Behavior of Vertical Piles Embedded in Sand under Inclined Loads near Ground Slope

Comportement de pieux verticaux ancrés dans une couche de sable à proximité d'une pente

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ABSTRACT: Pile foundations are used to support structures exposed to different types of loads. Among these loads are inclined loads which give axial and lateral loads. The main objective of the present paper is to investigate experimentally the effects of inclined load on axial pile displacement and lateral pile response for piles embedded in the level ground and near ground slope. The factors considered for this purpose are slenderness ratio for pile (L/D), relative density of sand (D_r), distance of the pile head from the slope crest (B/D), and the inclination of the applied load with the vertical. The behavior of the piles in the level ground was compared with the behavior of piles located near ground slope. Different results were obtained for combined axial and horizontal loading. From test results, the inclination of the applied load has a significant effect on the ultimate axial and lateral loads for pile, lateral pile deflection, and the bending moment along the pile shaft especially near ground slope. The coefficient of horizontal modulus of sub-grade reaction decreased when the inclination of the applied load increased.

ABSTRACT: Les fondations sur pieux sont envisages pour des structures soumises à différents types de chargement parmi lesquels on distingue ceux à composante latéral. Ce papier présente une étude expérimentale qui analyse l'influence de l'inclinaison d'un chargement sur le déplacement vertical et la réponse latérale d'un pieu ancré dans un sol à proximité d'une pente. Les paramètres d'influence sont l'élancement du pieu (L/D), la densité relative (D_r), la distance horizontale séparant le pieu de la pente (B/D) et l'inclinaison de la charge par rapport à la verticale. Le comportement des pieux dans un massif horizontal est comparé à celui de pieux à proximité de la pente à partir de résultats obtenus pour des chargements à composante verticale et horizontale. Il a été conclu que l'inclinaison du chargement à une influence considérable sur la capacité portante ultime sous charges verticale et latérale, le déplacement horizontal et le moment de flexion le long du fût du pieu, en particulier à proximité de la pente. Il a été également vérifié que l'augmentation de l'inclinaison du chargement conduit à une diminution du module de réaction horizontale.

KEYWORDS: Vertical piles, inclined load, sand slope, axial and lateral displacement.
MOTS CLÉS: Pieu vertical, charge incline, pente en sol sableux, déplacemenst vertical et horizontal

1 INTRODUCTION

Pile foundation for several types of structures is often subjected to simultaneous axial and lateral loading. According to current practice, piles are independently analyzed first for the axial load to determine their bearing capacity and settlement and then for the lateral load to determine the stresses and deflections. Several results of investigations on the behavior of piles subjected to inclined loading have been reported in the literature, e.g. by Chari and Meyerhof (1983), Sastry and Meyerhof (1990) and Abdel-Rahman and Achmus (2006).

Poulos and Davis (1980) suggested that the failure of a vertical pile exposed to an inclined load can be treated as the ultimate load capacity is a function of both the lateral resistance and the vertical load capacity of the pile. When the applied load deviates slightly from the axial direction, the failure will essentially occur due to the axial slip while lateral failure will occur when the inclination is large; that is the load becomes nearly perpendicular to the pile axis.

Six model tests were performed on aluminum closed-ended piles by Christos and Michael (1993) to investigate experimentally any possible effects of lateral loading on axial pile displacements and stresses as well as the influence of axial loads on the lateral pile response. The main findings were the following: the effect of axial loading on the lateral pile response was rather limited. The interaction between axial and lateral pile responses can be studied with a nonlinear finite-element analysis, while the conventional elastic half space and subgrade reaction methods of pile analysis cannot consider this interaction.

According to Vankamanidi and Geoffrey (1999), the lateral soil pressure, bending moments, pile displacements at the ground surface have been investigated. The results of these load tests are compared with theoretical estimates based on the concept of the effective embedment depth of equivalent rigid piles for ultimate and elastic case. Reasonable agreement has been found between the observed and the predicted behavior of flexible piles.

From the above literature, lack in the knowledge about the behavior of pile under inclined loads near ground slope was noted. Therefore, the main objective of this paper is use experimental model to study the behavior of pile adjacent to a slope crest under inclined loads.

2 MODEL DESCRIPTION

Vertical and lateral loads were conducted on the model pile in a rectangular steel test tank with the size of 1000 mm (length) x 500 mm (width) x 700 mm (height). The vertical edges of the tank were stiffened by using steel angle sections. The inner faces of the tank were graduated at 50 mm intervals to facilitate an accurate preparation of the sand bed in layers. The front long side was made of a 20 mm thick glass panel. The glass side allows the sand to be seen during the preparation and to minimize friction between the tank wall and sand particles.

Vertical loads were applied to the model pile by using a hydraulic jack. The magnitudes of applied loads were recorded with the help of a pre-calibrated sensitive proving ring. The lateral load was affected through a 2 mm diameter high-tension steel wire connected to the pile cap using an eye bolt. The other side of the wire ran over smooth adjustable pulley with a 70 mm diameter and supported a load plat form. In order to record the correct vertical settlement and lateral deflection of the pile for each load increment applied, four sensitive dial gauges of the least measurement of 0.01 mm were used, two for vertical and two for lateral and their average was taken.

A smooth steel model pile, with diameter of 10mm, and total length 110, 210, 310, and 410 mm were used in this study. The upper 10 mm of the pile is screwed part and the other length embedded in sand. The slenderness ratio (L/D) was chosen to be used in this research equal to 10, 20, 30, and 40. Five strain gages were stuck to the surface of the model pile with L/D = 40. The measurement of flexural strains can lead directly to bending moment curve.

The cap was designed as flexible as possible and the pile was not deeply seated through it, so that no restraint of the pile head rotation is available. One edge of the cap is bent up to allow horizontal dial gauges to be mounted. At the other side of the cap, a 1.5-cm hook was welded exactly at the center of this side.

3 SOIL PROPERTIES

The soil used in this study for all of the tests is clean sand, classified as poorly graded sand according to the Unified Soil Classification System. The moisture content (W_c) was about 2%. The following are the results of the sieve analysis test; effective grain size D_{10} = 0.14 mm and uniformity coefficient C_u = 4.357. The sand was placed to achieve three relative densities. The physical characteristics of these soils are shown in Table (1).

Table 1. Physical Properties of the Tested Soils.

Soil Condition	A	B	C
Relative density D_r (%)	25	45	68
Unit weight (kN/ m^3)	17.5	17.8	18.3
Voids ratio (e)	0.56	0.52	0.48
Porosity (n)	0.36	0.34	0.33
Angle of shearing resistance (Ø)	31°	34°	38°

4 PREPARATION OF EXPERIMENTAL SETUP

Before sand slope preparation, the model pile was then placed at a specific position. Then, model sand slope 150- mm high with slope angle, θ, of 26.56° (2H: 1V) was prepared in layers of 50 mm thick. The proposed testing geometry of the slope was first marked on the walls of the tank for reference. To obtain uniform density of the soil in the tank, controlled pouring and tamping techniques using a flat bottom hammer were applied. The pile was placed and fixed in its correct position before the formation of sand slope to simulate non displacement piles.

5 RESULTS AND DISCUSSION

An experimental testing program was designed to study the effect of inclined load on the behavior of vertical pile in sand on level ground and adjacent to ground slope. The geometry of the problem is illustrated in Fig. 1. As shown in this figure, the height of ground slope (H_{slope}) equal to 15 cm and its horizontal projection (X_{slope}) equal to 30 cm to achieve slope gradient (2H:1V). The location of the pile relative to the slope crest is the distance (B).

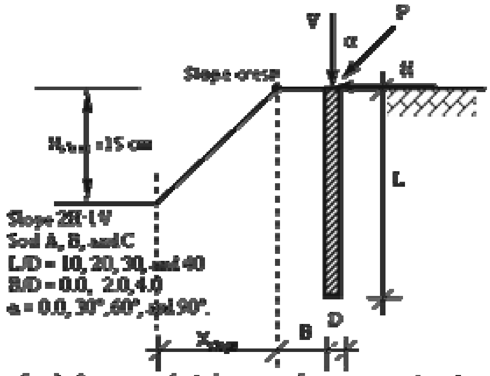

Fig. 1. Positions of pile in cases of experimental work.

The load-deflection curves were obtained by plotting the relationship between the vertical and lateral loads and its axial settlement and lateral deflections, respectively. According to Terzaghi (1942) and Tomilson (1980), the ultimate axial (V_u) and lateral (H_u) loads are defined as the loads, which cause a vertical or horizontal deflection of one tenth of the pile diameter (i.e. 10% of the pile diameter) to simulate the geotechnical failure in the soil.

5.1 *Ultimate capacity of pile in the level ground*

The ultimate axial load and lateral load of the pile increased during testing program when the slenderness ratio (L/D) was increased. As shown in Fig. 2, for dense sand (soil C), a significant increase for ultimate axial load (V_u) with increasing slenderness ratio. But for loose sand (soil A), the effect of slenderness ratio on the ultimate axial load found to be small. The ultimate axial load (V_u) decreased as the inclination of the applied load with the vertical (α) was increased.

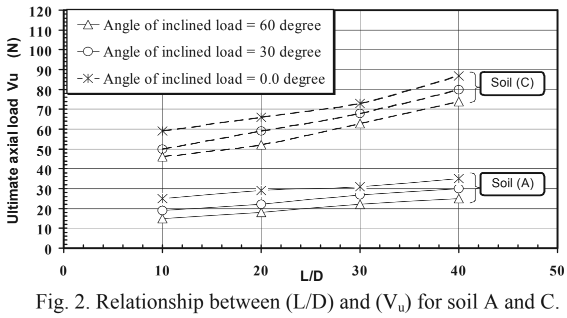

Fig. 2. Relationship between (L/D) and (V_u) for soil A and C.

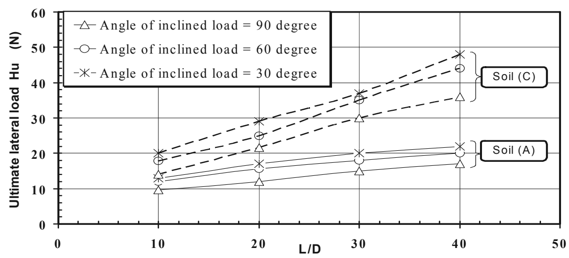

Fig. 3. Relationship between (L/D) and (H_u) for soil A and C.

From Fig. 3, it is clear that, the ultimate lateral load (H_u) dependent on the slenderness ratio (L/D). A significant increase on ultimate lateral load with increasing (L/D). This can be explained by the embedded length, for small (L/D) is not sufficient to create the full fixation of the pile. Increasing the inclination of the applied load (α) will increase the lateral load acting on the pile head. Therefore, the lateral piles displacement will increase and decrease the ultimate lateral load.

5.3 *Bending moment along the pile length*

Figures 4 and 5 presents the experimental bending moments along the pile length with L/D = 40 in sandy soil. The strain readings obtained experimentally are converted to bending moment. In general, the shape of the diagrams is compatible with the shapes investigated by Broms, 1964. It is obvious that, the increasing of (α) increased the maximum values of the bending moment along the pile length. The maximum bending moment in case of ($\alpha = 90^o$) for pile in soil (A) is about 29 % and 9 % larger than that in case of $\alpha = 30^o$ and 60^o respectively. These percentages are about 13 %, 8 % respectively for pile in soil (C). From the above mentioned figures, the bending moment may vanish before the end of the pile. The depth of the point of the maximum bending moment increases by increasing the inclination of the applied load with vertical (α).

It is obvious from the previous figures that, the maximum bending moments are usually higher for loose sand than the case of dense sand. Increasing the relative density of soil decreased the maximum bending moment along the pile length at the same (α).

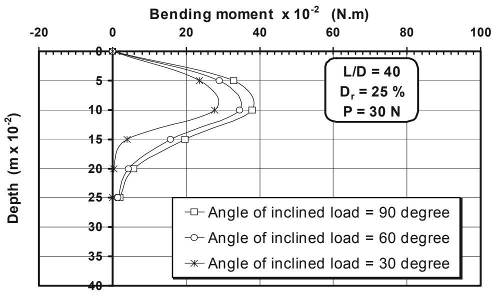

Fig. 4. Experimental bending moment along the pile length for soil A.

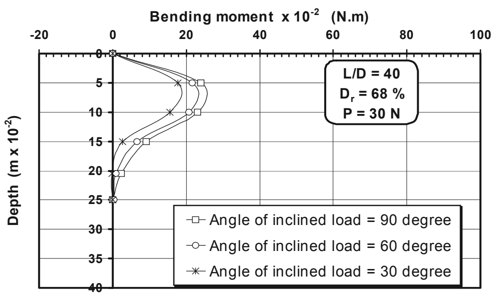

Fig. 5. Experimental bending moment along the pile length for soil C.

5.4 *n_h – deflection relationship*

According to Reese and Matlock (1956), the coefficient of horizontal modulus of sub-grade reaction (n_h) is related to the relative stiffness factor, (T) through the relation, $T = (E_p I_p / n_h)^{1/5}$ which is used in the analytical analysis. The value of (T) can be obtained from the following equation:

$$y_{gs} = y_{zg} \times H_{gs} \times T^3 / E_p I_p \quad \text{(Valid for vertical pile only) (2)}$$

where: y_{gs} is the lateral deflection of the pile at ground surface, y_{zg} is a non-dimensional coefficient that depends on the ratio, embedded length / T (for embedded length / T > 4, $y_{zg} = 2.435$), H_{gs} is the lateral load at ground surface, $E_p I_p$ is the Flexural stiffness of the pile, and (T) is the relative stiffness.

From load – deflection curves and by using the above equation, the values of (n_h) were calculated at each deflection. The results show that the coefficient of horizontal modulus of sub-grade reaction is significantly dependent on the deflections at the low load levels and is relatively insensitive to deflections at high load levels. Figure 6 shows the coefficient of horizontal modulus of sub-grade reaction versus deflection in the free head case for pile with (L/D=40) and inclined load with ($\alpha = 30^o$). From this figure it is clear that the coefficient of horizontal modulus decreases with the deflection increase. This conclusion agrees with that drawn by Alizadeh and Davisson, 1970. It is obvious from that; relative density of sand has a significant effect on (n_h) values.

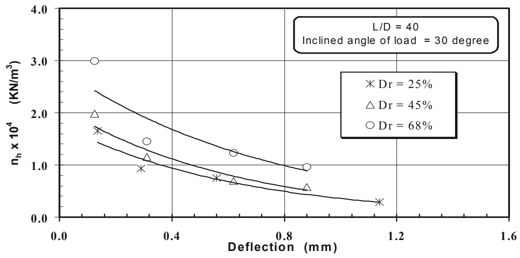

Fig. 6: n_h – deflection relationship for pile under inclined load = 30^o.

5.5 *Pile near ground slope*

There are many practical situations where piles are constructed near ground slope. Both axial and lateral loads were applied to the pile head at ground surface for pile near ground slope (2H: 1V). The test results from experimental model are presented. An important parameter defining the location of the pile head relative to the crest of the slope (B/D) is considered.

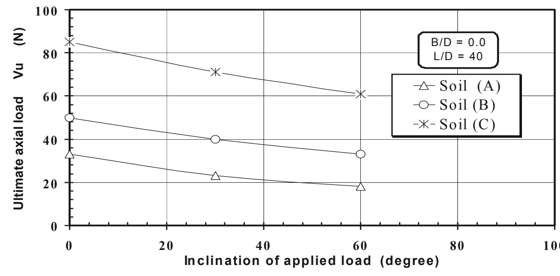

Fig. 7. Relationship between load inclination and (V_u) for pile at crest of slope 2H:1V.

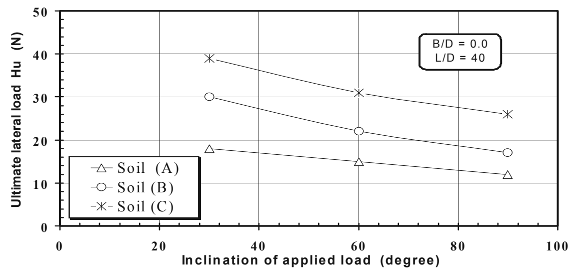

Fig. 8. Relationship between load inclination and (H_u) for pile at crest of slope 2H:1V.

The results in case of a ground slope are compared with the corresponding results obtained by considering the case of a horizontal ground surface. For pile with L/D = 40 and B/D = 0.0, the effects of the inclination of the applied load on the ultimate axial load (V_u) and the ultimate lateral load (H_u) are shown in Figs. 7 and 8. In these figures, the results are normalized with respect to the corresponding values in case of horizontal ground surface. The ultimate axial and lateral loads decreased as the inclination of the applied load with the vertical (α) was increased. Increasing the relative density of the soil will increase the ultimate load (axial and lateral) at the same load inclination (α). For soil (C) and ($\alpha = 60^o$), the ultimate axial load in case of pile at crest of ground slope having an inclination 2H: 1V is about 18% smaller than that in case of horizontal ground surface. This percentage increases to 31% for ultimate lateral load.

The ratio (B/D) represents the closeness of the crest of the ground slope to the pile head. According to Sakr and Nasr (2010), the ratio (B/D) is very important on the lateral behavior for piles near ground slope. Therefore, the ultimate lateral load is plotted against the pile distance from the slope crest (B/D) in figure 9 for pile with (L/D = 40) and ($\alpha = 30^o$). From the above mentioned figure, increasing of (B/D) will increase the ultimate lateral load for different soil densities. For soil (A), the effect of (B/D) on the ultimate lateral load can be neglected. For soil (C) and (B/D = 0.0), the percentage decrease in ultimate lateral load is about 21% than that in case of a horizontal ground surface. This percentage is 18% for soil (A).

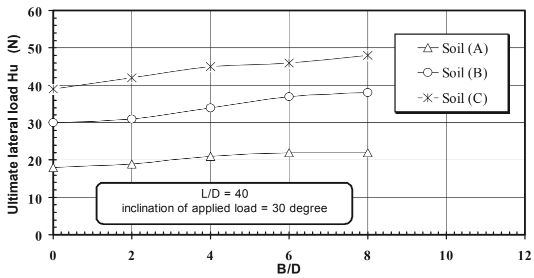

Fig. 9. Relationship between (B/D) and (Hu) for pile near ground slope 2H: 1V.

Figure 10 presents the experimental bending moments along the pile length for pile with (L/D = 40) embedded in loose sand (soil A) and (α) equal to 30^o, and 60^o respectively. From the above figure, increasing of (α) will increase the maximum bending moment. For example from experimental results and at ($\alpha = 60^o$), the maximum bending moment is about 31% larger than that in case of ($\alpha = 30^o$). It is clear that the depth of the point of the maximum bending moment is about 25% from the pile length measured from the ground surface.

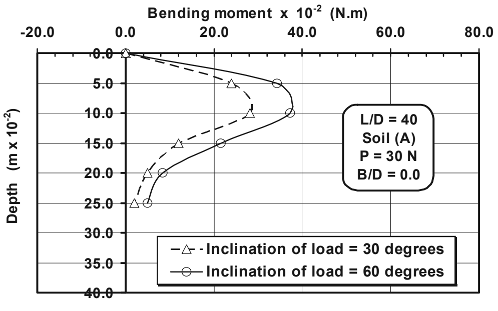

Fig. 10. Experimental bending moment along the pile length at different load inclination.

6 CONCLUSIONS

The results of an experimental model were presented in this research to study the general behavior of a single pile in sandy soil under inclined load. The following conclusions are drawn based on the results of tests for pile in the level ground and near ground slope 2H: 1V:

1- The ultimate axial and lateral loads decreased as the inclination of the applied load with the vertical (α) increased.
2- For pile embedded in dense sand and under inclined loads, a significant increase on the ultimate lateral load with increasing slenderness ratio (L/D).
3- Increasing the inclination of the applied load with vertical (α) will increase the lateral deflection along the pile length. For pile embedded in loose sand and at ($\alpha = 90^o$), the maximum lateral deflection at ground surface is about 53% larger than that in case of ($\alpha = 30^o$). This percentage is about 40% for pile in dense sand (soil C).
4- For the same soil and deflection, the values of (n_h) decreases by increasing the inclination of the applied load (α).
5- Increasing the distance of the pile head from the slope crest will increase the ultimate lateral load for piles embedded in different sand densities.

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