beam, and finally, continuing the sand pouring and tamping was preceded until final elevation was achieved. Controlled pouring and tamping techniques were employed to prepare the samples in 18 layers with the sand bed level and slope observed through the front glass side. In each layer, the sand compaction was carried out manually with relative density of about 65% using circular steel rammers.

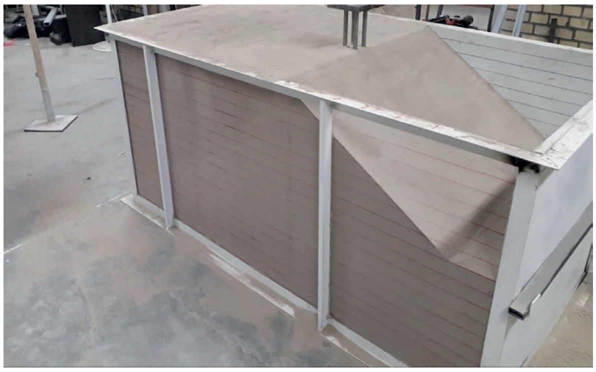
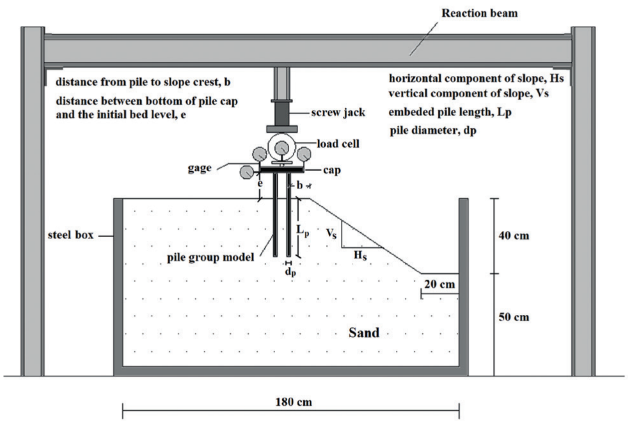
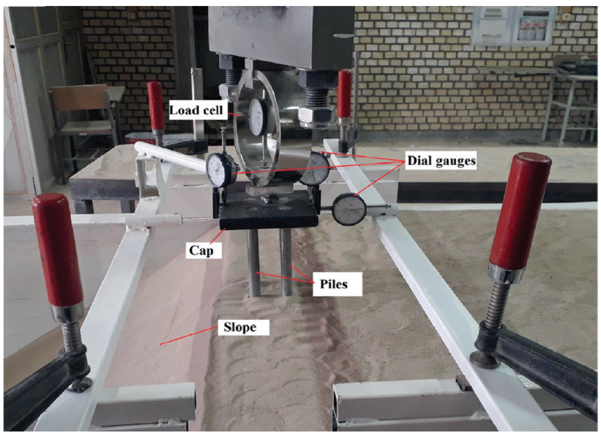


Fig. 2 Large-scale physical model test setup



(a)



(b)

Fig. 3 Large-scale pile-slope test setup: (a) Two-dimensional view of the experimental pile group-slope system; (b) Laboratory photograph of experimental setup

3 Results and discussion

In this study, a total of 35 model tests were carried out on the square (2 × 2) pile groups near a sloping ground. The effect of edge distance from slope crest, slope angle, pile diameter and embedded length of pile on the axial load-pile group settlement curve, reduction factor (RF), lateral displacement were obtained and discussed. A summary of the model tests is given in Table 2.

3.1 Effect of slope angle and edge distance

Fig. 4 shows the effects of edge distance from slope crest and slope inclination on the axial load–pile group settlement curves of pile groups consisting of four piles with diameter and embedded length of 18 mm and 300 mm, respectively. The results are presented for three slope inclinations (H_s/V_s = 1.5, 1.75 and 2). As shown from the results, the response of pile group is approaching to the level ground condition with the increase of edge distance for a given slope inclination. The change of horizontal and vertical stress can be used to reflect the effect of edge distance from slope crest on the response of pile groups. It is revealed that there is an increase in horizontal and vertical stress around piles as the distance between the pile group and slope crest increases. In this work, a non-dimensional Reduction Factor (RF), called the axial capacity reduction factor of pile was used:

$$RF = Q_{ps} / Q_{pg} , \tag{1}$$

where Q_{ps} and Q_{pg} are the axial load capacity of the pile group near a sloping ground and ground surface, respectively, at a settlement equivalent to 10% of pile diameter which is often regarded as the bearing capacity of pile [38, 42].

Fig. 5 presents the variation in RF values versus ratio of edge distance to pile diameter (b/d_p) for the three slope inclinations (1.5, 1.75 and 2). As shown from the results, the increase in edge distance leads to an increase in the RF, and the negative effects of the slope on the response of the pile group become negligible at higher b/d_p value. The RF value

Table 2 Summary of the model tests

Test Group	Edge distance (b/d_p)	Slope inclination (H_s/V_s)	Pile diameter (mm)	Embedded length (mm)
Group-1	0.5, 1.5, 2.5, 3.5, 4.5, 5.5	1.5, 1.75, 2	18	300
Group-2	0.5, 1.5, 2.5, 3.5, 4.5, 5.5	1.5	16, 18	300
Group-3	0.5, 1.5, 2.5, 3.5, 4.5, 5.5	1.5	18	150, 300, 500

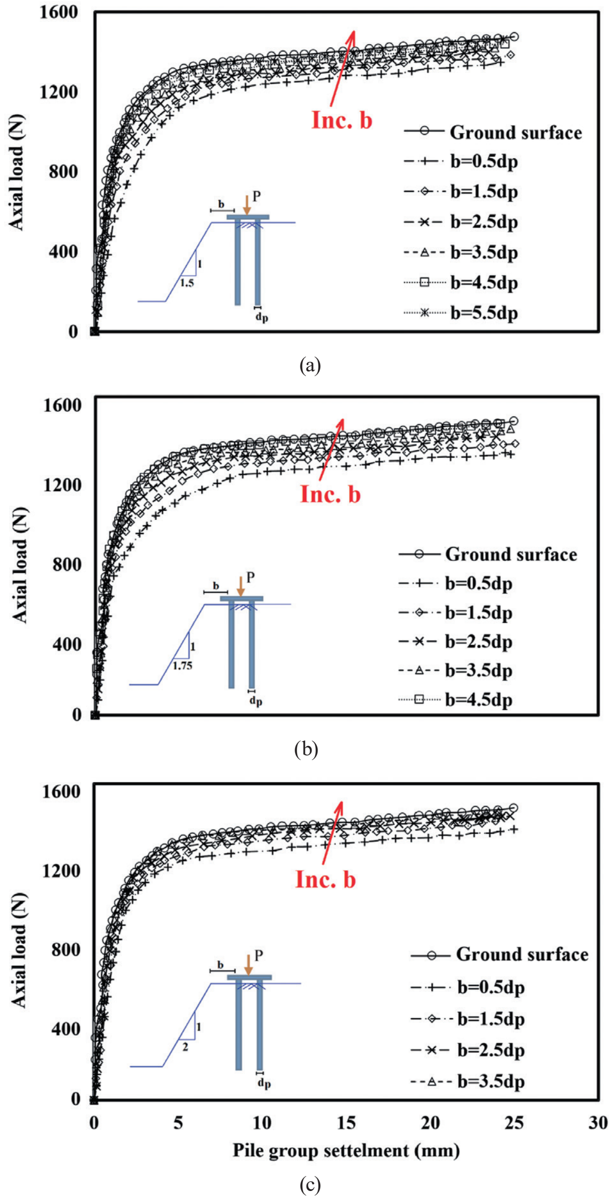


Fig. 4 Axial load-settlement curves for pile groups with pile diameter of 18 mm; (a) H_s/V_s = 1.5; (b) H_s/V_s = 1.75; (c) H_s/V_s = 2

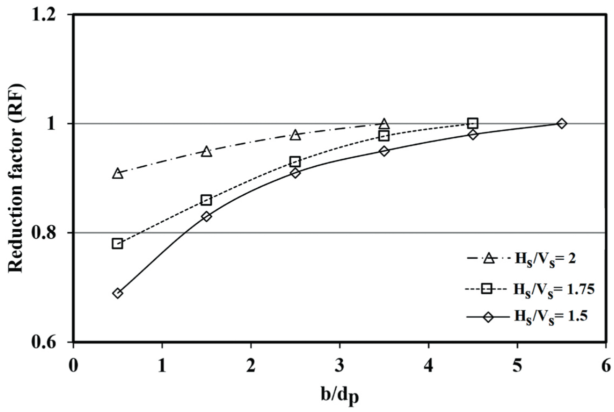


Fig. 5 Variation in RF of pile groups with pile diameter of 18 mm as a function of b/d_p at various H_s/V_s ratios

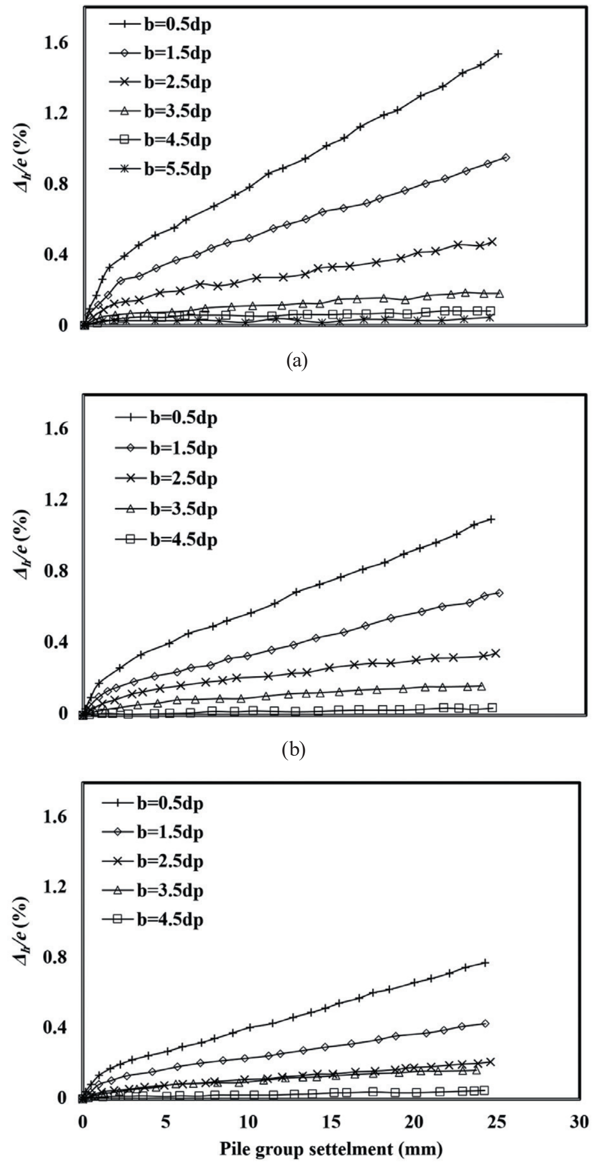
of pile group decreases with the increase of slope inclination for a given edge distance. It could be concluded that the effect of edge distance from the slope crest on the RF is dependent on slope inclination. The response of pile group on the slope with the inclination of $H_s/V_s = 2$ is approaching to the level ground condition around the edge distance of $b = 3.5\ d_p$ and after which the influence of slope could be neglected and the RF approaches to one. However, the RF approaches to one around the edge distance of $b = 5.5\ d_p$ for the pile group located at the slope with the inclination of $H_s/V_s = 1.5$. It could be concluded from the results that it may be necessary to move the pile to a certain distance from the crest of the slope to obtain a RF = 1 (i.e., the bearing capacity of pile group is unaffected by the slope) which is dependent on slope angle.

The variation in the horizontal displacement ratio (horizontal displacement/vertical distance of pile cap from ground surface = $\Delta h/e$) versus pile group settlement for different slope angles is presented in Fig. 6. The obtained results show that the horizontal displacement ratio depends on the slope inclination and distance of the pile group from the slope crest. It could be clearly seen that the horizontal displacement ratio increases as the distance of pile group from the slope crest decreases and slope inclination increases.

The variation in horizontal displacement ratio of pile group as a function of b/d_p at a settlement equal to 10% of pile diameter and various values of H_s/V_s is presented in Fig. 7. As shown from the results, the effect of slope inclination on the horizontal displacement ratio is more pronounced at lower values of b/d_p. The effect of edge distance from slope crest on the horizontal displacement ratio as well as on the RF is dependent on the slope inclination. The horizontal displacement ratio of pile group on the slope with the inclination of $H_s/V_s = 2$ is approaching to zero around the edge distance of $b = 3.5\ d_p$. However, for the pile group on the slope with the inclination of $H_s/V_s = 1.5$ the horizontal displacement ratio approaches to zero around the edge distance of $b = 5.5\ d_p$.

3.2 Effect of pile diameter

A series of tests was carried out on the pile groups consisting of four piles with diameter of 16 mm near the slope with $H_s/V_s = 1.5$ to study the effect of pile diameter on the response of pile group. Fig. 8 shows axial load–pile group settlement curves of the pile groups consisting of four piles with diameter and embedded length of 16 mm and 300 mm, respectively. As shown, the response of pile



(c)

Fig. 6 Variation in horizontal displacement ratio of pile groups with pile diameter of 18 mm versus pile group settlement for (a) $H_s/V_s = 1.5$; (b) $H_s/V_s = 1.75$; (c) $H_s/V_s = 2$

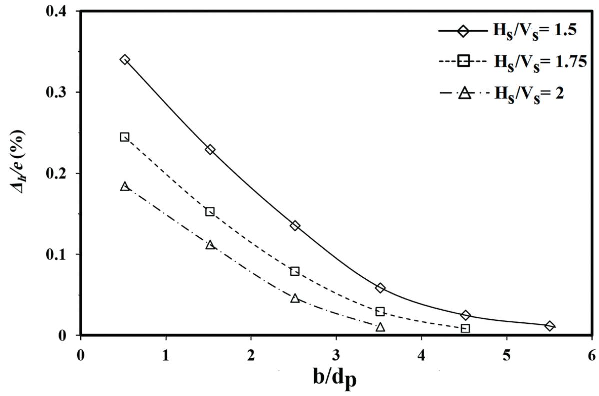


Fig. 7 Variation in horizontal displacement ratio of pile groups with pile diameter of 18 mm as a function of b/d_p at various H_s/V_s ratios

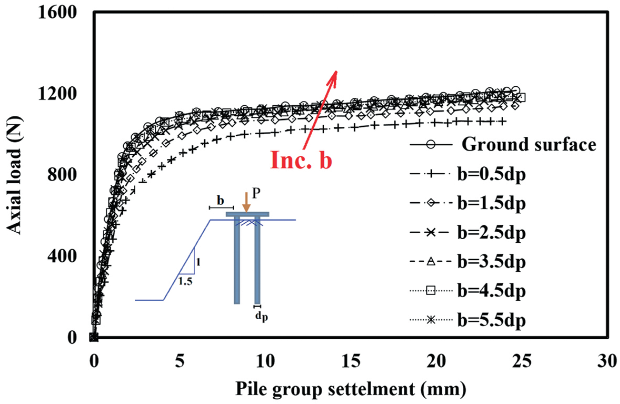


Fig. 8 Axial load-settlement curves for pile groups with pile diameter of 16 mm at $H_s/V_s = 1.5$

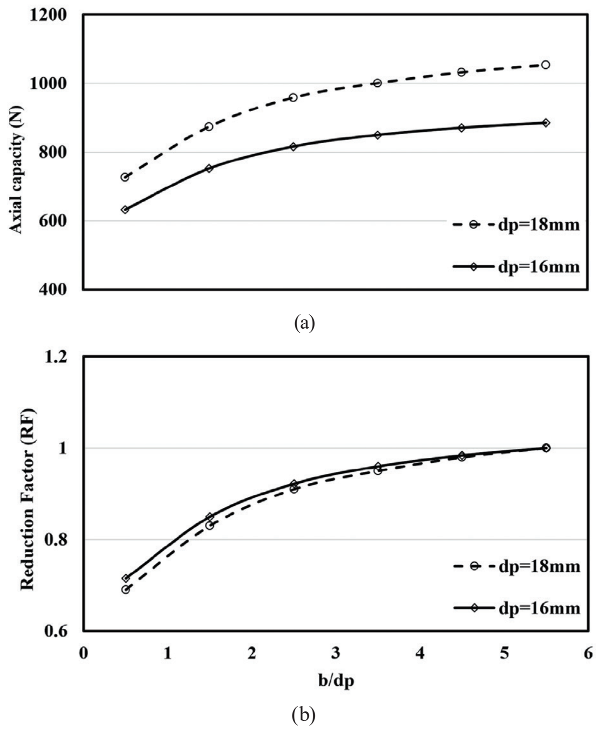


Fig. 9 Comparison of response of pile groups with pile diameter of 16 mm and 18 mm at $H_s/V_s = 1.5$ (a) Axial capacity versus ratio of edge distance to pile diameter; (b) Reduction factor versus ratio of edge distance to pile diameter

group is approaching to the level ground condition with the increase of edge distance from 0.5 d_p to 5.5 d_p which is the same as that found in the pile groups with diameter of 18 mm.

A comparison between the axial load capacity of the pile groups with diameter of 16 mm and 18 mm is also presented in Fig. 9. As shown, the pile diameter has a significant effect on the axial load capacity of the pile groups and this effect is more pronounced with the increase of edge distance from 0.5 d_p to 5.5 d_p. However, the pile diameter does not have important effect on the RF. There is a significant increase in the axial capacity due to increasing the pile diameter from 16 mm to 18 mm, but increasing the pile diameter causes a slight decrease in the RF for the small edge distance. The RF is almost independent of pile diameter for the edge distance higher than 4.5 d_p. Fig. 10 shows the variation of horizontal displacement ratio of the pile group with diameter of 16 mm versus pile group settlement for different edge distances. There is also a significant decrease in the horizontal displacement ratio due to increasing the edge distance from 0.5 d_p to 5.5 d_p. The effect of pile diameter on the horizontal displacement ratio is presented in Fig. 11. It is clear that the increase of pile diameter from 16 mm to 18 mm causes a small increase in the horizontal displacement ratio in small edge distance cases. However, the horizontal displacement ratio is almost independent of the pile diameter at the edge distance more than 3.5 d_p.

3.3 Effect of embedded length of pile

The embedded length of pile has important effect on type of pile response and on the response of axially loaded pile group near a sloping ground. Therefore, a series of tests was done to study the response of axially loaded pile group with diameter of 18 mm near the sloping ground

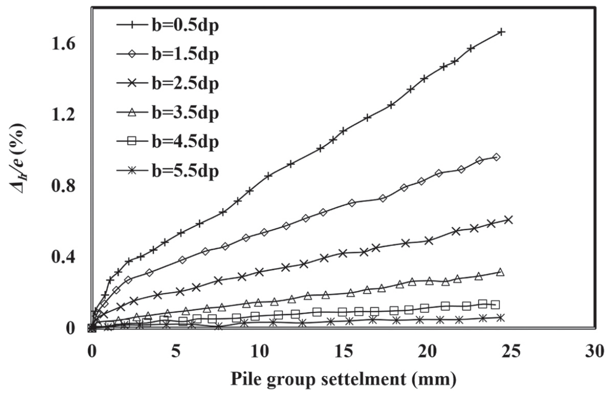


Fig. 10 Variation in horizontal displacement ratio of pile groups with pile diameter of 16 mm versus pile group settlement at $H_s/V_s = 1.5$

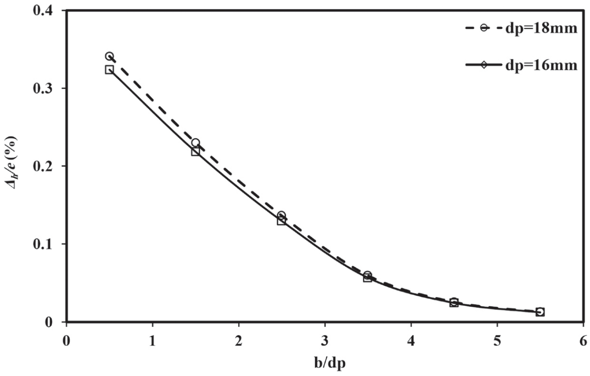


Fig. 11 Variation in horizontal displacement ratio of pile groups with pile diameter of 16 mm and 18 mm as a function of b/d_p at $H_s/V_s = 1.5$

(H_s/V_s = 1.5) using three different embedded lengths of 15, 30 and 50 cm (short, intermediate and long pile). The effects of edge distance from the slope crest on the axial load-settlement curves of pile groups with three different embedded lengths are shown in Fig. 12. As shown from the results, the response of pile group was approaching to the level ground condition with increase in the edge distance for all embedded lengths. However, the effect of edge distance from the slope crest is more pronounced with increasing embedded length from 30 cm to 50 cm. The load-settlement curves depicted in Fig. 13 show that the highest axial load capacity is observed in pile groups with embedded length of 50 cm.

The effect of embedded length of pile on the value of RF versus ratio of edge distance to pile diameter (b/d_p) is also shown in Fig. 13. As shown the value of RF increases with the increase in the ratio of edge distance to pile diameter and the embedded length of pile. The values of RF for all pile groups increased nonlinearly as the b/d_p increase. The effect of edge distance on the value of RF is not the same in three cases, and it is more pronounced

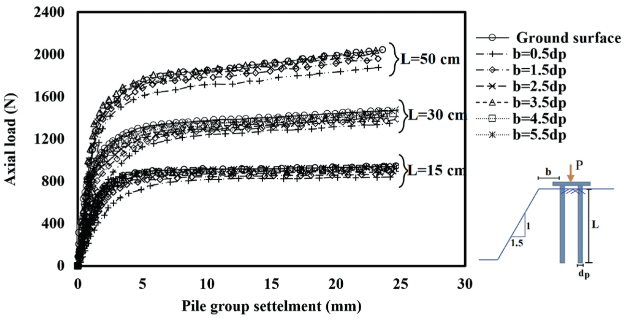


Fig. 12 Axial load-settlement curves for pile groups with pile diameter of 18 mm and various embedded lengths at H_s/V_s = 1.5

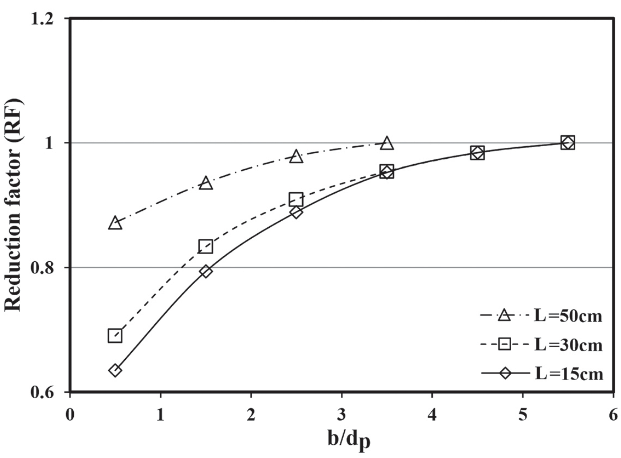


Fig. 13 Variation in RF of pile groups with pile diameter of 18 mm as a function of b/d_p at various embedded lengths and H_s/V_s = 1.5

for lower embedded length. The RF value for all pile groups decreased due to increasing edge distance and the response of pile groups on the slope is approaching to the level ground condition with increasing the edge distance. The response of the pile group with embedded length of pile of 50 cm is approaching to the level ground condition around the edge distance of $b = 3.5\ d_p$ and after which the influence of slope can be neglected and the value of RF approaches to one. However, the RF value of pile group with embedded length of pile of 15 cm approaches to one around the edge distance of $b = 5.5\ d_p$.

The variation in horizontal displacement ratio of pile groups as a function of b/d_p at a settlement equivalent to 10% of pile diameter and various embedded lengths of piles is shown in Fig. 14. As shown, the horizontal displacement ratio increases with decreasing edge distance and embedded length of piles. The effect of embedded length of piles on the horizontal displacement ratio is more pronounced with decreasing edge distance. The horizontal displacement ratio of pile group with embedded length of 50 cm is approaching to zero around the edge distance of $b = 3.5\ d_p$. However, for the pile group with embedded length of 15 cm, the horizontal displacement ratio approaches to zero around the edge distance of $b = 5.5\ d_p$.

4 Conclusions

In this study, a series of physical modeling tests were conducted to investigate the effects of pile diameter, embedment length of pile, slope angle, and location of pile groups relative to the slope crest on the response of pile group subjected to axial load. Based on the results, the following conclusions are reached:

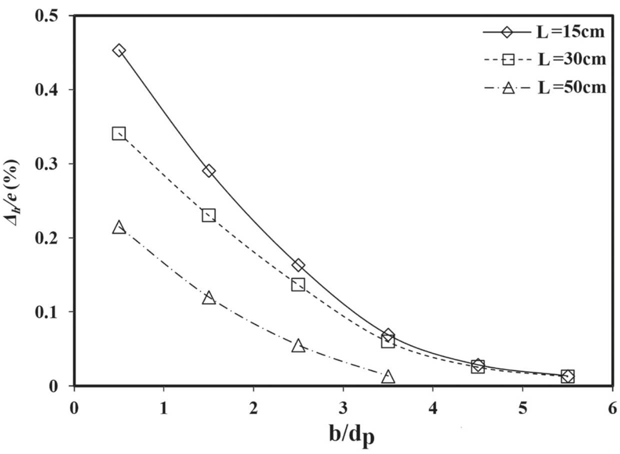


Fig. 14 Variation in horizontal displacement ratio of pile groups with pile diameter of 18 mm and as a function of b/d_p at various embedded lengths and H_s/V_s = 1.5

1. The response of pile group near the sloping ground approaches to the level ground condition with the increase in the edge distance from slope crest. This reflects the increase in the horizontal and vertical stresses around piles as the edge distance from slope crest increases. The effect of edge distance from the slope crest is more pronounced with increasing embedded length of piles. The negative effects of the slope on the response of the pile group would become negligible for the higher values of edge distance from slope crest. The RF value of the pile group decreases due to the increasing slope angle for a given edge distance.

2. Lateral displacement of pile group near a sloping ground is crucial to the safety of an overall structure. The horizontal displacement of pile group towards the slope face increases as the distance of pile group from the slope crest or the embedded length of piles decreases and slope angle increases. The effect of embedded length of piles on the horizontal displacement ratio is more pronounced with the decreasing edge distance. The increase of pile diameter from 16 mm to 18 mm causes a small increase in the horizontal displacement ratio for the small edge distance values. However, the horizontal displacement ratio is almost independent on the pile diameter for the higher values of edge distance from slope crest.

3. The pile diameter has a significant effect on the axial load capacity of pile groups near the sloping ground and this effect is more pronounced with the increase of edge distance from the slope crest. However, the pile diameter does not have an important effect on the RF, thus the RF decreases slightly when the pile diameter increases for a given edge distance. However, the RF is almost independent of pile diameter for the higher values of edge distance from slope crest.

4. The effect of edge distance on the RF is more pronounced with decreasing embedded length of pile. The response of the pile group with a higher embedded length of pile is approaching to the level ground condition in a shorter edge distance from slope crest in comparison with a shorter embedded length pile group.

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