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RESEARCH ARTICLE

Displacement Behavior of Strip Footing on Pile Stabilized in Clayey Earth Slopes

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Abstract

Man-made or natural earth slopes are created or used for different construction activities. Earth slopes can result from activities such mine excavation and dredging for berthing structures. Typical examples of the creation and use of earth slopes are rail and road embankments, and river training bunds. Both types of slopes can be high and subject to large lateral loads and thus, may require extra pile stabilizations to reinforce their stability. This paper presents the behavior of a slope and piles subjected to increasing loads applied to the strip footing just behind the crest. To evaluate the performance of a slope a small scale physical test model was built to reproduce a plain-strain state within a clayey soil slope. High resolution photographs were taken in short intervals through the glass wall of the model during the foot settlement and the soil deformation of reinforced slopes. The evaluation of the photographic data provided an interesting insight into the deformation mechanism and the progressive failure characteristics of pile reinforced slopes. The results indicate that stabilizing with piles has a significant effect on clayey earth slopes especially in terms of improving the bearing capacity and controlling the deformation behavior of the strip footing.

INTRODUCTION

Many high-rise buildings, transmission towers, and bridges are constructed near slopes and are supported by pile foundations. These structures are exposed to considerable amount of lateral load due to environmental activities which is ultimately transferred to the pile foundations. In such kind of situations piles can be subjected to axial (tension or compression) loads and lateral load or combination of these loads. In slope conditions one of the most complex and unpredicted load transfers to the pile occurs just front of the footing. The soil pile interaction mechanism in sloping ground is differs from that in horizontal ground. A pile subjected to a lateral load at the head and transmits that load to the soil is an active pile; whereas a passive pile is one that is subjected to a load from moving soil which induces forces and bending moment to the pile. (Poulos 1995).

Over the years the subject of stabilizing earth slope has become one of the most interesting areas for scientific research and has attracted a great deal of attention. In particular, the analysis of a laterally loaded pile embedded in the level ground has been the focus of much research over the past two decades (Reese and Matlock 1956, Davisson and Gill 1963, Matlock 1970, Poulos 1971, Reese and Welch 1975, Randolph 1981, Norris 1986, Budhu and Davies 1988, Prakash and Kumar 1996, Fan and Long 2005, Dewaikar et al. 2011, Kelesoglu 2009).

This paper presents the behavior of a slope and piles subjected to increasing loads applied to the strip footing just behind the crest. The aim of the study is to increase the understanding of the mechanical behavior of the pile group and settlement of the footing. To evaluate the performance of a slope a small scale physical test model was built to reproduce a plain-strain state within a clayey soil slope.

Although small-scale models are considered to have limited applications because some important similarity requirements cannot be met, however, these models can be a useful and low cost tool to study the behavior of geotechnical structures. From tests with small scale models experimental observations can be undertaken to provide a better insight into the deformation process occurring in various types of boundary problems. Thus, at Aksaray University new research has recently been carried out on a physical test apparatus built to reproduce a plane-strain state within a clayey soil slope.

2 Testing apparatus and test procedure

The test box shown in Figure (1) has inside dimensions of 1.0m x 0.7m in plan and 0.7m in depth there are three steel walls with a front wall made of 8 mm thickness glass and is the box corners were supported on two steel columns. In the design of test box, researchers were inspired from Cola S. & P. Simonini' s (2006) test box system, test equipment and investigation methodology.

These columns are firmly fixed in two horizontal steel beams which are firmly clamped in the floor of the laboratory using four pins. Plain strain conditions were considered in all the tests carried out on this slope model rig. The rigid footing model was made from a solid steel section with width of 32 cm, a thickness of 2 cm and a length nearly equal to the width of the test box to simulate a strip footing conditions.

[Fig. 1 in here]

The front wall of the box is a glass panel with a thickness of 4 mm to allow for the visual observations of the slope inclination. In all the tests the footing was placed just at the beginning of the crest of the slope model. The surcharge load was applied using a hydraulic jack on the footing in an incremental manner, in order for the non-linear load versus the displacement curve to be adequately defined. Each load increment was maintained as constant until the footing settlement stabilized. The settlement of the footing and the lateral deflection of the pile group were measured using 0.001 mm accuracy LVDT dial gauges placed on opposite sides across the center of the footing and the pile group direction x (lateral) and z direction (axial). The wall strains of the pile sections were also measured using electrical resistance biaxial strain gauge rosettes which allow for smooth profiles in the measurement of strain.

The piles were instrumented with 3 pairs of strain gauges at intervals of 100 mm. The dimensions of the gauge were 5 x 5 mm with a resistance of 350 ohm. To ensure an accurate reading, the strain gauges were calibrated by exerting a transverse load in the middle of the pile which is clamped at both ends prior to each test. In this study, strain gauges were calibrated using Eq. (1) created by Dalley and Riley (1978).

$$CF = (1-\upsilon o\ Kt)/(1+Kt/-\upsilon) \qquad (1)$$

Where CF is the calibration factor, ν0 is the Poisson's ratio of gauge (0.285), ν is the Poisson's ratio of HDPE material (0.4), and Kt is the sensitivity factor of instruments (0.004). The biaxial strain gauge rosettes were glued to the inside of the pipe section, followed by a layer of silicone and finally protected by a layer of rubber sheet to prevent the intrusion of external effects.

3 Deformation measurement with single camera

Digital image and computer technologies provide tools and far more information from images than was possible a decade ago. Small differences between pairs of images can be readily detected, changes can be quantified in pixel counts or area percentages and images are time stamped for easy sequencing and animation. Another advantage of photogrammetric techniques is the non-contact measuring; the tested objects are not affected by the measuring device and the objects do not have to be accessible. If primarily one-dimensional deformations are expected, a single camera can be sufficient Figure (2). (Maas H, 1998, Benning et al. 2000, Hampel et al. 2001).

[Fig. 2 in here]

To process monocular image sequences, the coordinates of the targets and the exterior camera orientation parameters can be determined beforehand by a multi camera bundle adjustment. (Albert et al. 2002).

When the image plane and the slope surface are parallel it is sufficient to take a scale factor (magnification factor) by one known distance of two targets on the slope surface, pile cap and footing. A full reconstruction of the exterior orientation is not needed, it should only be constant over the measuring period, or the changes should be determined by stable reference points in the soil box surface. The movements Δx, Δy of the object points are given by measured image coordinates (Eq. 2,3) Δx, Δy and the magnification factor β:

$$\Delta X = \beta \cdot \Delta x \qquad (2)$$

$\Delta Y = \beta \cdot \Delta y$ (3)

In the case of low deflections systematic errors such as lens distortion and the CCD chip will hardly affect the deformation measurements due to their original nature.

4 Materials

The cohesive soil used in the model tests was available locally. The soil was identified as CL according to uniform classification system. For the model test soil particles were passed through B.S sieve No. 40 and kept in oven for 24 hours under 110 Co temperature. The results of the unconfined compressive strength tests and vane tests were carried out on clay samples of different water content and variations of undrained shear strength are presented in Figure (3).

[Fig. 3 in here]

The clayey soil was thoroughly mixed and placed by hand into the model test box to the required geometry of the slope. The properties of soil are given in Table (1).

[Table 1 in here]

The model pile has lengths of 200, 300 and 400 mm. The outer diameter of the model pile is 32 mm with a wall thicknesses of 15 mm. Its shear stiffness was selected to be at least 3 orders of magnitude larger than the stiffness of the clay tube to ensure a uniform displacement distribution over the pile segment and not to exceed the elastic range of structural element. Table (2) shows the results of the tensile test of the model pile (aluminum tube). At a yield load of 13 kN, the model pile showed an approximate yield stress of 169000 kN/m2.

[Table 2 in here]

According to the test results, the average flexural stiffness of the model pile is 93.1 x 10-6 N/mm2 which was found using simple beam bending test.

A model strip footing made of wood was used. The footing was 320 mm long, 75 mm wide and 20 mm thick, it was footing was installed on the top of the slope just behind the crest. The length of the footing was made almost equal to the width of the test box in order to maintain plane strain conditions. The two ends of the footing plate were polished smooth to minimize the effects of friction. A rough base condition was achieved by fixing a thin layer of sand onto the base of model footing with epoxy glue.

5 Experimental studies

The main objective of the experimental studies is to discover the relationship between the variable parameters of the pile group and the settlement behavior of the footing. Then, to determine the best location of the pile group that gives the greatest improvement in the footing bearing capacity.

For all the tests, the clayey soil samples are prepared by mixing dry soil and water in ratio that corresponded to the target moisture content, of approximately 30 % water) The soil was then spread over the inside the middle compartment of the box.

The proposed testing geometry of the slope was first marked on the transparent glass wall for reference then clayey soil was placed in the box by hand. Secondly; the footing and the pile group were placed on the proposed position which were the crest, middle and the toe of the slope body. When carrying out model tests using pile systems, a major difficulty is the installation of the pile in the clayey soil. In this study the pile group was pushed into the clayey soil at a rate of 1.2mm/sec using a handle jack in this process. It is important to ensure there is minimum disturbance to the soil medium. In order to evaluate the installation effects on soil distribution, vane tests were conducted at points near and far from the pile groups. According to the vane shear strength tests differences between the two points measured less than 5% which is within the acceptable limit. Three model tests with different pile lengths were carried out. Before beginning the test series, response and settlement behavior of model footing which is constructed on the unreinforced slope was determined in order to evaluate the efficiency of the reinforcement on slope stability and footing deformation behavior. The second step of the test focused on determining the most effective position of the pile group on the slope body. In the tests three different points were evaluated and were repeated with piles of different lengths. The load increments on the footing revealed three important effects on the reinforced slope. These are the footing settlements on vertical axes, the lateral deflection of pile group and the total deformation behavior of the clayey soil medium. These three effects were measured simultaneously during the test procedure. The footing settlement and lateral deflection of pile group were measured using LVDT and the total deformation of the slope medium was observed using a photogrammetric technique. In all the tests the camera was positioned horizontally to the slope body and nearly level in order to achieve a homogeneous magnification. The scale factor was calculated by comparing the known distance of two targets (pile and footing) on the elements in the slope body. As only small deformations of a primarily two dimensional nature needed to be measured, the precision of the scale factor in the single camera setup was not critical. The object deformation is given directly by multiplying the image coordinate difference by the scale factor Eq (2) since low number of the deflections only a basic knowledge of camera calibration parameters is sufficient. The precision of the image coordinate difference measurement is crucial for the accuracy potential of the method. For optimum evaluation the over-exposure of the targets has to be avoided. The following two techniques were used for the measurements of the image coordinates and the image coordinate differences (Luhmann, 2000).

*The image coordinates of the signalized points were measured by an ellipse operator

*The image coordinate changes of signalized points or surface patches with sufficient local image contrast were determined by least-squares matching (LMS)

Both operators offer the potential of sub-pixel accuracy measurements, allowing the high geometric accuracy of CCD sensors is exploited. The foot settlement under incremental surcharge loading is shown in Figure (4). The foot settlement patterns and deformation shapes were similar in all tests. However, it is evident that the pile position is much more effective on the foot settlement. All the figures show that minimum settlement occurred when the pile group was embedded in the crest position of the slope body.

[Fig. 4 in here]

In all the tests the foot settlement and lateral movement of the pile group under surcharge load were measured and determined by photographic chance detection simultaneously. In Figure (5) the lateral movement of the pile group is presented. The optimum pile length was found to be 30 cm in this particular test series.

[Fig. 5 in here]

Figure (6) shows the bending moment distribution throughout the length of the pile. Strain gauges were installed at the middle of the single pile in the group. As seen in Fig (6), bending moments increased proportionally with the pile height. The maximum bending moment occurred at a 40 cm pile length in the pile group located in the crest region of the slope. Thus, in that situation, it can be concluded that the when a large part of the pile is embedded part in the stable underlying soils there is less rotation of the pile and hence less lateral deformation.

[Fig. 6 in here]

As seen in Figures 4,5, and 6 that the nearer the pile row is placed to the slope crest the better the response of the footing in terms of settlement deformation. In addition, the most effective pile group location being on the slope crest can be explained by the fact that the passive wedge under the footing becomes relatively shallow and hence the mobilized passive resistance is increases when the pile row are placed on the crest. The main role of the pile is to reduce the distortion rate in the sheared zone and reduce the ultimate shear stress generated in the shear zone. The same conclusions are confirmed by (Azzam W. R. et al. and Sawada et. al 2010).

Based on observations of the deformation mode of the slope shown in Figure (7) the settlement deformations and cracks under 90kPa surcharge load can be seen over the whole slope body.

[Fig. 7 in here]

Tensile (transverse) cracks were especially marked behind the pile group and in front of the footing. It can be clearly seen that major failure zones and radial deformations began after the reinforcements. This confirms the effectiveness of the piles that control the slope movement under high surcharge loadings. Another notable measurement is the occurrence of heaving at the toe of the model slope. This is partly because of the characteristics of the slope slide behavior and partly due to the boundary conditions of the soil box facility.

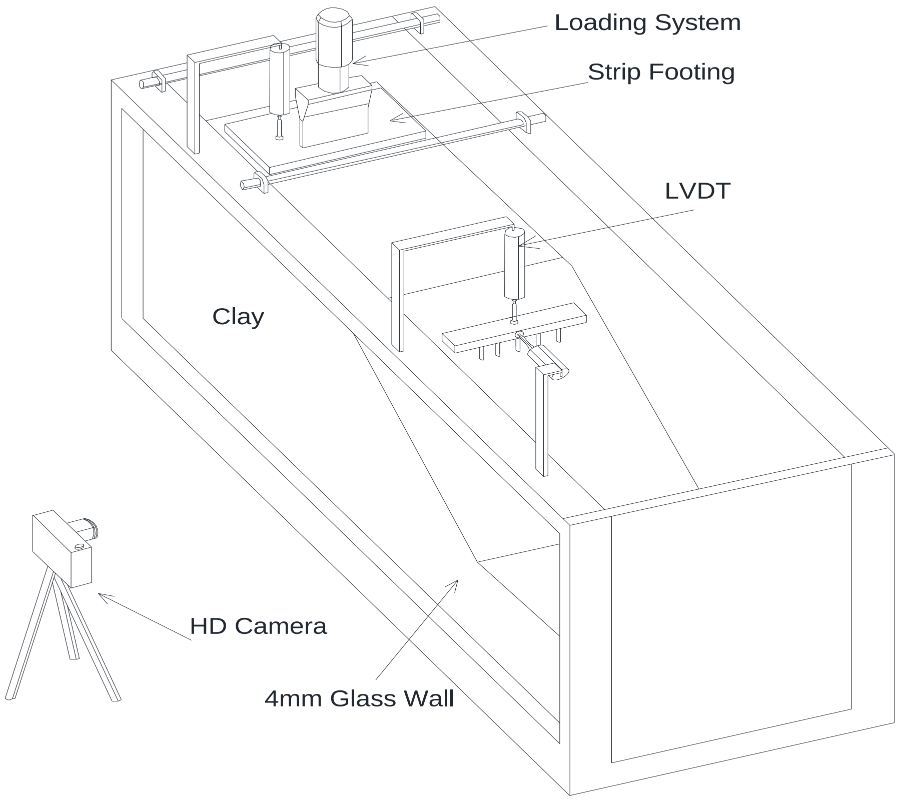

Fig. 1 Test box and instrumentations (Cola S. et al 2006)

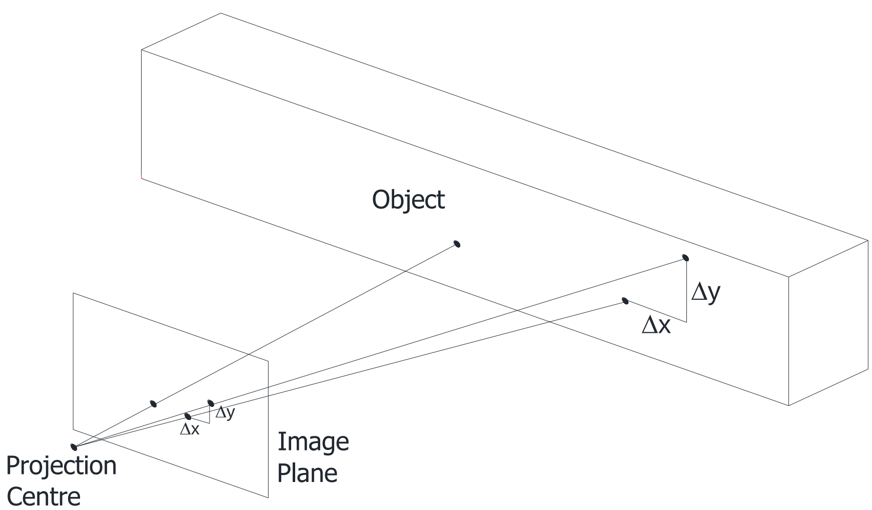

Fig. 2 The principle of single camera deformation measurement (Albert et al. 2002).

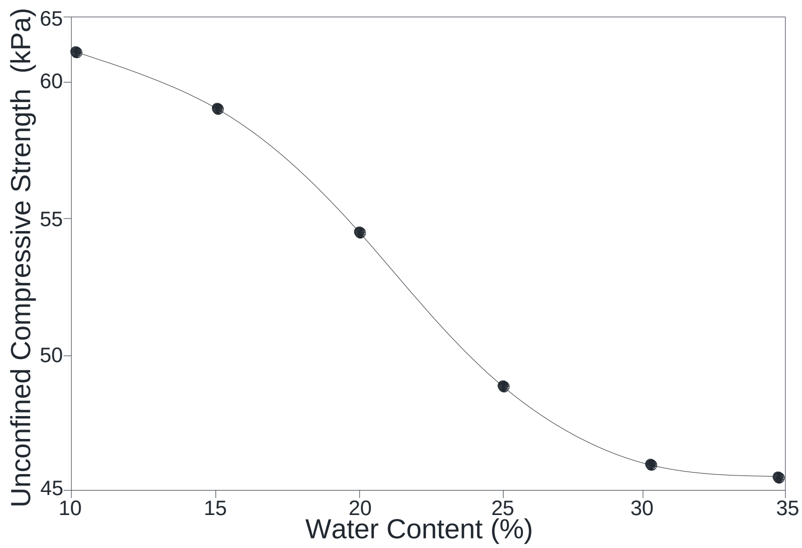

Fig. 3 Unconfined compressive strength of clay

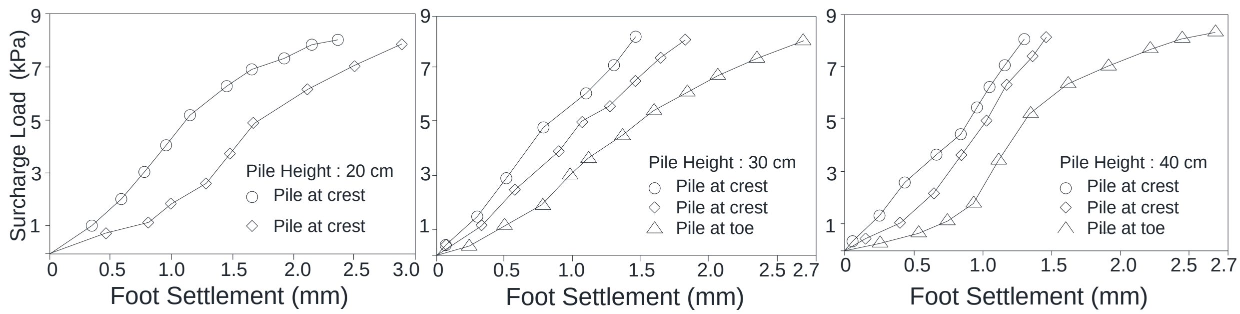

Fig. 4 Foot settlement under incremental surcharge load

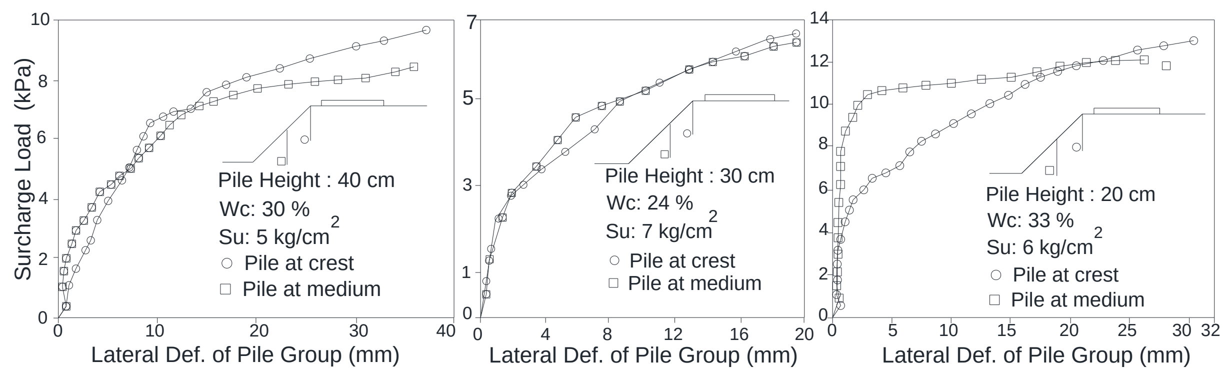

Fig. 5 Lateral deflection of pile group

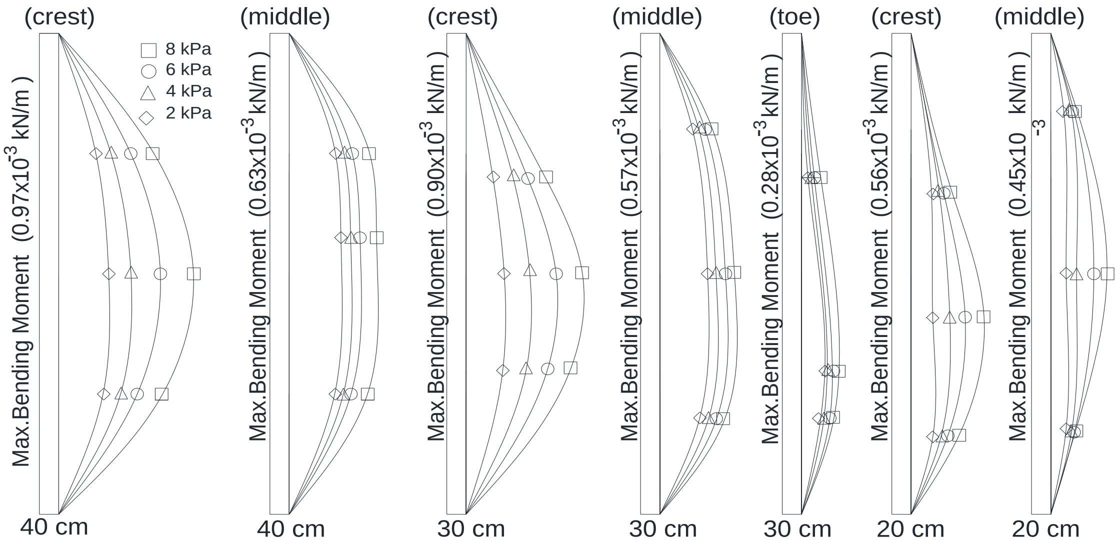

Fig. 6 Bending moment distribution on the pile section

Fig. 7 Deformation behavior of the reinforced slope

Parameter	Value
Color	Dark Brown
Specific Gravity	2.69
Sand Content (%)	17.33
Silt Content (%)	6.22
Clay Content (%)	76.44
Liquid Limit (%)	43.9
Plastic Limit (%)	21.8
Unified Soil Classification	CL

Table 1 Average geotechnical properties of Clay at 30% water content

Yield Load (kN)	Yield Stress (kN/m^2)	Yield Bending Mom.(kN/m^2)
13.8	169000	6.77×10^{-2}
12.6	154000	6.16×10^{-2}
12.8	157000	6.28×10^{-2}

Table 2 Tensile test results of model aluminum pile

6 Conclusion

The existence of the piles in the slope body, especially in front of the footing mitigates the vertical settlement, controls the horizontal soil movement underneath the footing and decreases the slope deformations. Stabilizing an earth slope using row of piles has a significant effect on improving the bearing capacity of the strip footing supported on clayey soil adjacent to the slope crest. The longer is the height the higher would be the bearing capacity improvement. This is because the passive resistance is mobilized on increased embedment of pile when the embedment length of the pile increases.

It is hoped that the results of this study will stimulate further experimental work that covers wide variations in the loading rate, pile characteristics, and different soil properties to arrive at conclusive conclusions about the effects of footing behavior and lateral loading capacity of pile groups.

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