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Effect of Type of Pile and Its Installation Method on Pile Bearing Capacity by Physical Modeling in Frustum Confining Vessel

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***Abstract*—**Various factors such as the method of installation, the pile type, the pile material and the pile shape, can affect the final bearing capacity of a pile executed in the soil; among them, the method of installation is of special importance. The physical modeling is among the best options in the laboratory study of the piles behavior. Therefore, the current paper first presents and reviews the frustum confining vessel (FCV) as a suitable tool for physical modeling of deep foundations. Then, by describing the loading tests of two open-ended and closed-end steel piles, each of which has been performed in two methods, “with displacement" and "without displacement", the effect of end conditions and installation method on the final bearing capacity of the pile is investigated. The soil used in the current paper is silty sand of Firuzkuh, Iran. The results of the experiments show that in general the without displacement installation method has a larger bearing capacity in both piles, and in a specific method of installation the closed ended pile shows a slightly higher bearing capacity.

***Keywords*—**Physical modeling, frustum confining vessel, pile, bearing capacity, installation method.

I. Introduction

DEEP foundations can be classified according to the pile material, the method of installation, the amount of soil disturbance, the pile bearing performance, the pile cross section, the ground the pile installed in, the pile installation angel, the pile length, groundwater level, and the structure for which the pile is designed. For example, given the pile material, the piles are classified into four categories of concrete piles, steel piles, timber piles, and composite piles. In terms of soil disturbance, the piles are classified into three categories of high displacement, low displacement and non-displacement piles. Given the bearing capacity piles are classified into the point-bearing pile, the friction pile, or a combination of both. Clearly, each of the above that can be called the installation effects may affect the performance of deep foundations [1]-[4].

Physical modeling to study deep foundations is done by low stress modeling like simple chambers (lg), and high stress modeling like calibration chamber (cc), centrifugal device and FCV [5], [6]. Simple chamber devices, despite being cheap, cannot model high level stresses in the laboratory for us. Although the calibration chamber creates a high level in the soil, but in them the stress does not change in the direction of height and they are only suitable for studying stress at a certain depth. To solve this defect, a centrifuge device was provided, but the important drawback of this device is that it is expensive, so recently, the FCV device, which is very cheap despite the ability to change stress at depth, has been developed [5].

In this research, after introducing the FCV device made in the Amirkabir University of Technology (FCV-AUT), the effect of end conditions on the final bearing capacity of the pile is investigated by performing two types of closed end and open-end piles in the FCV. Each of the piles is run in the soil by two methods of with displacement (driving) and without displacement in order to evaluate the effect of the installation method.

II. Frustum Confining Vessel

FCV is a device in the form of an incomplete cone with the ability to model deep elements that have been created and developed for physical modeling in geotechnical engineering. According to schematic view in Fig. 1, the top of the device is in contact with the open air and models the distribution of vertical and horizontal stress that are relatively linear (as in site) being pressed by a rubber membrane embedded in the floor of the device due to its special geometric shape. Such that, the vertical stress is zero at the top of the device, and it is added with increasing depth to reach a proportion of the floor pressure applied to the device. The horizontal stress inside the device, which is a function of vertical stress and soil characteristics, increases with the depth of the device [7].

According to Fig. 2, rubber membrane and hydraulic pressure are used to apply floor pressure to the device, such that first the compressed air enters an air-oil tank and directs the oil to the space between the rubber membrane and the metal plate with high pressure causing applied pressure to the sample floor [7].

The first FCV was developed in McMaster University of Canada to describe the device and investigate the stress distribution with depth in the device axis [5]. The second sample of the device was developed in the University of South Florida. This device was a bit bigger that made it possible to model larger physical models. The University of South Florida FCV device was used in post-injected piles as part of a joint biennial project between the University and the Florida Department of Transportation.

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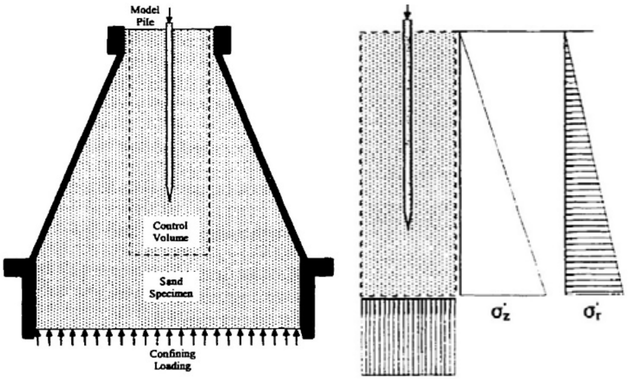


(a) (b)

Fig. 1 (a) Schematic of the FCV, (b) Idealized distribution of stresses within control volume [7]

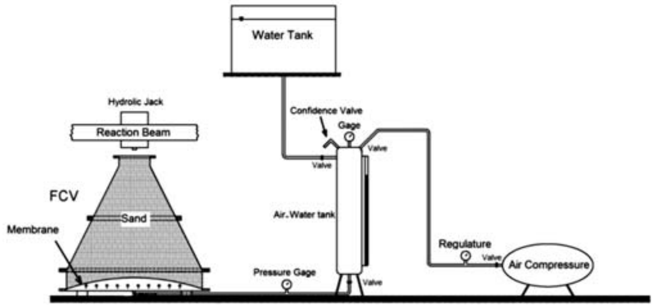


Fig. 2 Schematic profile of FCV at AUT and detailed bottom pressure system [8]

The third FCV was sample was developed by AUT in Iran which was the sole device in Asia and Iran in 2012 to know more about the device and study different deep foundations, post-injected piles, soil improvement effects on pile and in general examine various deep elements in a cost-effective device most compatible with reality [5]. FCV-AUT device depicted in Fig. 3 is larger than two similar samples. The larger device makes it possible to execute larger piles in it and thus reduce the errors of scale effects and boundaries [5].

FCV-AUT is a 1-meter-high open cone with vertical wings at the top and bottom of the tank at a height of 100 mm and 200 mm, respectively. Upper and lower diameters are 300 mm and 1350 mm, respectively. The floor pressure of the device is supplied by a 10-bar compressor and an air-water tank, such that first compressed air enters the air-water tank and directs the water with the desired pressure on the rubber membrane of the floor of the device. The maximum pressure that can be applied from the floor of this device is 600 kPa which corresponds to a soil pressure of about 35 m depth, this device is easily capable of modeling 30 meters long piles which is the usual pile displacement depth in reality [2], [3].

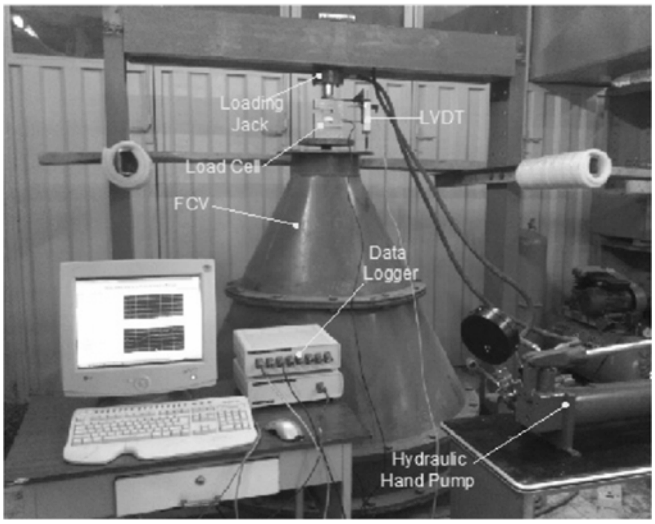
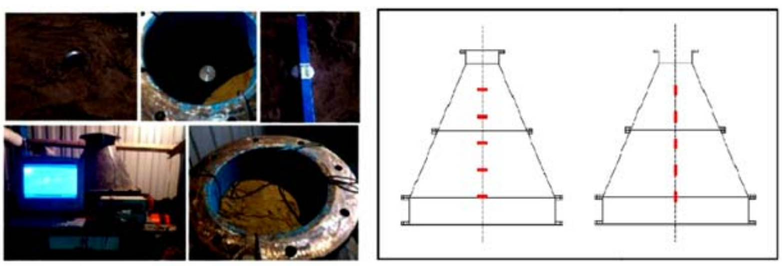


Fig. 3 Overview of FCV at AUT and its accessories [5]

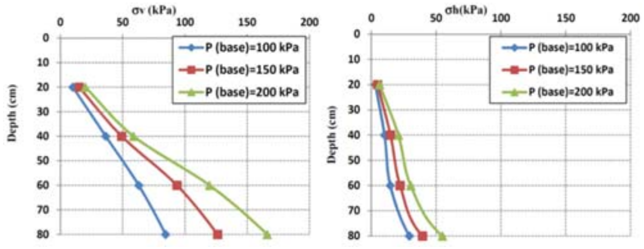
In the device made in Amir kabir University, soil pressure sensors in four different height codes have been used to measure the stress field inside the device after applying pressure to the bottom of the device. In the first test, these four sensors were placed horizontally in different height codes to be able to measure vertical stress (normal). In the next stage, the sensors were turned in the vertical direction so that the horizontal (radial) stress could be applied approximately at the same location. The floor loading process also includes increasing the stress level from 1 bar to 2 bar (100 to 200 kPa). Fig. 4 shows placement of soil pressure sensors and how to determine the stress field inside the device. Fig. 5 shows vertical and horizontal stress changes along the center line with depth.



(a) (b)

Fig. 4 (a) Schematic view of placement of soil pressure sensors, (b) how to determine the stress field inside the device [5]

Fig. 5 shows vertical and horizontal stress changes for floor pressures of 100, 150 and 200 kPa. According to the figure, vertical and horizontal stress values increase gently from the top to the bottom of the device and the slope of the stress change with depth graph becomes smoother with increase in device floor pressure and slightly moves out of linear mode that is acceptable.



(a) (b)

Fig. 5 Vertical (a) and horizontal (b) tension changes along the center line with depth measured by FCV-AUT [5]

III. Materials and Methods

The current paper used Firuzkuh fine-grained sand, which is classified as Silty Sand (SM) type soil taking into account grain testing on soil using Unified Method. For this research relative density test was performed on the soil to determine the maximum and minimum dry specific gravity according to ASTM-D-4253 and ASTM-D-4254 standards. The relative density of the samples poured into the device is in the range of 20-35, which is a loose density soil. To achieve the desired density, we divided the soil inside the device into several layers and having poured the soil and spreading it evenly in each layer we hit it with a wooden hammer to reach the desired relative density. We used a sampling similar to single-axial device sampling method to achieve the desired density of the layers. Tables I and II show Firuzkuh sand and tested piles specifications, respectively.

TABLE I
Basic Properties of Tested Sand

Item	Quantity
Effective particle size (D_{10}) (mm)	0.01
Average particle size (D_{50}) (mm)	0.17
Uniformity coefficient, C_u	18.5
Coefficient of curvature, C_c	5.4
Maximum dry unit weight, $\gamma_{d,max}$ (kN/m^3)	16.34
Minimum dry unit weight, $\gamma_{d,min}$ (kN/m^3)	13.25
Maximum void ratio, e_{max}	1
Minimum void ratio, e_{min}	0.63
Specific gravity, G_s	2.65
Classification	SM

TABLE II
Model Piles Characteristics

Installation method	Pile type	L* (mm)	D**(mm)	L/D
Non-displacement	Open-ended steel pile Closed-ended steel pile	750	35	21
Driving	Open-ended steel pile Closed-ended steel pile	750	35	21

As shown in Fig. 6, the piles used in this test are divided into two types of Open-ended and Closed-ended steel pile, each of which is installed by two methods of without displacement and driving (with displacement). It should be noted that the closed-ended pile at the midpoint and tip has sensors to determine the percentage of participation of the shaft and tip of the bearing capacity. To install driven piles, following the filling up the FCV-AUT device with soil, first a conductor is placed on the top of the device. Then by placing a rigid steel plate on the pile, the pile is driven into the soil in the device using a metal hammer. Piles are driven in several stages and each stage is checked following the driving for surface leveling using a bubble level. This continues until the piles reach the desired depth of 750 mm. The prefabricated driven piles ends are conical for better installation.

(a)

(b)

Fig. 6 Different piles used in the FCV-AUT: (a) closed-ended steel pile; (b) open-ended steel pile

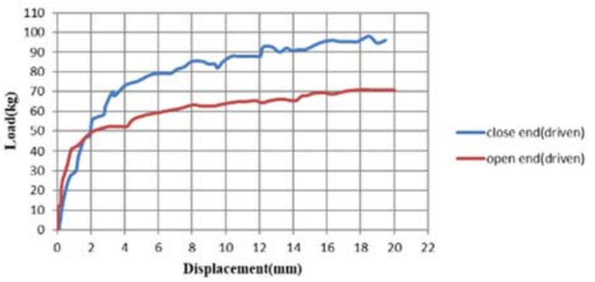
For installation of piles by the without displacement method, first, the soil is poured into the FCV so that the soil reaches the desired level of the pile tip, then the pile was placed in the center of the chamber where its tip was in contact with soil surface and the remaining amount of sand was poured into it. Since the pile does not move, the soil around the pile does not become denser.

Once the pile has been installed, the loading step must begin. There are several methods for static loading of piles. ASTM-D-1143 has introduced seven methods to test axial loading. The current paper has used the rapid load test. Maintenance of each loading step for a short time and a large number of loading steps is the basis of this method [9]. Loading continues to the final bearing or maximum specified bearing, so in this paper, first an estimation of pile bearing capacity is presented and then loading equal intervals are specified accordingly and thus a fraction of bearing capacity is applied per interval. The loading step and time interval of this test was equivalent to 2 kN every 2 minutes. To load the piles, a manual hydraulic system with a loading jack has been used. A Load Cell and a LVDT (Linear Variable Differential Transformer) by 50 mm course were used to apply force and move the piles head corresponding to the load. The data are recorded by a data logger and sent to a computer. It is noteworthy that in both piles loading tests, loading continues until a displacement equal to 30% of the pile diameter is reached. Also, it should be noted that in all tests, the load on the FCV floor is equal to 1 bar (100 kPa), which is similar to the pressure at a depth of 10 meters of soil in normal conditions.

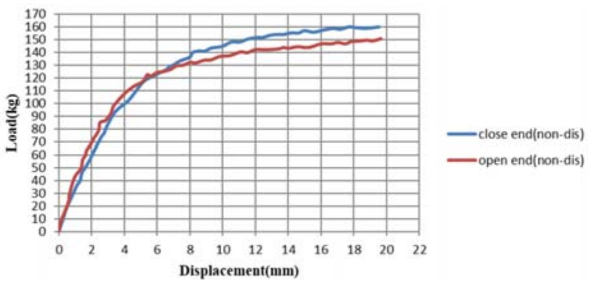
IV. Results

The load–displacement curves of the driven and non-displacement piles are shown in Fig. 7. It can be seen that in both methods of installation, the closed-ended pile shows a higher bearing capacity than the open-ended pile; this increase in bearing capacity is more significant in the driving method. The reason for this increase is that in the closed end pile, the passive earth pressure coefficient is used, but in the open-end pile (due to less soil displacement) the "at-rest" coefficient of lateral earth pressure is used. In addition, the results show that with the non-displacement installation method, a higher bearing capacity can be achieved. That is because by driving the pile, the soil is disturbed and cannot be in good contact with the shaft of the pile.

In Fig. 8, for the closed-ended pile, a load-displacement curve is drawn to show the share of the shaft and the tip of the pile in its bearing capacity.



(a)



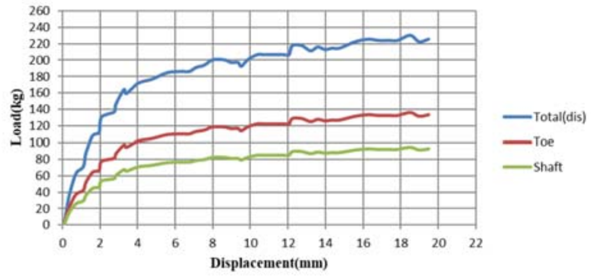
(b)

Fig. 7 Load–displacement curves of piles according to their end conditions and method of Installation: (a) with displacement (b) without displacement

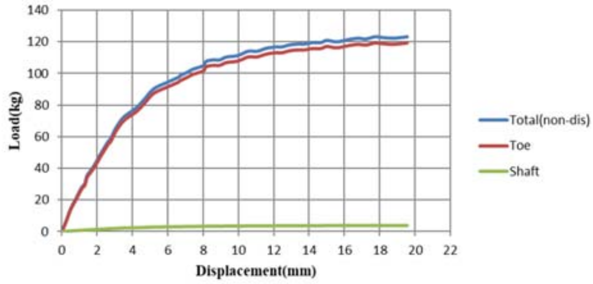
It can be seen that in the non-displacement method, the lateral friction does not contribute much to the bearing capacity of the pile and most of the bearing capacity is provided by the tip. Because in this method (especially in dry soil), there is no good interaction between the soil and the shaft of pile.

V. Estimating the Ultimate Bearing Capacity

Cook and Whitaker, by testing pile loading, showed that the final strength of the shaft happens in a displacement equivalent to 0.5% to 1% of the diameter of the pile and the final strength of the tip happens in a displacement equivalent to 10% to 15% of the diameter of the pile [10]. Rudolf, with the help of loading and numerical modeling, showed that the shaft strength and tip strength reaches their maximum at in a displacement equivalent 0.5% to 10% of the diameter of the pile [11]. Therefore, in this study, the load equivalent to the displacement of 10% of the pile diameter is selected as the load corresponding to the ultimate bearing capacity of the pile. This value for different curves (in Fig. 7) is given in Table III.



(a)



(b)

Fig. 8 Load–displacement curves of closed-ended pile in two installation method: (a) with displacement (b) without displacement

TABLE III
Ultimate Bearing Capacity of Pile

Type of pile and installation	Load at 10 % of the pile diameter (kg)
Close end(driven)	70
Open end(driven)	51
Close end(non-dis)	90
Open end(non-dis)	90

VI. Conclusions

FCV is an advanced modeling physical device in geotechnical engineering capable of modeling vertical and horizontal stress gradient consistent with depth. AUT developed a version of this device. Experiments have been performed to determine the amount of horizontal and vertical stress in this device, which showed that this device can well create stresses similar to the site within itself. These stresses can be controlled by increasing or decreasing the floor pressure of the device.

In this paper, to investigate the effect of pile type and installation method, two open end and closed end steel piles were loaded by two methods "with" and "without" displacement inside the FCV device. The following results were obtained:

- Experiments showed that the closed-ended pile shows a higher bearing capacity than the open-ended pile; this increase in bearing capacity is more significant in the driving method.
- With the non-displacement installation method, a higher bearing capacity can be achieved.
- In the non-displacement method (for closed-ended pile), the lateral friction does not contribute much to the bearing capacity of the pile and most of the bearing capacity is provided by the tip.

- In displacement method (for closed-ended pile), about 59% of the total bearing capacity is provided by the tip of the pile and 41% by the shaft.

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