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Uniform large scale cohesionless soil sample preparation using mobile pluviator

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Abstract. This research work deals with the development of air pluviation method for preparing uniform sand specimens for conducting large scale laboratory testing. Simulating real field conditions and to get reliable results, air pluviation method is highly desirable. This paper presents a special technique called air pluviation or sand raining technique for achieving uniform relative density. The apparatus is accompanied by a hopper, shutters with different orifice sizes and numbers and set of sieves. Before using this apparatus, calibration curves are drawn for relative density against different height of fall (H) and shutter sizes. From these calibration curves, corresponding to the desired relative density of 60%, the shutter size of 13mm and height of fall of 457.2 mm, are selected and maintained throughout the pluviation process. The density obtained from the mobile pluviator is then verified using the Dynamic Cone Penetrometer (DCP) test where the soil is poured in the box using defined shutter size and fall height. The results obtained from the DCP test are averaged as 60±0.5 which was desirable. The mobile pluviator used in this research is also capable of obtaining relative densities up to 90%. The instrument is validated using experimental and numerical approach. In numerical study, Plaxis 3D software is used in which the soil mass is defined by 10-Node tetrahedral elements and 6-Node plate is used to simulate plate behavior in the validation phase. The results obtained from numerical approach were compared with that of experimental one which showed very close correlation.

Keywords: cohesionless soil; DCP; mobile pluviator; relative density

1. Introduction

In the field, many constructions work requires well compacted sand fill to avoid foundation failure, excessive settlement and liquefaction in case of earthquake or any other event resulting in vibration. The simulation of the field conditions in such cases requires proper understanding and accurate evaluation of the soil properties. For instance, in the evaluation of site response analysis of a soil deposit the dynamic properties of the soil deposits such as the shear modulus and damping are significantly important Khari *et al.* (2011). These properties highly depend on the relative density or the density index of the soil which indicates the strength characteristics of the cohesionless soils. Also, reconstructing soil samples in the laboratory similar to natural soil conditions depends on the method of deposition as well. Previously some researchers have investigated methods for uniformity (Choi *et al.* 2010 and Fretti *et al.* 1995) and for obtaining suitable relative density in sandy samples (Dave *et al.* 2012, Lo Presti *et al.* 1993, Miura *et al.* 1982, Rad *et al.* 1987, Saussus *et al.* 2000). In the light of previous research, the mechanical properties of sandy soil were a function of its relative density. For achieving better results and better accuracy during the testing process, uniform soil samples must be obtained. Repeatable and undisturbed samples can be obtained in case of clays but it is very expensive and difficult to extract in case of sands because of little or no cohesion. Because of this, preparation of a uniform sand sample is very difficult and these samples should be individually prepared for each test. Researchers have developed several methods for the preparation of sand samples such as dry funnel, wet deposition and sedimentation Della *et al.* (2010). Vinil Kumar Gade et al. (2017) used portable and mechanized travelling pluviator to achieve the relative density of cohesionless soil conforming to the field conditions. Srinivasan *et al.* (2016) studied the optimization process to determine the orifice diameter in sieve plate for achieving maximum density. With no account and determination of field relevant soil properties, soil may subject to settlement under critical loading like eccentric case, studied by (Pooya Dastpak *et al.* 2020, Bildik and Laman 2015), which would need proper reinforcement for enhancing their bearing power, Tabaroei *et al.* (2018). Choi *et al.* (2017) studied the interaction between foundation components in correlation with different relative densities obtained through mobile pluviator method.

The properties of the sand samples obtained from these methods are studied by researchers and they have found that these sand samples have different resistances when subjected to different events. For instance, the resistance to liquefaction offered by the sand sample obtained through sedimentation method was found more in comparison to the samples obtained through other processes such as dry funnel and wet deposition. In addition to this, the resistances of the latter two samples were not equal and were different from one another. In case of wet deposition, the only factor which can't be ignored is the particle size gradation which can lead to reduction in falling velocity during the sedimentation process. Bhaumik *et al.*

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(2020) studied the effect of sand sample preparation on volumetric behavior under multidirectional shear. They concluded that sand sample preparation methods can change the volumetric response significantly. Among in all these methods, the most reliable method is the air pluviation. Air Pluviation technique is widely used in large scale and small-scale experimental testing of model foundation Walker and Whitaker (1967), triaxial testing, and centrifuge testing Zhao *et al.* (2006).

Using this approach, one can obtain a wide range of densities ranging from 10% to 98% (Khari *et al.* 2014, Gade *et al.* 2016) researched two methods for sand sample preparation which include vibratory and stationary pluviation method. They found that in case of vibrator method, soil particles separation will be minimum when low pneumatic pressure is use. They further recommended that vibratory methods are quicker than pluviation method. Tabaroei *et al.* (2017) compared two different methods of sand sample preparation which includes a rainer system with perforated plate and portable curtain rainer system. They concluded that effect of height of fall is substantial for lower relative density values and becomes more when height of fall is more than 600 mm Kazemi and Bolouri (2018). Furthermore, they concluded that to achieve heigh relative density, the rate of deposition should be low. Destpak *et al.* (2021) performed a parametric study on three types of sand to determine the effect of plate porosity on relative density. They concluded that relative density is mostly affected by size of the mesh rather than porosity of the plate. They also concluded that relative density increases with the increase in height of fall till critical height and also critical height of fall is dependent on type of perforated plate and sand type. Ghosh *et al.* (2016) performed a series test to determine the optimize opening area which could result in maximum deposition intensity with desired relative density. Although different types of instruments have been used to obtain uniform sand samples using this process but they were not able to cover a large area and hence smaller samples were produced in the past. Because of this reason a special device called mobile pluviator has been fabricated and used in this research which has the capability to be moved easily in the horizontal and in vertical direction for vertical and horizontal uniformity of sandy samples. Using this procedure, physical geotechnical modelling in sandy soil can be perform at large scale under control condition.

The second problem which usually occur in physical modelling is to verify whether the relative density obtained from the above methods is in the desired range or not. (Mohammadi *et al.* 2008) performed a series of test using small scale dynamic cone penetrometer on cohesionless soil and developed a correlation between penetration value per blow and relative density. Shahadat (2009) also developed a relation between penetration value of small scale DCP and relative density based on significant number of tests in sandy soil. So, in this research work, the relative densities for sand are obtained using various shutter sizes and heights. After that corresponding to the desired density of 60% and 13 mm shutter, the height of fall is selected, which in this case obtained as 18 inches. The height obtained through the mobile pluviator is then checked and verified through DCP test which is used to access the in-situ resistance to penetration of the underlying soil strata. The resistance to penetration was then related with the density of the sand and it was observed that the results obtained through the DCP are very close to those obtained from the mobile pluviator. Later on, the densities obtained from mobile pluviator is also verified experimentally using plate load tests and numerical approach of Plaxis 3D which also gave satisfactory results of obtaining relative densities that can be seen from the comparative graphs below.

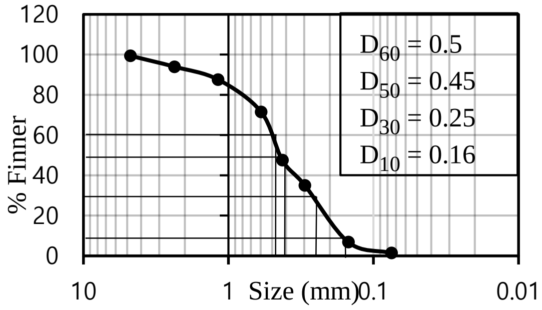

Fig. 1 Gradation curve for sandy soil

2. Soil properties

Locally available Khanpur soil was used and necessary geotechnical laboratory testes like Sieve and hydrometer analysis, maximum and minimum relative density and direct shear test were performed as per ASTM standard procedure to find the basic soil properties as shown in Table 1. The gradation curve is also shown in Fig. 1.

3. Test setup

The experimental work was performed in three stages. The first and second stage includes calibration of mobile pluviator and verification of the density obtained by mobile pluviator through DCP test. The third stage consist of plate load tests to check the effects of relative density on load settlement curve. For calibration purpose, a cylindrical mold of 203 mm inner diameter with 305 mm height was used. For DCP and plate load test, a soil box of 0.9x1.2 m with a height of 1.5 m was used. Cylindrical mold and soil box are shown in Figs. 2(a) and 2(b)..

3.1 Fabrication of mobile pluviator

Mobile Pluviator is an apparatus which is used in the laboratory to achieve a specific uniform relative density through air pluviation (sand raining) process. The different components of the Mobile Pluviator are;

- Adjustable Frame
- Hopper
- Wheels
- Shutter, & Sieves

All these components play a specific role in the Pluviation process. The main function of the adjustable frame is to use the apparatus as per the user requirements. Using this adjustable frame, the height and width of the Pluviator can be adjusted depending upon the size of the sand box.

(a) Calibration mold (b) Soil box

Fig. 2 Calibration mold and soil box

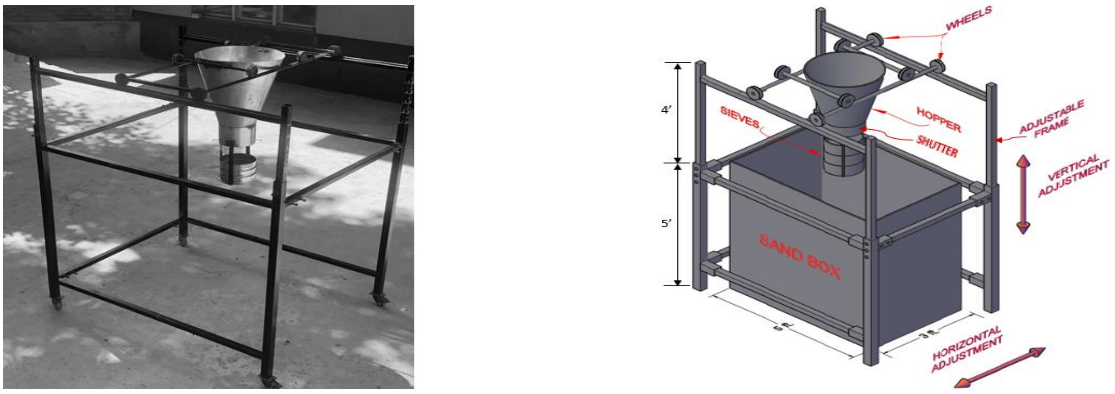

Fig. 3 Mobile pluviator and its components

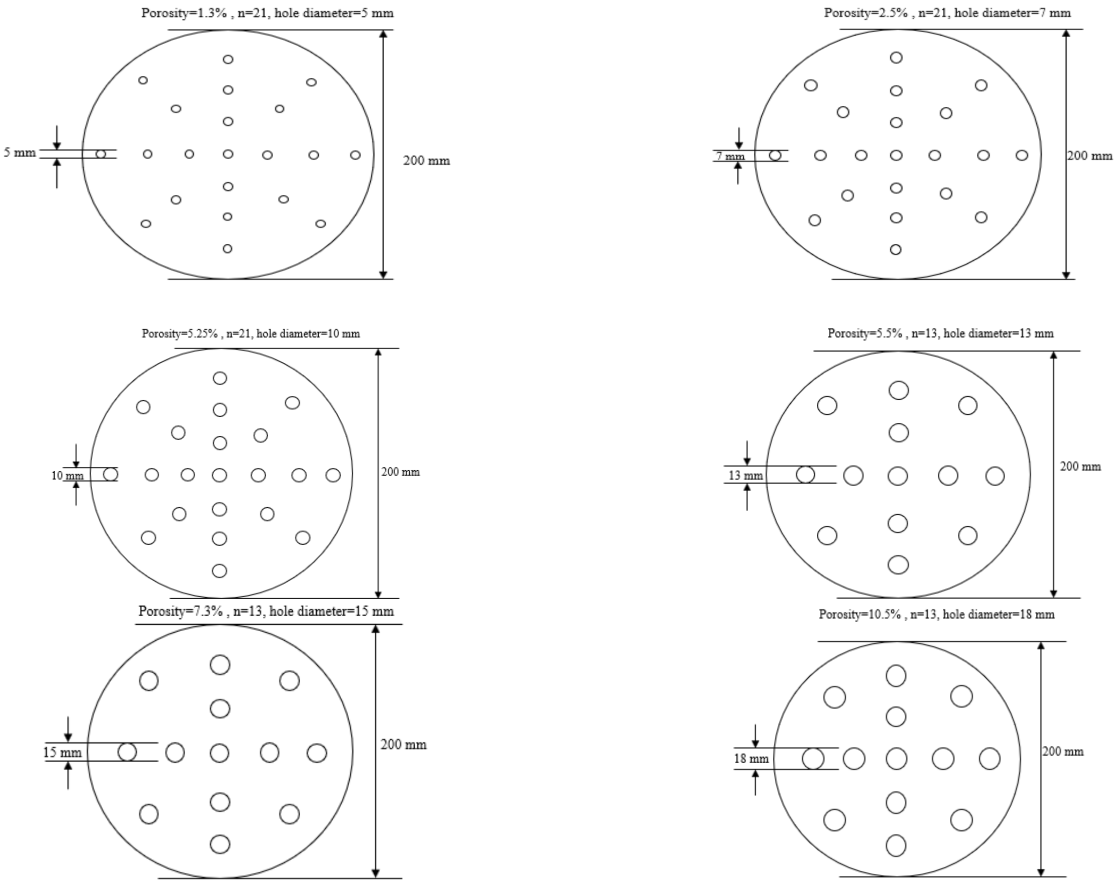

Fig. 4 Shutters

Table 1 Soil properties

D_{10}	D_{30}	D_{50}	D_{60}	C_u	C_c	Sand Fraction	Gravel Fraction	Fine Fraction	ϕ	γ_{min} (kN/m^3)	γ_{max} (kN/m^3)	G_s
0.16	0.25	0.45	0.5	3.125	0.66	97.96	0.65	1.39	36°	13.9	17.04	2.64

The main function of the hopper is to receive the sand during pluviation process. With the help of wheels, the hopper can be moved in the horizontal plane in both directions to ensure that the sand reaches to the extremities of the box. A total of seven shutters were fabricated from wood with different porosity. Shutters can be of different types based on the size & number of holes (Porosity) in the shutter. The schematic details of shutters are shown in Figs. 4. The function of the shutter is to control the flow rate or discharge of the sand falling into the box. Increasing the shutter porosity will increase the discharge but will decrease the relative density & vice versa. A set of three #4 sieves are installed at the bottom of the hopper below the shutters. The main function of the sieves is to ensure uniform raining. The fabricated mobile pluviator and schematic view with components are shown in Fig. 3.

3.2 Calibration

Mobile pluviator should be calibrated first for different parameters which is expected to change the soil relative density. Shutter porosity, height of fall, distance between shutter and the top sieve and the soil type are the main parameter which affects the relative density. In this study, the shutter size and height of fall was calibrated against relative density as these two parameters are considered to affect the relative density significantly. While checking the effect of one parameter the other parameter was kept constant. It is worth mentioning here that the distance between the shutter bottom and top of sieves was kept constant throughout this research work for easiness and simplicity. Change in this distance will also modify the relative density. For calibration purpose, a small cylindrical mold with inner diameter 203 mm and height 305 mm was fabricated resulting in area of 61900 mm^2 as shown in Fig. 2(a).

A total of forty-two calibration was performed, seven on each shutter with different height of fall. The height of fall was varied from 127 mm to 889 mm. Great attention is required during calibration as calibration of mobile pluviator is the most important step before using in physical modelling.

That's why, during calibration process, a plastic sheet was wrapped around the hopper in circular pattern till the ground level to prevent the effects of wind on relative density. The mold and mobile pluviator was marked at interval of 76. 2 mm to maintain same height of fall. A steel wire mesh was installed on hopper top to remove entrance of large size debris which may cause stoppage in shutter holes. The calibration process involved the following steps;

- Installation of specific shutter in hopper bottom.
- Feeding the sand into the hopper.
- Passage of sand through the Shutter.
- Passage of sand through the Sieves.

During pluviation process, the hopper level was raised in an increment of 76.2 mm after sand level in mold reaches. After every 76.2 mm, the hopper level was raised through the vertical adjustment screws provided in the mobile pluviator in order to maintain that specific height of fall. This process was continued until the whole mold was filled with sand.

- After filling, the excess soil was removed through levelling tool and unit weight of the soil “g_d” was measured.
- Using the following Eq. (1), the relative density was calculated.

$$Dr=\left(\frac{\gamma_d-\gamma_{min}}{\gamma_{max}-\gamma_{min}}\right)\left(\frac{\gamma_{max}}{\gamma_d}\right)\mathrm{x}100 \qquad (1)$$

The calibration curves which are drawn between relative density and height of fall are shown in Fig. 5. Using these curves, any desire relative density can be achieved in the range of 34% to 92% on any scale for this specific mobile pluviator.

3.3 Dynamic Cone Penetrometer (DCP)

Various techniques including, shear wave velocity method, density cans and small-scale dynamic one penetrometer are used to confirm the density achieved by mobile pluviator technique.

The uniformity of sand sample can be verified by dynamic cone penetrometer. The dynamic cone penetrometer was first developed in South Africa in 1956 for the in-situ evaluation of pavement layer strength. Since then, this device came in use in many other countries including United Kingdom, United States and Australia because of being portable, simple, economical and a quick means of the in-situ measurement of the pavement layers and subgrade strength. Recently, DCP has been standardized as per ASTM (ASTM D 6951-03). In this particular study, the dynamic cone penetrometer (DCP) tests were conducted according to the procedure as per ASTM-D6951-3(2003). The purpose of performing this test is to verify the calibration values. The apparatus consists of 16 mm diameter steel rod to which a 60° steel cone having 20 mm base diameter is attached at the lower end. The DCP consists of 8 kg hammer which is dropped from a height of 575 mm. After each drop, penetration of the cone is measured & recorded. Fig. 6 shows the complete details of the dynamic cone penetrometer. All the components of DCP are made of stainless steel for better efficiency and longer life time.

The various components of DCP are:

- Handle
- Hammer
- Guiding Rod
- Lower Shaft
- Anvil, & Cone

Handle is provided on top of the guiding rod. The function of the handle is to enable the operator to properly grip the equipment during testing. The function of the hammer is to drive the cone into the soil. The 8 kg hammer is manually raised & then dropped imparting its energy to anvil & in this

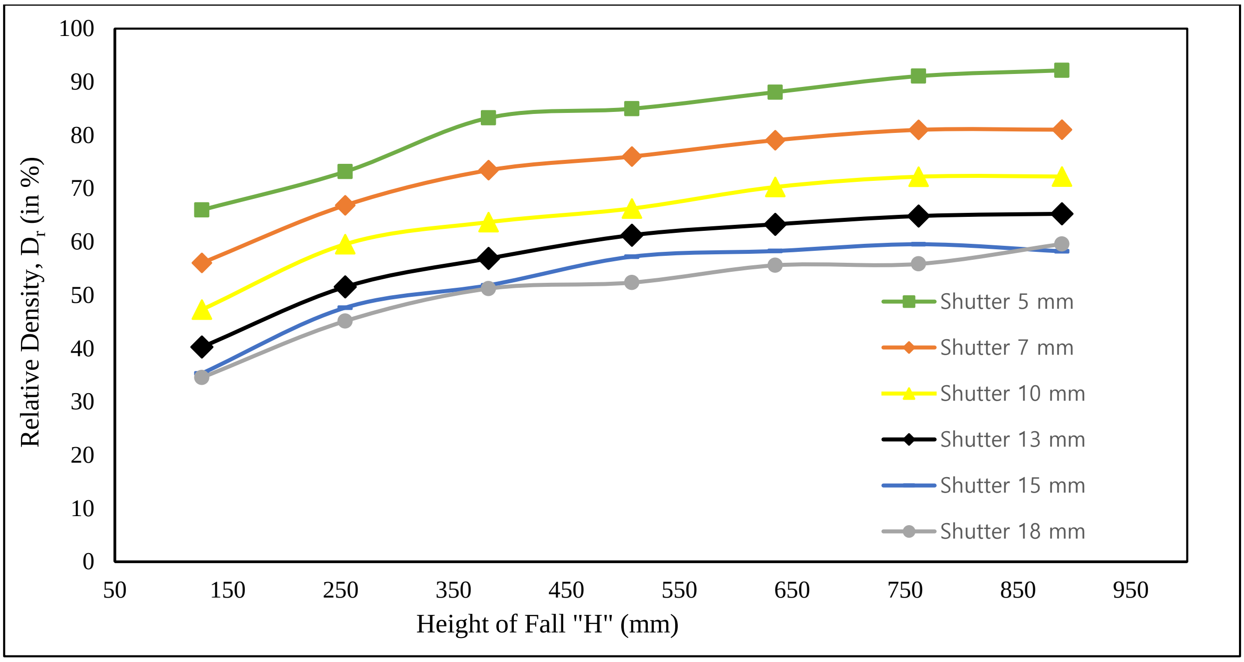

Fig. 5 Dr (%) Vs Height of Fall curve

way the cone gets penetrated into the soil. The function of the guiding rod is to guide the hammer during its fall. The guiding rod guides the hammer to fall on the anvil and prevents the hammer from falling on the soil. The lower shaft gets penetrated into the soil & the amount by which the instrument gets penetrated into the soil is recorded with the help of lower shaft. The main function of the cone is to facilitate the penetration process. Two types of cones are generally used in DCP testing depending on the soil conditions. In stiffer soil 30° is used while in medium to stiff soil 60° cone is used. In either case, the cone base diameter is 20 mm.

The soil box as shown in Fig. 2(b) was filled through air pluviation with a specific shutter height. The soil box was filled in layers of 76.2 mm which results in total layers of twenty. For each layer, the mobile pluviator height was adjusted to ensure that specific height of fall. To gain homogenous relative density throughout the surface of the box, the hopper was moved horizontally in both direction during pluviation. After pluviating the soil in twenty layers, the box was filled and the surface was levelled by removing the excess soil. For verification purpose, 457.2 mm height was selected from 13 mm shutter calibration curve which will result in 60% relative density. The pluviation was performed keeping height of fall equal to 457.2 mm between bottom sieve and top of deposited sand as shown in Fig. 7. The DCP is then performed as shown in Fig. 12 at five different locations on soil surface top, one at the center and four at corners of the box. The penetration values per blow was recorded and by putting the values in the correlations shown in Eq. (2), the relative density can be calculated. Eq. (2) was developed by Shahadat (2009) for cohesionless soil based on significant number of tests. The initial elastic modulus of cohesionless soil can be calculated from DCP penetration using Eq. (3) developed by Mohammadi *et al.* (2008). Using Eq. (2) and (3) for relative density and initial elastic modulus respectively, values calculated for central point of the soil box are shown in Table 2.

$$D_r(\%) = 97.4035\, e^{\frac{-P_{index}\sqrt{D_{50}}}{80.7707}} + 3.0971 \tag{2}$$

Where, P_{index} is mm/blow

D_{50} mean particle size in mm

$$E_i(MPa) = 55.03/(DPI)^{0.54} \tag{3}$$

Where, DPI is penetration in cm/blow

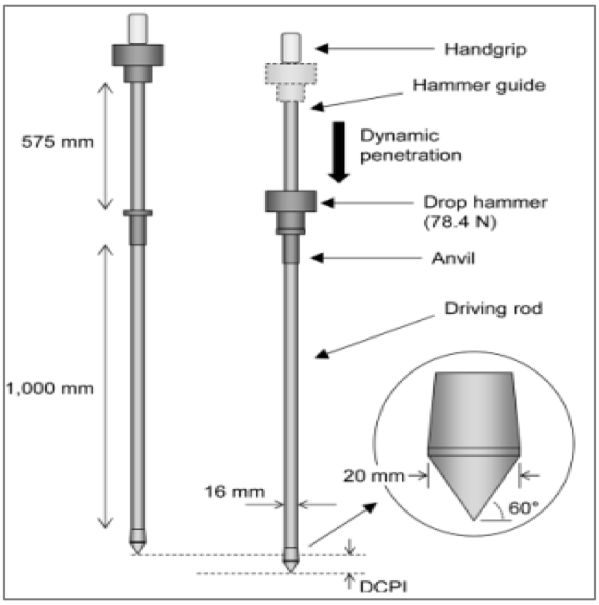

Fig. 6 DCP parts, Hong and Lee (2018)

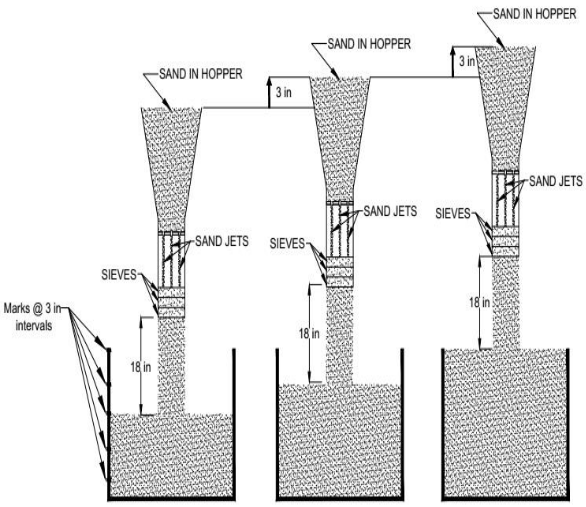

Fig. 7 Pulviation process for 60 % relative density

Fig. 8 DCP Test

Table 2 DPI and E_i values at 60% D_r

DPI (cm/blow)	P_{index} (mm/blow)	D_r(%) (using Eq.(2))	E_i (MPa) (using Eq. (3))
7	70	57.56	19.62
6.6	66	59.40	20.24
6.4	64	60.34	20.57
6.3	63	60.82	20.75
6.4	64	60.34	20.57
6.2	62	61.30	20.92
6.3	63	60.82	20.75
6.3	63	60.82	20.75
6.3	63	60.82	20.75
6.2	62	61.30	20.92
6	60	62.27	21.29
Average		60.65	20.65

3.4 Plate load test

Three plate load tests were performed on different relative densities of 60%, 70% & 90% obtained through pluviation. These densities were verified through DCP. A plate of 304.8 x 304.8 mm was fabricated from 25 mm thick aluminum plate. For the real time monitoring of plate load test 4 potentiometers, one at each corner to ensure unform settlement, and a load cell at raft was fitted. An incremental load of 5000 N was applied through steel plates. The results are described by Fig. 9(a) where it is clear that as the relative density increase the settlement decreases. At a relative density of 60%, plate load test shows a linear behavior up-to the load limit. As the relative density increase the stiffness increase and load settlement curve becomes parabolic type.

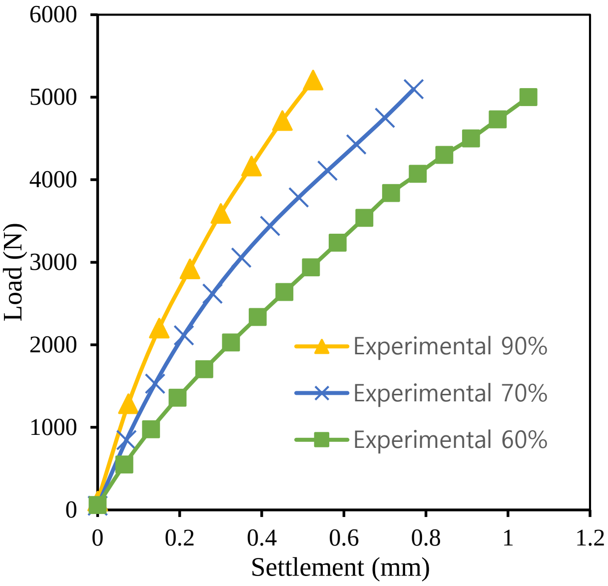

Fig. 9 Plate load settlement curves

4. Numerical modelling

Numerical modelling of the plate load test was performed in PLAXIS 3D finite element software in which the soil mass is defined by 10-Node tetrahedral elements and 6-Node plate is used to simulate plate behavior in the validation phase. The purpose of numerical simulation was to validate the experimental results at mentioned relative densities. Mohr-Columb constitutive model available in PLAXIS 3D was used to simulate the mechanical behavior of sandy soil. The pictorial view of the FEM model is shown in Fig. 10. The main input parameter required in Mohr-Columb is stiffness which were calculated from the DCP results using correlations provided by (Mohammadi *et al.* 2008) shown in Eq. (3) and values calculated from DCP are shown in Table 2 and Table 3 for 70% and 90% relative density respectively. An average value of Initial tangent modulus was taken for each relative density and used in the corresponding numerical model. The main input parameters required are shown in Table 5. The effective angle of internal friction was calculated from relative density using Eq. (4) suggested by Meyerhof (1959). An interface was provided under the raft to account for the reduction of strength due to different material under contact i.e., Raft and soil. Course meshing with local refinement near the raft was made for better results. Same number of elements (23013) and nodes (34893) was used in each model. For load verses settlement

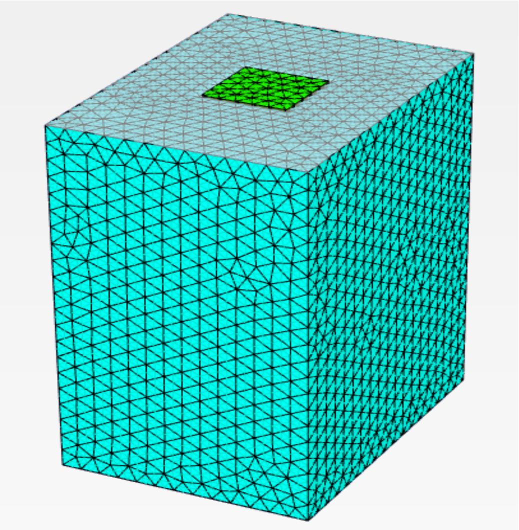

Fig. 10 FEM model in PLAXIS 3D

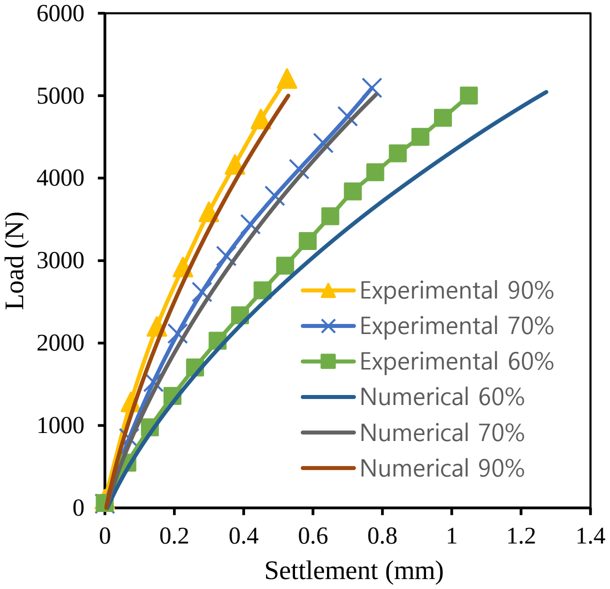

Fig. 11 Plate load settlement curves

curves 5 points, one at center and one at each corner on raft was selected before running the analysis and the average of settlement was drawn with load. The comparison between experimental and numerical result is shown in Fig. 11.

$$\phi=28+0.15\ (D_r) \tag{4}$$

Where Dr is the relative density

Table 3 DPI and E_i values at 70% D_r

DPI (cm/blow)	P_{index} (mm/blow)	D_r(%) (using Eq. (2))	E_i (MPa) (using Eq. (3))
4.5	45	70.13	24.43
4.4	44	70.69	24.72
4.5	45	70.13	24.43
4.2	42	71.82	25.35
4.3	43	71.25	25.03
4.2	42	71.82	25.35
4.4	44	70.69	24.72
4.3	43	71.25	25.03
4	40	72.97	26.03
4.3	43	71.25	25.03
4.2	42	71.82	25.35
Average Dr		71.51	25.05

Table 4 DPI and E_i values at 90% D_r

DPI (cm/blow)	P_{index} (mm/blow)	D_r(%) (using Eq. (2))	E_i (MPa) (using Eq. (3))
2	20	85.59	37.85
1.5	15	89.09	44.21
1.5	15	89.09	44.21
1.7	17	87.67	41.32
1.6	16	88.38	42.69
1.4	14	89.81	45.89
1.4	14	89.81	45.89
1.3	13	90.53	47.76
1.5	15	89.09	44.21
1.6	16	88.38	42.69
1.5	15	89.09	44.21
Average Dr		88.78	43.72

5. Result and discussion

From the calibration curves, it has been concluded that increase in the height of fall increases the relative density up to certain limit after which no proper increase in the relative density take place, which means that after this critical height, the height of fall has no effect on relative density. It is also concluded from the result that as much as the shutter size increases, Dr decreases. With increase of shutter size rate of discharge increase and the particles don't find enough time to deposit in best place and hence results in decreased of relative. The second reason behind this trend can be, as the porosity of soil increases, the rate of discharge increases, which results in more collision between the falling particles and hence more obstruction to the movement of falling. The particles strike the surface of sand with less velocity than expected and hence results in less relative density. For 457.2 mm height of fall, 5 mm shutter shows 85% relative density, 7 mm shows 75%, 10 mm shows 65%, 13 mm shows 60%, 15 mm shows 55 % and 18 mm shows 51% relative density. The calibration values of relative density obtained from mobile pluviator is verified through DCP test which are found in very close relation to the desired 60% relative density. The values of relative density obtained from DCP is in the range of 57.56% to 62.27% which shows the vertical uniformity of the sandy sample preparation using air pluviation. Similarly, the ranges for 70% and 90% relative density obtained from DCP are 70.13-72.97% and 85.59-90.53% respectively. Overall, the average values obtained from DCP was in good range with the desire relative density through the horizontal surface as well as along the depth of the soil box. Plate load

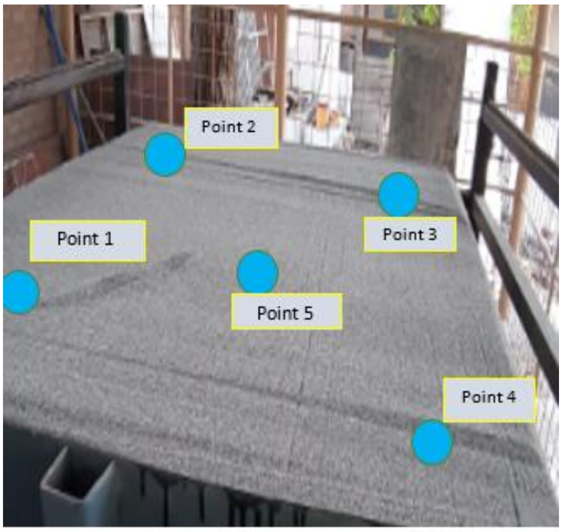

Fig. 12 DCP performed on five different location

tests are performed at a relative density of 60%, 70% and 90% to check the effect of relative density on the load settlement curve. The load settlement curve become stiffer with the increase in the relative density. The plate load settlement response was also simulated in FEM software PLAXIS 3D. The main input parameter for numerical model is the elastic modulus of soil which is obtained from DCP using Eq. (3) developed by Mohammadi *et al*. (2008). The numerical simulation shows a very close match with the experimental response of load settlement curve. This close match shows that the desired relative densities are obtained accurately. The plausible reason for the small difference in the load settlement experimental and numerical response may be due to approximation of the soil model in PLAXIS 3D and elastic modulus values obtained from correlation. Concluding that the relative density obtained from the developed mobile pluviator is more accurate and proved very reliable for large scale laboratory testing.

6. Conclusions

- Using free fall theory for dry sand we can achieve various relative densities by changing height of fall. The height of fall effect on relative density become insignificant when it reaches critical value i.e., height where particles achieve critical velocity.
- Maximum density of 92% is achieved for sand with given grain size at critical height.
- Relative density of sand also depends on rate of discharge of soil which is controlled by shutter porosity. With constant height of fall the relative density increased by 91% when shutter porosity is decreased from 10.5% to 1.3%.
- The DCP fabricated in this case is very reliable to achieve any desired density on large scale.
- Moreover, the newly fabricated mobile pluviator has adjustable frame, which can be said to cover the desired area.
- The results of plate load test numerical simulation in PLAXIS 3D shows that we can use mobile pluviator to achieve uniform relative densities over wide range of area, and hence is useful in experimental work on small as well as on large scale.

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