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Study of Physical Modelling for Piles

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Abstract

Physical modeling due to its simulation ability of real conditions has been developed as a proper method to study engineering issues. In this paper after the introduction of usual physical modeling systems in geotechnical engineering, we focused on a low known device of physical modeling in geotechnical practice, especially applicable in deep foundations. It is named Frustum Confining Vessel (FCV) that is one of the calibration chamber forms. It can apply high stress level by a relatively linear stress distribution. Thus, it can simulate actual states for piles in laboratory controlled conditions. The FCV test results can be used for real project by multiply scale factors. Scale factors can be explained by dimensional and similar analyses in every model and apparatus. In this study the relatively largest size of FCV among others in the world, which called FCV-AUT, was used to study physical purposes. Several various model piles (deep foundations) were made by 4 mm thick steel plate with height of 750 mm. All model piles tested in Babolsar sand as surrounding soil via FCV, and two full scale piles tested in similar conditions in the field. The experimental results and outcomes indicated the FCV can be used as a suitable device for physical modelling aims. Thus, it can be realized the FCV is more effective than simple and calibration chambers as well as laminar boxes and more economic than centrifuges.

Keywords

Physical Modeling, Frustum Confining Vessel (FCV), Model Pile, Stress Level

1. Introduction

Physical modeling which recognized as a method to study engineering problems can simulate real conditions in experimental researches. It can be explained by dimensional and similar analyses and can be compared and generalized to executive projects. The system has been used from many years ago. For example,

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in ancient Egypt, Iran and Rome, some small scale structures were made to investigate civil problems. In new era after the Second World War, some researchers applied physical modeling to study civil engineering projects, including structural, geotechnical, hydraulic structures and etc. Nowadays, physical modeling has a very important role in understanding interactions behavior, especially in dynamic states [1].

According to Azizi (2000), fundamental principle of physical modeling is simulation of actual structures conditions [2]. It must be provided by using modeling systems to create similar conditions on small scale models. Thus the most important requirement of simulation theory can be geometric, kinematic and dynamic similarity to the original structure. So, several rules are established that correlate the experimental and original models. The Equation (1) can be written when simulation theory between the model and prototype is run [3].

$$P_p = N * P_m \qquad (1)$$

where P_p and P_m are prototype and model dimensions, respectively and N that is called "scale factor", is defined to convert original properties to model properties. Table 1 indicates some scale factors that are more used in geotechnical modeling.

Existence of accurate measuring instruments for recording of displacements, forces, accelerations and other quantities caused further attention to modeling. Various types of physical modeling in civil engineering designed and developed. In each project one of these modeling types is selected due to the project engineering requirements, costs, construction limitations, time and etc. Physical modeling usage in civil projects is inevitable, so, different physical modeling sets and tests were recognized and developed. The main question of this research can be a device introduction for physical modeling, especially applicable in piles.

In this paper a physical modeling system for piles that is called FCV is introduced and results of several piles testing by FCV are compared with full scale tests. We tried to show FCV accuracy and advantages. First physical modeling devices for pile testing are introduced in Section 2, and then FCV is described in 3 and FCV-AUT as test vessel is introduced in Section 4.

2. Physical Modelling for Piles

Physical modeling is a very important and complex method for study of deep foundations that is taken into consideration since the mid 50 s for geotechnical engineers. This method although takes more time and cost in compare with numerical modeling, but physical model in more used because of intense implications of numerical modeling.

Physical modeling can be performed in several systems include: simple chambers (1 g), calibration chambers (CC), laminar shear box, centrifuge apparatus (ng) and frustum confined vessel (FCV). Almost all of models in these procedures are made smaller than actual structures and few studies carried out in full scale. Popular devices are introduced in the next, succinctly.

2.1. Physical Modelling by Simple Chamber

As mentioned in last paragraph physical and small scale models for study of deep foundations can be implemented in several ways. Simple chambers (1 g) are made easily and have low cast. Thus, they are a popular apparatus. The most important limitation of simple chambers is low stress level in compare to real condition of piles surrounding soil and deep foundations in the field. The 1g stress field is not compatible to the true overburden stress distribution of proto-type piles and a simple correlation cannot be performed. Hettler and Gudehus (1985), Franke and Muth (1985), attempt in order to account for stress distortions in model responses [4] [5]. These procedures, however, are mostly developed for simple problems under service state or quasi-elastic soil responses, and cannot be applied to the problem of load test on 1g model piles. A simple chamber indicated in Figure 1.
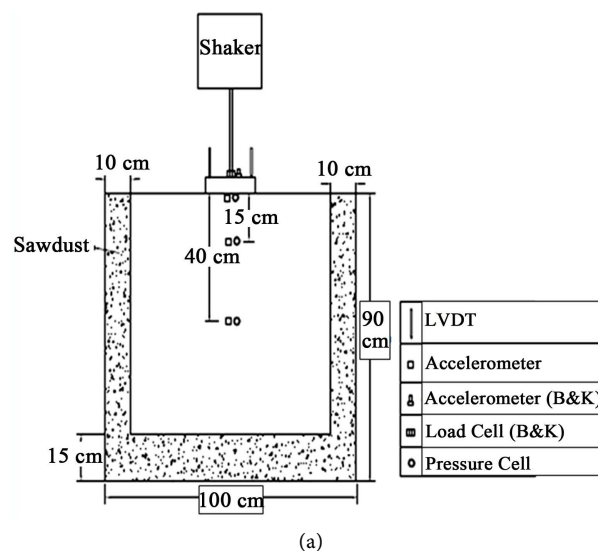

(a)

(b)

Figure 1. A simple chamber: (a) Schematic form; (b) Its real photograph (Jafarzadeh and Ghasemzadeh, 2009).

2.2. Physical Modelling by Calibration Chamber

According to Baziar and Ziaie Moayed (2006) Calibration chambers have been used to help in the process of developing correlations between in-situ test results and different soil parameters [6]. Since its early development in the late 1960s, the calibration chamber has been an important research tool to study soil and foundation interactions. As Zare and Eslami (2014) confirmed, it can be used as well for modeling some tests like CPT and PMT [7]. In calibration chambers modeling, lateral and vertical stresses level can be increased; however, the creation of constant lateral stresses did not produce realistic stress gradients, especially the linear increase of stresses with depth which generally govern the axially loaded piles. So, to overcome some shortcoming, centrifuge modeling has been evolved.

Ghionna and Jamiolkowski (1991) listed many calibration chambers all over the world and investigated various boundary conditions in this system [8]. **Figure 2(a)** shows its schematic and **Figure 2(b)** indicates a calibration chamber photo.

2.3. Physical Modelling by Geotechnical Centrifuges

Geotechnical centrifuge modeling provides a proper tool to analyse geotechnical problems. It can simulate soil real conditions because models and soil samples in centrifuge are set under a right radial acceleration. The acceleration acts as a gravitational acceleration with a magnitude equal several times the gravity acceleration and the stress in soil top level is about zero. The stress increases versus the model depth according to soil density and applied acceleration. That is why the centrifuges have been widely used in geotechnical engineering [9].

Bucky (1931) illustrated principles of centrifuge modeling to study mines structural failure and other researchers like Panek (1952), Schofield (1969), Shen *et al.* (1982) and Mikasa and Takada (1984) developed the centrifuge theories
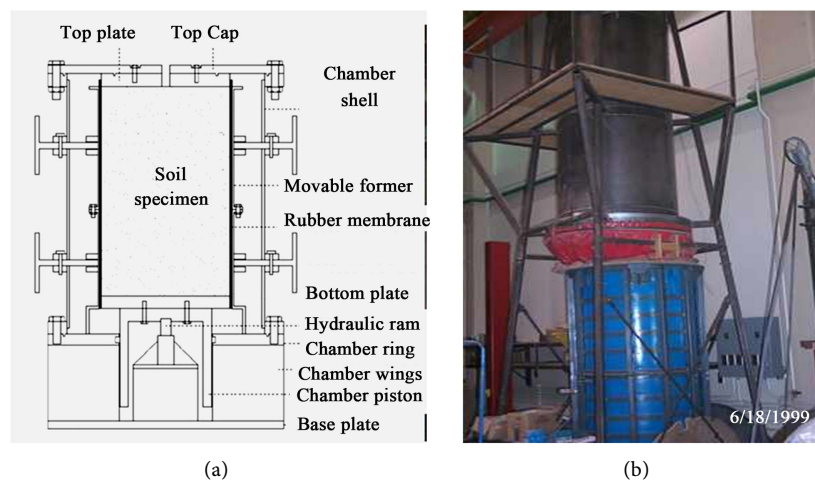

(a)   (b)

Figure 2. Schematic of calibration chambers, a) Kim, *et al.* (2008) apparatus, (b) calibration chamber of University of Calgari for testing model piles (Pournaghiazar *et al.*, 2010).

and systems [9] [10] [11] [12] [13]. One of the largest geotechnical centrifuges all over the world has been made at the University of California at Davis in recent decade. The device has a radius of 30 feet (about 9 meters) that can produce a maximum acceleration of 133 g. The main problem in centrifuge modeling can be its cost, moreover, the device not be found anywhere [5].

2.4. Physical Modelling by Laminar Box

Use of flexible walls for soil modeling was recognized since 1970s years. During these years some researchers designed various wall systems. Hushmand (1988), Philip, *et al.* (1986), Gibson (1997), Prasad, *et al.* (2004), Jafarzadeh (2004) and Eslami, *et al.* (2009) carried out several studies on soil behavior by this method and developed it to a multi layered box which horizontal movements imposed on various levels of the devices [14]-[19]. According to Ahmadi, Eslami and Arabani (2016), now, at being time the laminar boxes usually insist of a series of laminar segments, each 50 mm or less in height, which can freely move over each other in one direction. For model loading a jack is provided on the top of the box. It transfers a vertical constant load over the surface of soil placed in the box. This loading jack can be used to simulate the loads and settlements of a small scale model on soil while the box is subjected to lateral cyclic shakings. A data acquisition system is attached to the box to record required data [20].

Eslami *et al.* designed and constructed a transparent laminar shear box apparatus in Gilan University[1]. A general overview of the box and its accessories is presented in Figure 3. The presented box has 600 mm in 600 mm in plan and 580 mm in height and hence, can be regarded as a medium scale one [19]. Based on the laminar box details, it can be used to achieve some purposes like:

Physical modeling of shallow foundations, constant and cycling loading, measuring of settlements and vertical movements of soils, observation of failure
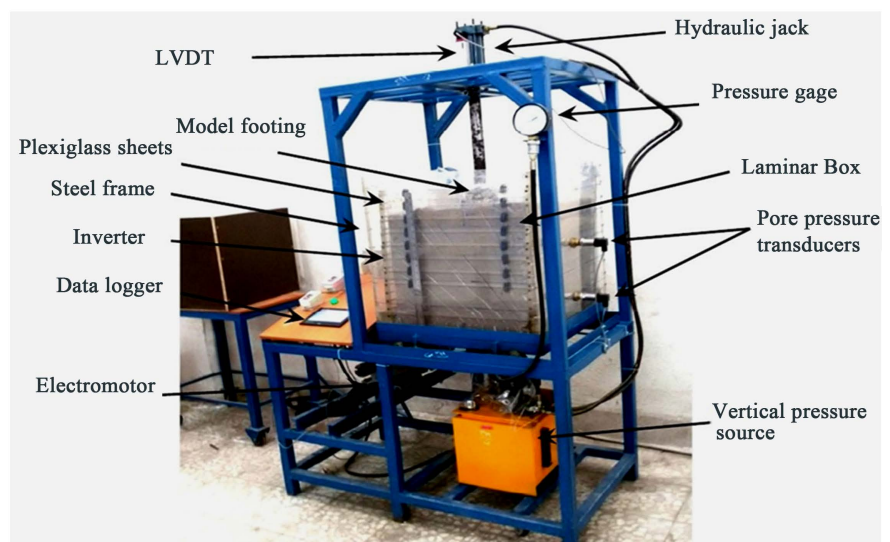

Figure 3. General overview of the transparent laminar box (Ahmadi, Eslami, 2016).

[1]Located in the north of Iran.

forms and soil displacements because of its transparent box, modeling of water and pore water various conditions and also capillary and drainage in soil, soil improvement, study of layered soils and non-uniform soils, investigation of soil changes through compaction, study of liquefaction and etc.

In this paper a non well-known physical modelling is introduced which named "FCV" that means frustum confining vessel.

3. Physical Modelling by Frustum Confining Vessel (FCV)

According to Horvath and stole (1996) Frustum Confining Vessel (FCV) is a new apparatus that has been developed for physical modeling of piles [21]. It is a proper tool for modeling the piles behavior and CPT test. This device is a truncated cone shape that applies a steady pressure on its bottom, so a linear stress distribution is created along its vertical central core. This specification can be the most important advantage of Frustum Confining Vessels (FCV), because it simulates field real overburden and lateral stress conditions. The vertical stress in the soil at the top is zero and it increases with depth to the stress value that applied in the bottom by pressure system [22].

FCV was Patrick Bermingham's idea and at first, have been built in McMaster University of Canada in 1996 by participation of "Berminghammer Foundation Equipment Inc" [4]. Horvath and Stole (1996) and Sedran (1999) tested several model piles by FCV in various void ratios and base pressures. They illustrated that there is a linear stress distribution via depth in FCV. Figure 4 shows FCV form and system.

Another advantage of FCV is possibility of in-situ making of model piles directly in the FCV chamber. To use FCV test results, scaling factors must be applied to test results. Scaling factors using for FCV, can be calculated by simulation theories, depending on the degree to which it is pressurized. Sedran (1999) reported the factors relevant to FCV as shown in Table 1.

Table 1. Scaling factors (Sedran, 1999).

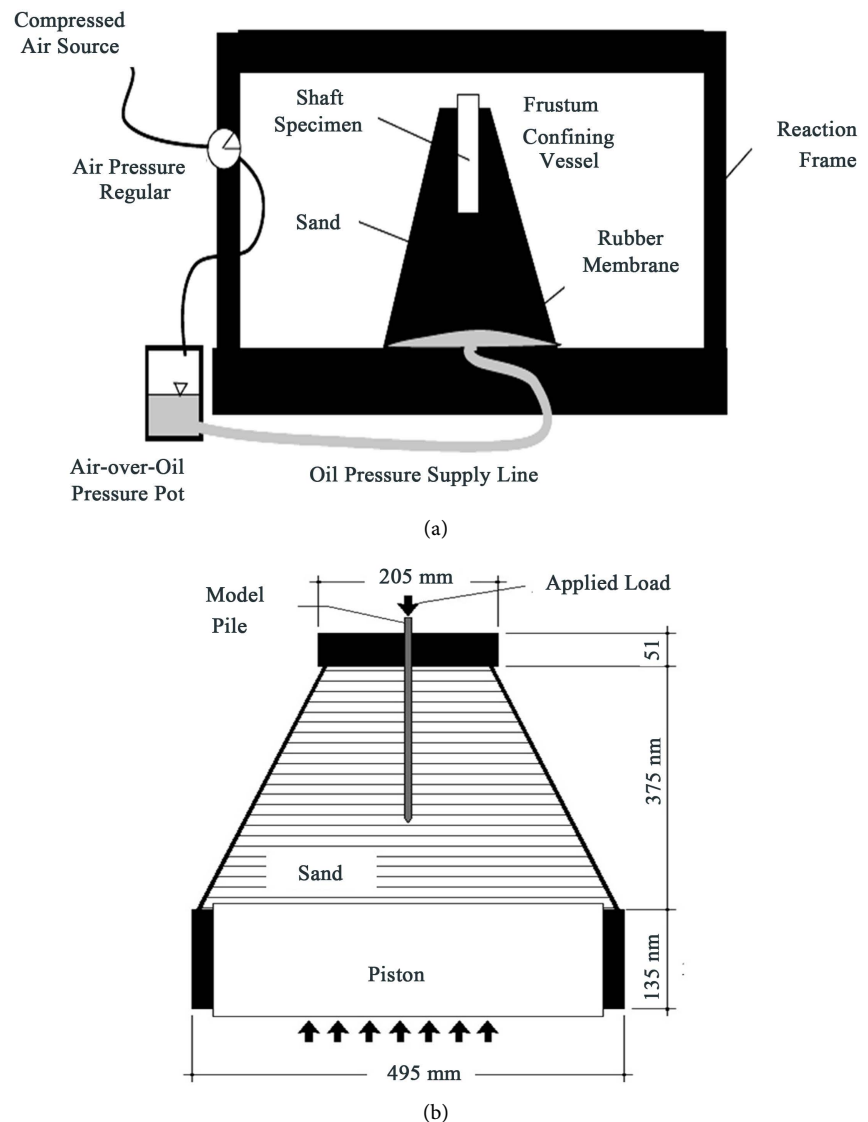| Dimension	Scale Factor
Length & Displacement	$\lambda_L = L_p/L_m$
Area	$\lambda_{\text{Area}} = \lambda_L^2$
Volume	$\lambda_{\text{Volume}} = \lambda_L^3$
Density	$\lambda_\rho = 1$
Mass	$\lambda_M = \lambda_L^2$
Stress	$\lambda_\sigma = 1$
Strain	$\lambda_\varepsilon = 1$
Force	$\lambda_F = \lambda_L^2$
Damping	$\lambda_C = \lambda_L^2$
Elasticity Modulus	$\lambda_E = 1$
Stiffness	$\lambda_k = \lambda_L$
Time	$\lambda_T = \lambda_L$
Acceleration	$\lambda_{\text{acc}} = 1/\lambda_L$

(a)

(b)

Figure 4. Schematic of FCV system, (a) FCV component in south Florida University (Mullins, 2001); (b) Applied loads in FCV (Sedran, 1999).

According to Sections 2 and 3, FCV is the best suitable chamber for studying piles. Table 2 presented some researches performed by physical modeling. It illustrated that FCV is a proper device for piles physical modeling.

4. FCV-AUT

The FCV-AUT focused in this study has been built by Zare and Eslami in Amir Kabir University of Technology (AUT) and named FCV-AUT. As seen in Figure 5, it has a height of 1200 mm, with top diameter of 300 and bottom diameter of 1350 mm. It was the first FCV in Iran and the biggest one in the world. It is made of 10 mm thick steel plates in two separable sections as indicated in Figure 5. Device floor is made of 15 mm thick steel plate and a rubber membrane is placed between the floor and sample soil to transfer the base pressure. Through
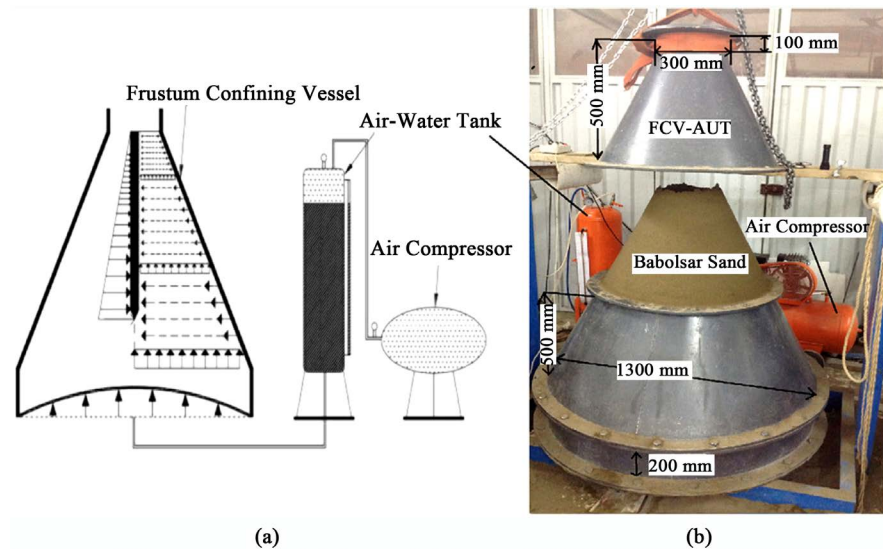
Figure 5. The FCV-AUT: (a) schematic diagram; (b) photograph (Zarrabi and Eslami, 2016).

Table 2. Some researches by physical modeling.

Subject	Researchers	Physical Modeling
Dynamic Behavior of Foundations on Sand	Jafarzadeh and Ghasemzadeh (2009)	Simple Chamber
Dynamic Behavior of Piles Group in Slopes	Mehdizadeh *et al.* (2009)	
Behavior of Reinforced Composited Foundations	(Wang *et al.*, 2010)	
CPT Test in Unsaturated Soils	Pournaghiazr *et al.* (2005)	Calibration Chamber (CC)
Penetration Rate Effect on Cone Penetration Results in Clay	Kim *et al.* (2008)	
Sand Behavior under Cyclic and Seismic Loading	Takahashi *et al.* (2001)	Laminar Box
Behavior of Anzali Sand	Eslami *et al.* (2009)	
Seismic Behavior of Sand	Lee *et al.* (2012)	
Dam Stability	Kimura (1998)	Geotechnical Centrifuge
Earth Settlement in Soft Soils	Elis *et al.* (2006)	
Deformation of Railway Sand ballasts	Vinogradov *et al.* (2015)	
Study of Model piles	(Sedran, 1999)	
Study of Post-Grouted Model piles	(Mullins, 2001)	
Study of Model piles	(Zare and Eslami, 2014)	Frustum Confining Vessel
Construction Effects on Model piles Performance	(Zarrabi and Eslami, 2016)	
Study of Model piles	(Fateh and Eslami, 2016)	
Site Effects on Model piles Performance	(Karimi and Eslami, 2016)	

the application of bottom pressure range from 100 to 600 kPa, the *in-situ* overburden stress conditions equivalent up 10 to 60 m soil deposits almost consistent to the embedment depth of commonly used piles. To apply bottom pressure in the AUT-FCV a membrane has been installed according Sedran (1999) that demonstrated the stress distributions along the centerline obtained by membrane loading are smoother than the piston loading case [22] [23] [24].

The FCV device consists of four major parts such as the frustum body, bottom pressure system, loading system (loading frame, hydraulic hand pump and hydraulic jack) and instrumentation system. Hydraulic jack designed and made to apply tension and pressure loads. Maximum load is 15 tons and maximum displacement is 150 mm. Power of jack, which is designed to apply hydraulic pressure up to 600 bars, is provided by a hydraulic hand pump with a switch valve. Instrumentation system includes Data Acquisition System (DAS) and sensors. DAS includes an eight channel data logger, power pack and computer. Sensors include a 10 ton S-shape load cell, an LVDT with 50 mm courses and five soil pressure cells with 1000 kPa capacity. **Figure 6** and **Figure 7** indicate FCV-AUT system loading of piles and applying base pressure to FCV, respectively. Water container is a 75 liter cylindrical chamber and air compressor has 110 liter capacity which can produce 10 bar pressure of compacted air that is seen in **Figure 7**.

For testing program in FCV, six model piles were made from 4 mm thick steel plate with 750 mm height which three of them had 89 mm diameter as usual simple piles form. Other three ones were made as helical pile form with 32 mm shaft diameter and 89 mm helices diameter. For surrounding soil, approximately uniform fine-grained sand was used that was provided from a coastal city in north of Iran named Babolsar. The sand had uniformity coefficient (C_u) and coefficient of gradation (C_c) equal to 1.67 and 1.23, respectively and categorized as SP in Unified Soil Classification System (USCS). Maximum of sand dry density was 1.799 and its minimum measured 1.485 T/m^3. The soil placed in the chamber with three different relative densities include loose, medium and dense sand which their relative densities were measured 20% - 25%, 45% - 50% and 65% - 70%, respectively. The medium sand was similar to field condition. The
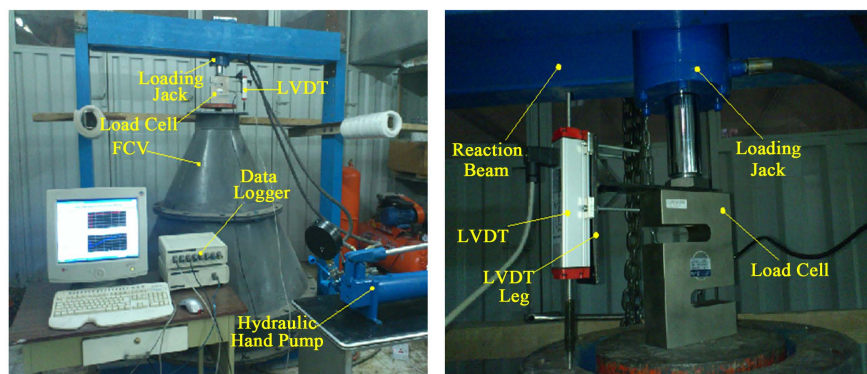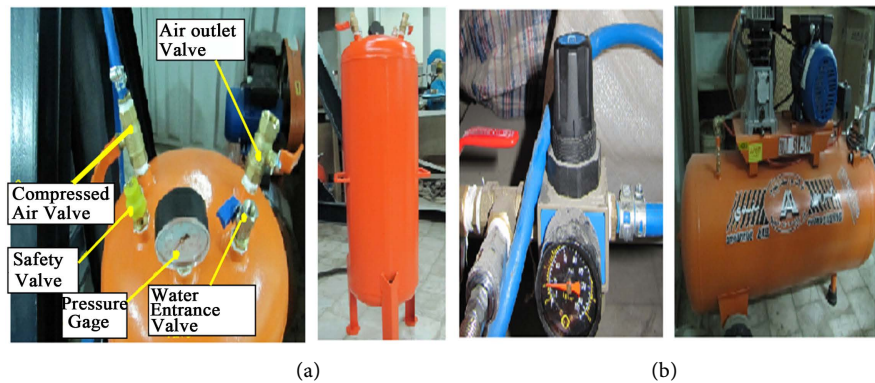

Figure 6. FCV-AUT loading system.

Figure 7. FCV-AUT equipment for applying base pressure, (a) water container; (b) air compressor.

model piles were installed and bottom pressure of FCV set on 200 kPa before start of pile loading. FCV-AUT can enhance the base pressure to 600 kPa, equal to medium sand with about 35 m height. Achievement to this stress level in test conditions is a good development in pile testing.

5. Tests and Results

Test results in this paper illustrated that the FCV can be used for physical modeling in piles as well. Before start of study program two tests performed to indicate FCV proper functioning. As mention in Section 4 uniform fine-grained sand of Babolsar with three various densities filled in the FCV as surrounding soil, base pressure adjusted on 200 kPa, then loading started. Figure 8(a) and Figure 8(b) showed that there is a relatively linear increase in vertical and horizontal stresses in FCV along central line. As seen in the figs, the stress in top is zero and in bottom is proportioned to base pressure of FCV. To test and investigate the issue of linear stress distribution, four sensors were installed in four soil levels in the FCV (Figure 9). Firstly, four sensors were set horizontally to record vertical stresses and then sensors rotate to vertical state for recording horizontal stresses. Another primary test that conducted to evaluate the performance of the FCV was model piles loading repeatability. A 750 mm height Concrete model pile with 89 mm diameter was installed in FCV and tested twice consecutively. As illustrated in Figure 10, result resemblance demonstrated that the result would be reliable and acceptable.

Three model piles including one open and two closed-end model piles were tested by FCV-AUT. Open end model pile installed by knocking and closed-end models were installed by knocking and jacking. Figure 11 presents behavior diagrams of model piles testing in FCV-AUT. Due to the soil relative density and FCV base pressure, the normal stress in model piles toe is equal to normal stress in full scale piles toe with 11 m embedment length in the field. Hence, a closed-end pile, was tested in field in sandy soil which the closed end piles was 267 mm. Accordingly, performance of full scale piles, tested in that field, seen in Figure 12.
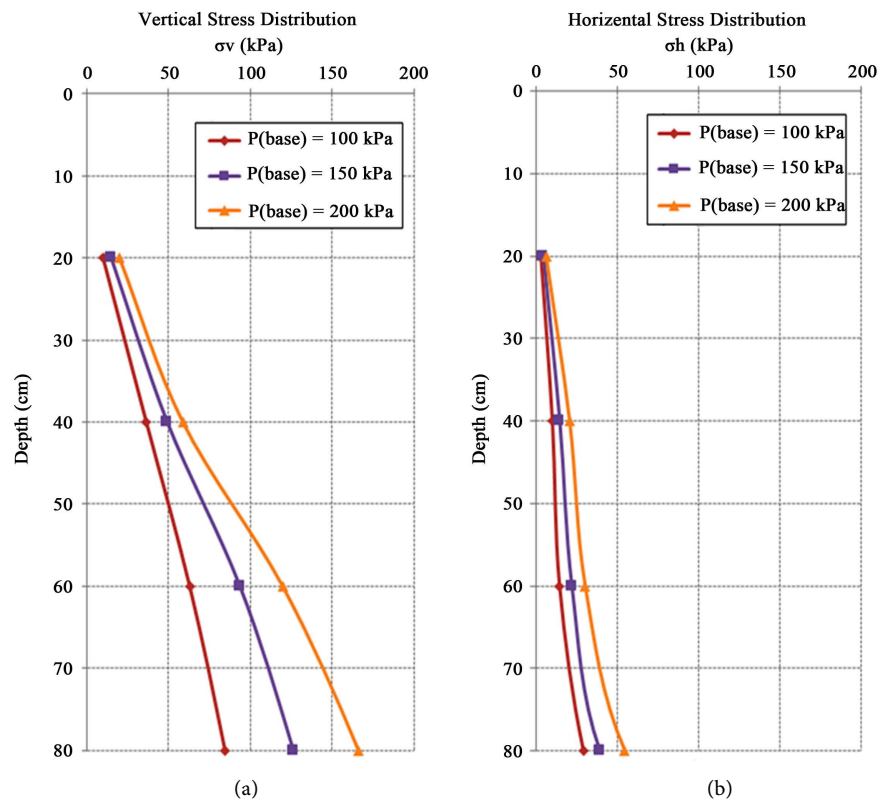
Figure 8. Stress distribution in FCV-AUT, (a) vertical; (b) horizontal.

Figure 9. Sensors for studying vertical and horizontal stress distribution in FCV-AUT.

6. Discussion and Verification

As discussed in Section 3 the main advantages of FCV was possibility of applying high stress level and a relatively linear stress gradient, proportional to the depth, that can simulates real distribution of stresses in foundations. Tested
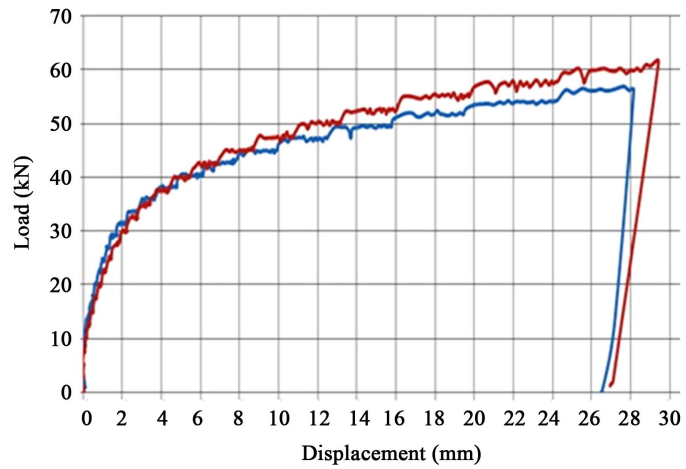
Figure 10. Load-Displacement in FCV-AUT for indicating test repeatability.
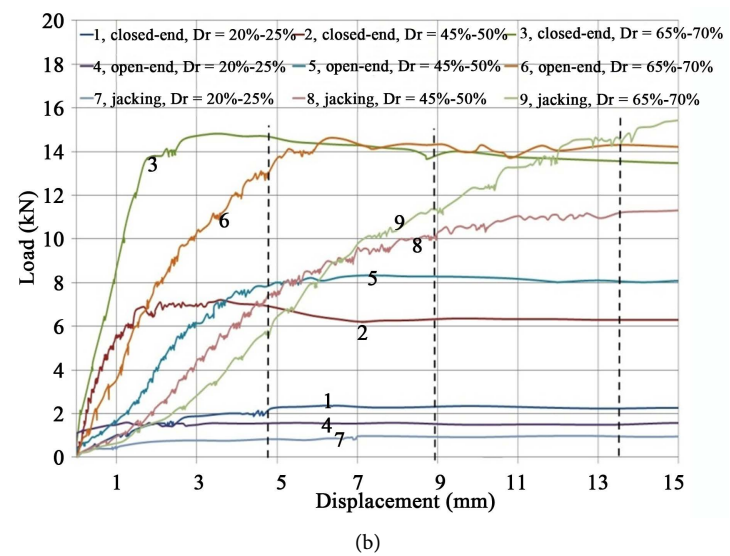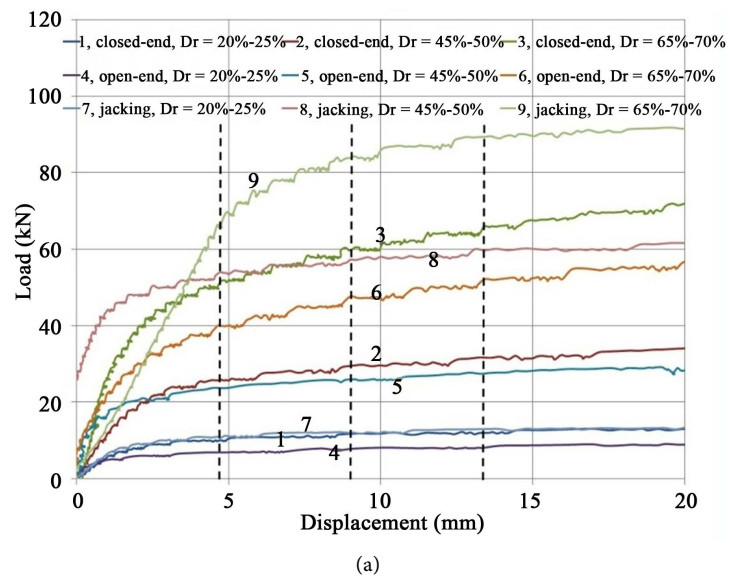

(a)

(b)

Figure 11. Load-Displacement in FCV-AUT, (a) compression; (b) tension.
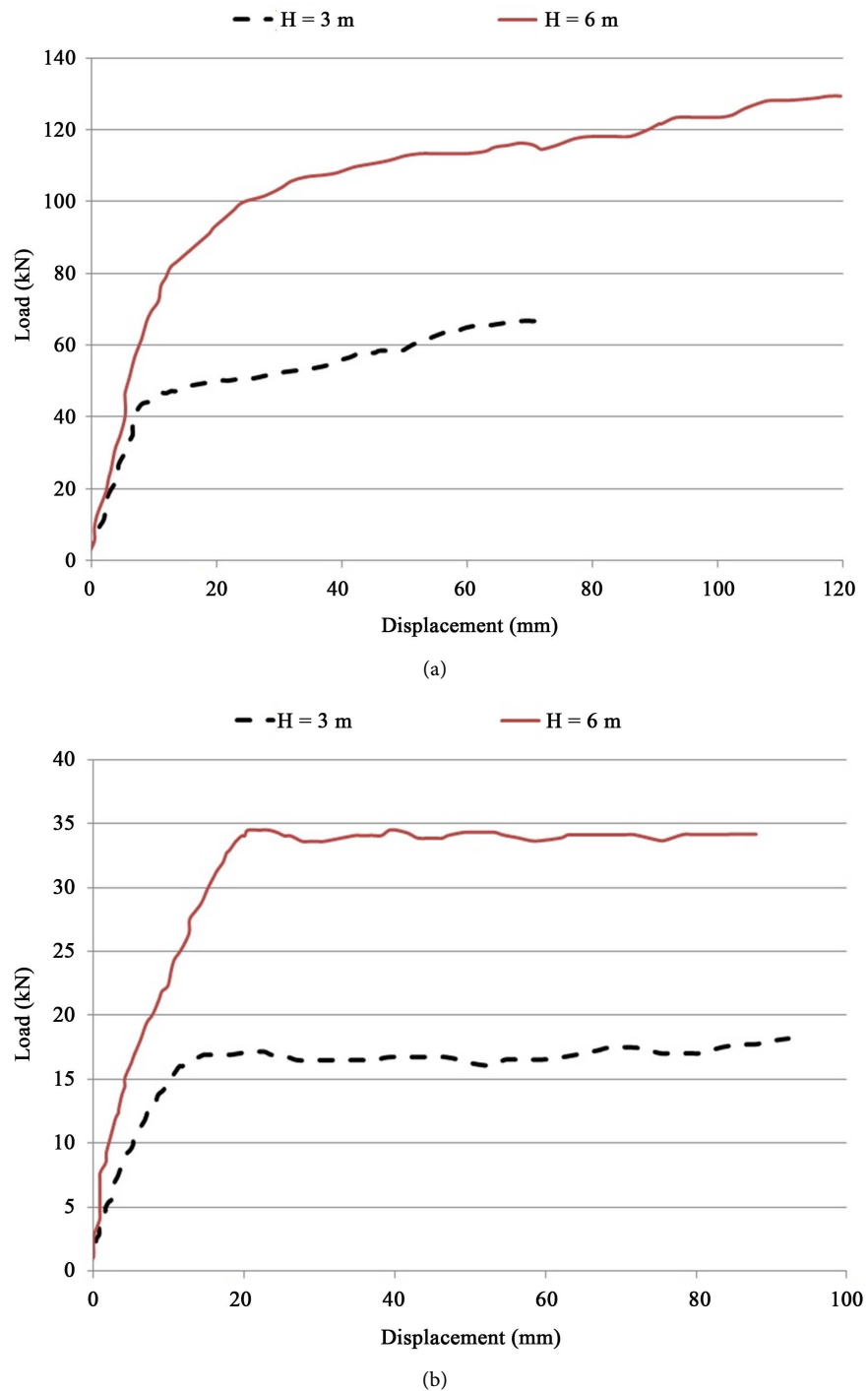
Figure 12. Load-Displacement full scale piles in sandy soil, (a) compression; (b) tension.

model piles confirmed that the device can create realistically overburden stress in the desired control volume along the central core. So, FCV is more efficient in compare with simple chamber, calibration chamber and laminar box. The centrifuge system although works more effective, but centrifuge testing is very expensive and difficult. Thus, FCV can be introduced as a superior chamber for physical modelling of piles.

Based on test results of this paper, **Figure 8(a)** established linear increasing in stress via depth for vertical stresses and horizontal stresses illustrated in **Figure 8(b)**. The figure also, indicated the lateral earth pressure ratio, *k*, (ratio of the horizontal stress to vertical) for Babolsar Sand is between the active and rest states.

$$K_0 = 1 - \sin(\varnothing) \quad \text{Rest state}$$

$$K_a = \frac{1 - \sin(\varnothing)}{1 + \sin(\varnothing)} \quad \text{Active state}$$

Model piles tested in FCV-AUT had load-displacement diagram as seen in **Figure 11** that shows a reasonable procedure in pile testing results. So, it can be resulted that the FCV-AUT has a proper performance and can be a very popular system.

Figure 12 that is resulted from a field full scale loading in the Babolsar sand, indicates that real capacity of piles are related to $N = \dfrac{D_p}{D_m}$. According to paper tests, after equivalent of FCV and field tests, it is clearly observed that field results in all cases are more than FCV but the difference is limited to about 15% - 20%. It can be caused by sufficient length of field piles that allow soil friction along the outer wall of pile mobilized. So, it was seen this difference is greater in longer piles. Also, in files test, an increase in low displacements is seen that can be caused from test method and measuring.

7. Conclusions

For physical modeling study, the FCV has advantages including suitable simulation of actual field stress distribution, work conformability and being economic in comparison to simple and calibration chambers, laminar boxes and centrifuges. On the other hand, the most limitations associated with simple and calibration chambers and also laminar boxes can be eliminated when model piles (deep foundations) are tested in the FCV. Therefore, due to its cost saving, the FCV device presents an efficient and practical alternative to centrifuge devices.

Based on FCV-AUT instrumentation and loading tests with two series of sensors, it is confirmed that both vertical and horizontal stresses in FCV-AUT increase approximately linear from top to bottom along the centerline of FCV just like real states in the field. The results of stress field tests clearly showed that FCV could simulate the stress gradient in reality where the full scale piles are performed. Also, comparison between the pile modeling test results in FCV and static analysis prediction indicated a good compatibility and agreement.

Performed tests on piles with embedment length about 750 mm, diameter of 89 mm and bottom pressure of 200 kPa in FCV can be representative of approximately prototype piles with 10 to 20 m length.

According to results of field tests, FCV-AUT results with multiply scale factors on them can be used in executive projects. The obtained load from this pro-

cedure is different about 15% to 20% to full scale tests, which is reasonable and can be justified in geotechnical practice.

Based on FCV properties some studies suggested to do, like relationship between FCV and CPT results for pile designing, study of pile lateral loading, pile test results in different problematic soils and improved soils.

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