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Original article

Assessment of a new pluviation system designed to prepare uniform samples of sand

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ABSTRACT

In soil and soil-structure interaction laboratory experiments, the technique applied to prepare the sand deposit remarkably influence the performance of the system, including the stress–strain behavior. Air pluviation techniques represent the most suitable choice when a wide range of densities is required. This study presents the details of a simple and effective air pluviation system designed to be suitable for reconstituting small specimens of sand. Many of the previous studies have focused on traveling the pluviator in the horizontal direction only, without paying much attention to the vertical movement during pluviation. The apparatus described in this paper has the ability to overcome this issue by providing automatic lifting tools to the sand container while the thickness of the sand deposit builds up inside the collecting mold. To understand the influence of grain size distribution of sand on the achieved relative density (RD), three different samples of poorly graded sands were used in the experiments. Parametric studies, including the influence of the height of drop (HD) and deposition intensity (DI) on the relative density, were carried out on the three sand samples. It was observed that the range of obtained RDs depends mainly on the grain size distribution of the sand used. Three distinguished zones were observed in the RD-HD relationship, starting with a linear variation, followed by a nonlinear relationship until achieving a constant RD regardless of the increase of HD value. The uniformity of pluviated sand was assessed using a cone penetration test (CPT). Results of the CPT test showed that denser and more uniform samples could be obtained by raising the container up during the pluviation process.

1. Introduction

It is well-known that the circumstances of in-situ soil are extremely difficult to be scaled down or simulated completely and identically to laboratory tests. However, the inaccuracy and deviation of small-scale test results can be minimized, taking into consideration a number of steps. In soil and soil-structure interaction laboratory experiments, the first and most important step towards trusted results is using a reliable soil specimen preparation method. This process is relatively easier in consolidated clayey soils in comparison to sandy soils. The cohesion nature of clay contributes positively to obtaining and maintaining undisturbed samples in the laboratory or in the field. However, achieving a uniform density of sand sample over its three dimensions is rather difficult, especially when repeating prepared samples is required. To reduce the variation in sand density and thus confirm the reliability of soil-structure laboratory test results, researchers have suggested several techniques to prepare sand specimens ranging from simple tamping to more advanced pluviation or vibration methods, e.g. (Al-Refeai, 1992; Hossain and Ansari, 2018; Srinivasan et al., 2016; Ghosh et al., 2016; Logioia et al. 2006; Miura and Toki, 1982; Wood et al., 2008). These techniques include (1) air pluviation, where single or multiple sieving systems located at a certain height of fall are used in the stationary apparatus, and an opening or funnel moved over the entire area of the box in a certain pattern is used in the movable apparatus, (2) spreading the sand into layers of 3–10 cm in thickness, and then tamping each layer to reach the desired density. The exact value of the targeted density is difficult to achieve as the tamping energy per unit area is difficult to control in this case, and (3) placing the whole mass of the sand in the testing box and then vibrating the box by either a shaking table or tapping hammer.

The accuracy and consistency of any proposed sand preparation technique can be better checked in a time-effective manner by conducting tests using small specimens first. After conducting a calibrated investigation and studying parameters that control the

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uniformity and homogeneity of sand beds, the proposed technique can then be extended to large specimens.

For air pluviation techniques, a common conclusion achieved by many researchers stated that as the height of the fall increases, the relative density of the sand increases (Zhao et al., 2006; Kodicherla et al., 2018; Hakhamaneshi et al., 2016; Khari et al., 2014; Vaid and Negussey, 1984). However, the range of relative densities is a function of many factors. The most important is the sand grain distribution and the design of the pluviation apparatus, which controls the discharge rate of sand. Accordingly, some researchers were able to obtain values of relative densities out of limits achieved by following standard procedures described by codes for both maximum and minimum relative densities, e.g. (Lo Presti et al., 1992; Cresswell et al., 1999; Hariprasad et al., 2016). Another advantage of pluviation methods over the vibratory procedures adopted by, for example, the ASTM or British Standards is the ability to avoid the crushing action of sand particles during compaction.

In addition to the height of the fall, the resulting density can be affected by the rate of deposition and the uniformity of sand pluviation (Tabaroe et al., 2017; Gade and Dasaka, 2017). The latter is a function of the pattern, size, number, and shape of sieves used in the pluviation system, which control the mode of falling and the manner in which the sand particles are distributed during the deposition process.

The uniformity of the sand bed can be measured at various locations over its cross-section using several methods. The simplest option is the use of small molds of known volume distributed over the area of pluviation to collect the falling sand and then calculate its density (Abdollahi and Bazaz, 2017; Dastpak et al., 2021). This method may not be sufficient when a density profile over the depth is required. Standard or modified cone penetration test has been used widely and effectively to estimate the in-situ and laboratory density of different kinds of soils, e.g. (Baghdadi et al., 1990; Al-amoudi et al., 2015; Fretti et al., 1995; Aldefae et al., 2019). Also, digital imaging techniques were limitedly used to assess the uniformity of sand, e.g. (Kodicherla et al., 2018; Al-Shibli et al., 1996).

The apparatuses used to pluviate sand in the air can be either stationary or movable. Each technique has its own drawbacks and benefits. The main problem in stationary apparatus is the separation of sand particles into different zones depending on their size during discharge from meshes. This case of segregation is more pronounced in well-graded samples. Attempts have been made to overcome this phenomenon by considering some propping tools in the design of the pluviator, e.g., (Yoshimine and Koike, 2005; Huang et al., 2015). Despite its ability to separate sand grains evenly over layers, a movable pluviator can not be used when a wide range of densities is required (Fretti et al., 1995).

Although a wide variety of techniques, apparatus, and requirements was covered in the previous studies, there are still some issues that need to be taken into special attention. In the current study, small sand specimens were prepared using an air pluviation technique. An investigation program was applied to assess the uniformity of prepared sand in both vertical and horizontal planes. A simple and easy-to-use pluviation apparatus was designed and fabricated at the Department of Civil Engineering, the University of Basrah, for this purpose.

2. Description of the pluviation system

The apparatus used in the experiments are designed to meet the following requirements: (1) Simple design and easy to use, (2) The sieving system is developed to obtain a wide range of opening sizes (0 – 10 mm) without changing the perforated plates, (3) The apparatus can be used efficiently to prepare small samples for triaxial, and shear box tests, (4) Capable to lift sand container automatically, and (5) Sand container can be lifted up with speed equal to the rate of sand deposition inside the collecting mold.

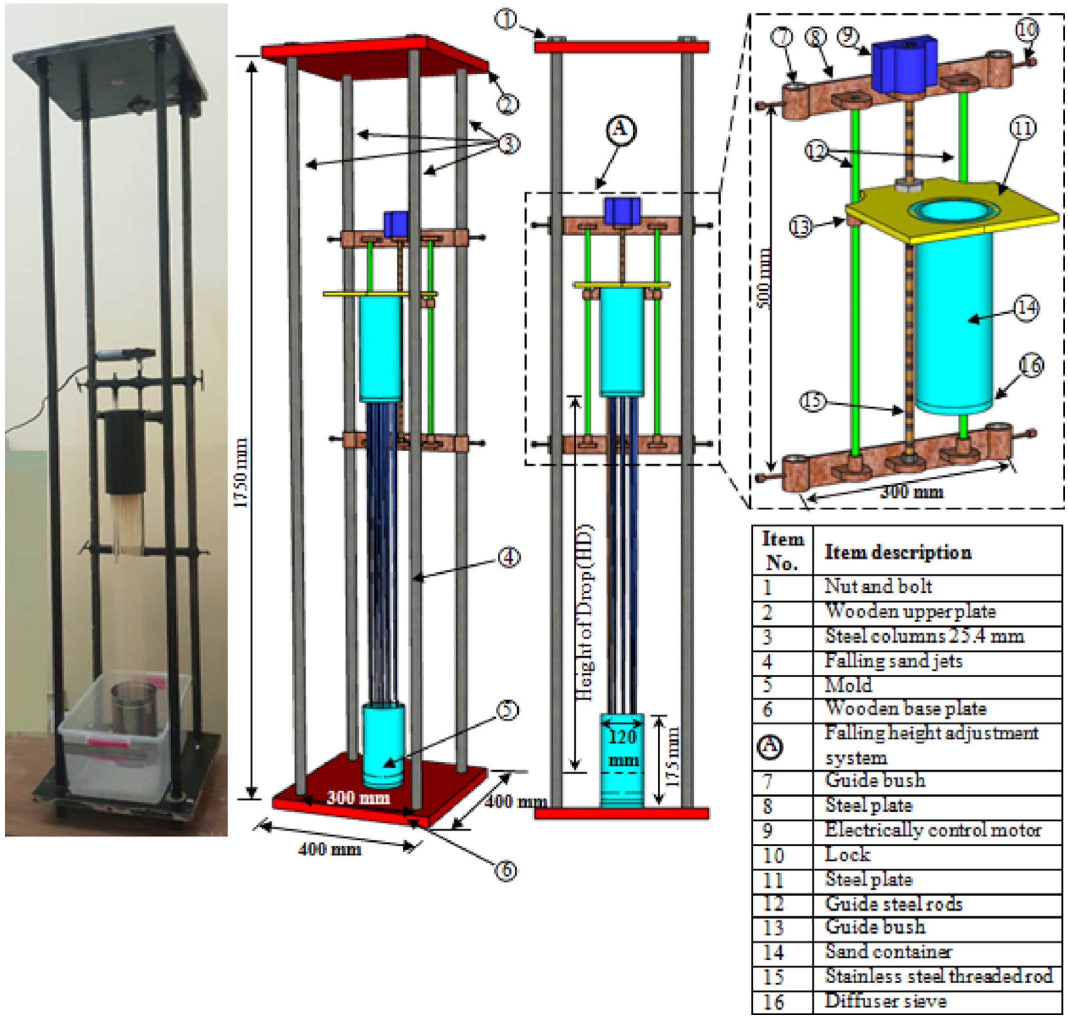
Regarding the last point, the influence of the continuous lifting of sand containers during the pluviation process on the reconstituted sand specimens was neglected by many investigators. However, it is suggested that raising the sand container is an effective way to reduce the non-uniformity of pluviated sand. In this way, the effect of the continuous decrease of the height of the drop on the sand density can be minimized.

The main components of the apparatus are the holder frame and the falling height adjustment unit (Fig. 1). The holder frame consists mainly of four steel columns attached to wooden plates at the top and bottom, with a total height of 1750 mm. The falling height adjustment unit can be smoothly moved up and down along the rear columns of the main frame to achieve the desired height of drop (HD), which is defined as the distance between the perforated sieving plate and the sand surface in the container mold. The movement of the pluviator unit can be controlled either manually by unscrewing the four bolts used to attach the unit to the frame and then tightening them at the targeted height or automatically by means of an electrical motor. In the automatic lifting technique, the motor rotates a threaded steel rod which, in turn, holds the sand container utilizing a steel plate and a nut. The presence of the nut can serve the plate and the container to move vertically during the rotation process. It is possible to provide the required rate of movement by controlling the speed of the motor using the changeable voltage power supply. Therefore, the speed of lifting was calibrated to follow the increase in the height of the sample collected in the mold. In this manner, the height of the drop is held constant during pluviation. One of the advantages of keeping a constant distance between the sieve and the surface of the pluviated sand is avoiding the spatial variability of density along the specimen's height caused by fixing the sand container at a certain HD. The problem can be of major influence when deep collecting mold is used with a small HD. This phenomenon can be eliminated simply and effectively by lifting the sand container at a constant rate equal to the rate of sand deposition inside the collecting mold. In this manner, the sand container was lifted with a height equal to the depth of the collecting mold. The time required to reach this height was calibrated with the time required to fill the collecting mold with sand. This technique will be hereafter referred to as the 'constant HD' technique.

Two perforated aluminum sieve plates of 100 mm diameter were used in this study. Each plate has 19 openings of 10 mm diameter arranged in a hexagon pattern, as shown in Fig. 2. The two plates were attached together and installed at the bottom of the sand container. The inner plate was kept fixed while the outer plate could be slightly slipped over the inner ones by unscrewing the two screws connecting them. By changing the position of the outer plate up to 10 mm, the desired sieve opening size can be achieved. Big care was given to this process to ensure that all openings have exactly the same size. Any variation in the size of the produced openings can be highly influenced the results. The shape of the opening resulted using this arrangement is a lens with two axes of different lengths. In the current study, the value used to describe the opening size (d) is the length of the minor axis.

3. Testing procedure

At first, the sieve plates were adjusted to obtain the required opening size. Then, the sand container was placed in its position in the pluviator unit, which was, in turn, mounted on the main frame at the selected height. The capacity of the container can be increased by attaching another part at the top of the container. After that, the container was filled with a selected sand sample.



Item No.	Item description
1	Nut and bolt
2	Wooden upperplate
3	Steel columns 25.4 mm
4	Falling sand jets
5	Mold
6	Wooden base plate
A	Falling height adjustment system
7	Guide bush
8	Steel plate
9	Electrically control motor
10	Lock
11	Steel plate
12	Guide steel rods
13	Guide bush
14	Sand container
15	Stainless steel threaded rod
16	Diffuser sieve

Fig. 1. Details of the Pluviation system.

The sand was not allowed to flow in this stage, utilizing a plastic plate stopper. The sand used is commercially available. It was sieved to form three samples of poorly graded sand of different particle size distributions, as shown in Fig. 3. The reason behind using such types of sand is to explore the influence of particle size distribution on the obtained results. The physical properties of sand are illustrated in Table 1.

The plate stopper was removed, allowing the dry sand to rain from the sieve into the collecting mold. Two kinds of molds were used to collect the falling sand. A small cylindrical mold with 400 cm^3 volume was used for direct calculations of density, and a bigger and deeper one, with 2150 cm^3 volume, was used for the cone penetration test.

Preparing sand samples, in general, requires not only obtaining the same density at each pluviation process but also ensuring that the pluviated sand is uniformly and evenly distributed over the depth and cross-sectional area of the collecting mold. In the current study, the cone penetration test (CPT) was used to assess the uniformity of the sand samples prepared. The standard setup of the CPT test was modified to meet the scaling requirements of the specimens. A special apparatus was designed and fabricated carefully for this task. Details of the modified CPT used are presented in Fig. 4. A steel cone of 250 mm length and 3.45 mm diameter was manufactured and used in the experiments. The resistance force is transmitted to a load cell of (100 kg) capacity installed between the cone and the main frame. The sample was set on the base plate of an electrically controlled jack, which in turn, can move the sample up and down. The jack was connected to a power supply with changeable voltage to control the movement speed and, thus, the penetration rate. The latter was set to 1.6 mm/sec for all tests. This value was chosen arbitrarily as the measured cone resistance is not affected by the rate of penetration (Dayal and Allen, 1995). Even though test results can be influenced by boundary and scaling effects, the CPT test is widely used to investigate the uniformity of sand beds (e.g., Bolton et al., 1999; Dave and Dasaka, 2012).

For uniformity investigation, two samples of each type of sand pluviated at two values of HD were tested. The prepared samples cover various states of density ranging from very loose to very dense, as described in Table 2. The penetration test was carried out at five different locations of the samples' cross-sectional area.

4. Experimental results

The experimental program consists of four groups of tests for each sample of sand. The aim of the first group of tests was to find the deposition intensity (DI) of sand poured through different sizes of sieve openings. The deposition intensity of sand was obtained by weighing the quantity of sand falling into the collecting mold, then dividing this weight by the unit area of the collecting mold

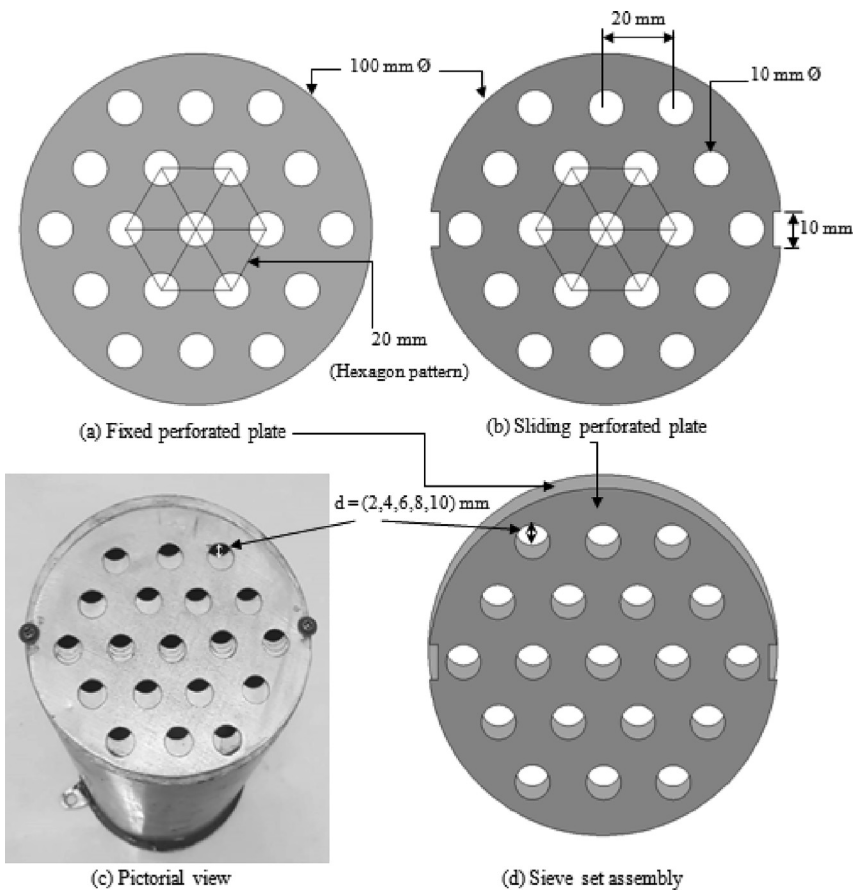


Fig. 2. Details of perforated plates used in the sieving system.

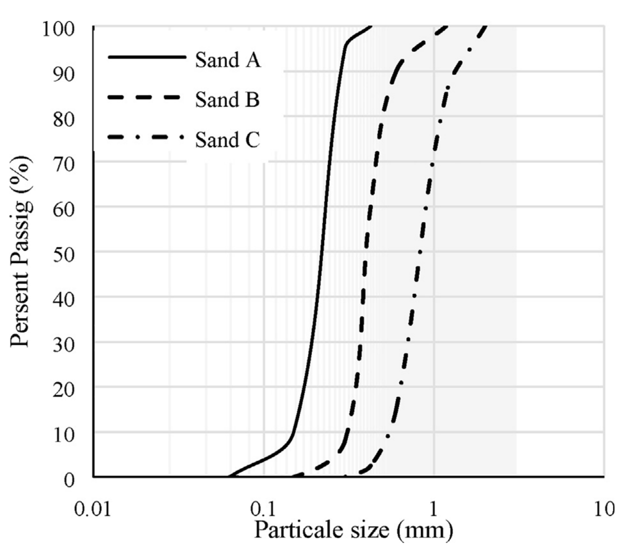


Fig. 3. Particle size distributions.

(cm^2) per unit time required to fill the mold(s). Then, a series of sand raining tests was conducted for the three types of sand in order to investigate the effect of the height of the drop on the relative density achieved. The third group of tests was carried out by filling a bigger and deeper collecting mold with different samples of sand rained from the different heights of drops, the prelude to being tested by the CPT test, which represents the fourth group of tests.

Table 1
Physical properties of sand.

Parameter	Sand A	Sand B	Sand C
D_{10} (mm)	0.16	0.30	0.60
D_{30} (mm)	0.19	0.36	0.72
D_{50} (mm)	0.21	0.40	0.82
D_{60} (mm)	0.25	0.46	0.90
C_u	1.50	1.53	1.56
C_c	1.25	1.28	1.32
ρ_{min} (g/cm^3)	1.447	1.480	1.503
ρ_{max} (g/cm^3)	1.539	1.618	1.677
e_{min}	0.72	0.64	0.58
e_{max}	0.83	0.79	0.76
G_s	2.65	2.65	2.65

Fig. 5 shows the variation of deposition intensity (DI) when sieve diameter (d) changes from 2 mm to 10 mm in a successive manner for the three samples of sand. It can be noticed that as the sieve diameter increases, the value of the deposition intensity increases. The results suggested that the value of DI substantially depends on the particle size distribution of the sample, particularly the mean particle size (D_{50}). For the same value of d, it can be seen that the larger the value of D_{50} is, the smaller the obtained DI will be. This observation might be explained by the fact that arching and friction in fine sand are less than those in coarse sand, leading to an increase in the velocity at which sand particles exit the sieve openings, resulting in a higher rate of flow for fine sand than that observed in coarse sand. To avoid unnecessary complexity, the variation can be considered approximately linear, especially beyond d = 4 mm onwards. This linear tendency can be clearly observed in Fig. 6 when d is normalized with D_{50}. Some researchers

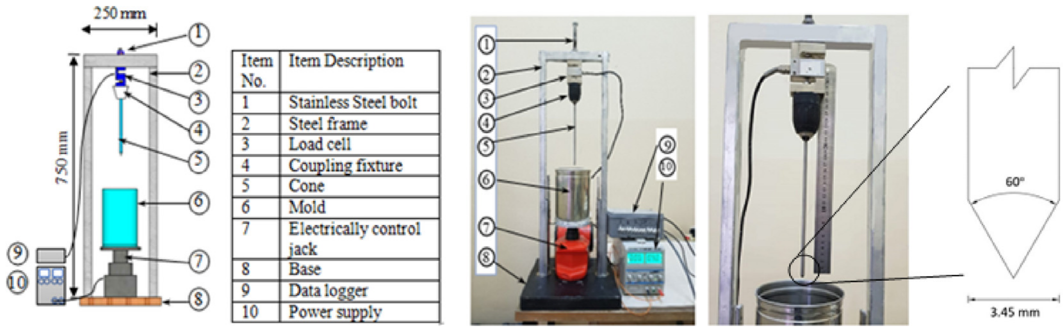


Fig. 4. Details of CPT test.

Table 2
Details of samples prepared for CPT testing.

Sample type	HD (cm)	*d* (mm)	RD (%)	Description
Sand A	5	4	9	Very loose
Sand A	25	4	26	Loose
Sand B	20	4	45	Medium
Sand B	30	4	58	Medium
Sand C	25	4	76	Dense
Sand C	40	4	87	Very Dense

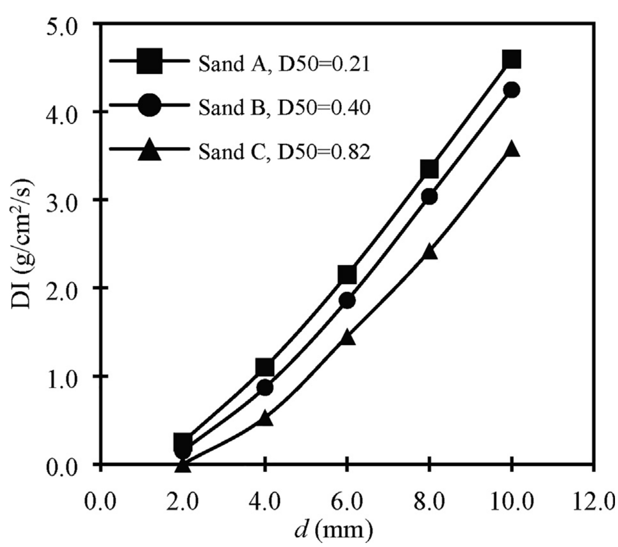


Fig. 5. Variation of DI with sieve diameter (d) for different sand samples.

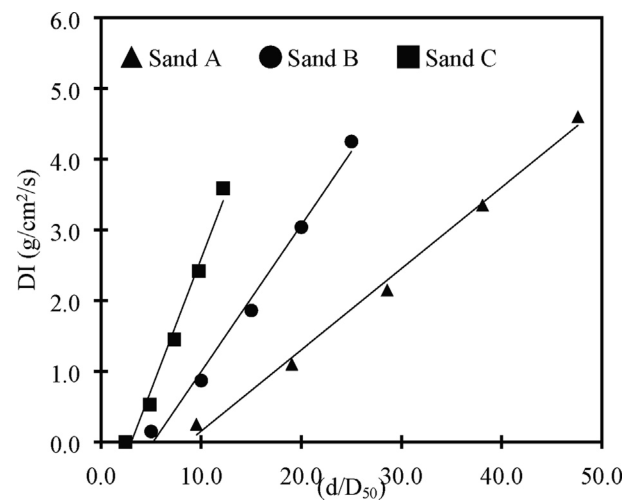


Fig. 6. Effect of d/D_{50} value on the calculated DI.

have suggested a nonlinear or quadratic variation with very little curvature (e.g., Gade and Dasaka, 2016; Dastpak et al., 2021). The variation in the three equations of DI-d/D_{50} relationships adopted in Fig. 6, in addition to the different relationships and curves gained by other researchers, makes the comparison and even the classification of sand into a certain group not valid for this type of experiment. This is because of the unlimited options of grain size distributions involved in different sand samples.

The influence of the height of drop (HD) on the relative density (RD) was investigated by varying HD = 5 – 60 cm for the three sand samples. Each test was repeated three times, and the average weight was considered in the calculation of sand density. It was noted that the differences in weighted samples were approximately negligible, with no more than a 1% difference in weight. These results suggested that the pluviation technique is reliable for obtaining repeatable samples of sand.

Fig. 7(a), (b), and (c) present the variation of RD at different values of HD for Sand A, B, and C, respectively. It can be seen that, in general, the RD-HD relationship is approximately linear at the very early stages of pluviation (HD = 5–15 cm). A sharp increase in the density can be observed for coarse samples pluviated from small opening sizes. This linear variation is followed by a distinct nonlinear relationship up to about 20–40 cm of HD, and finally, a constant relative density is achieved. The value or the range of HD at which each of these stages starts or continues is a function of the sand type and deposition intensity. The measured RD increases linearly with the increase of HD as a result of increasing the impact energy of falling sand. When HD reaches a certain value, the RD reaches its maximum value and remains constant despite the continuous increase in HD. The height at which the effect of raining sand becomes negligible is a function of the sand type and sieve size and is known as the critical HD. Beyond this height, it is not important to pay any attention to the height of the drop, as the density will not change. Moreover, it can be recognized that low relative densities were achieved by pluviating sand using a large diameter of sieve openings accompanied by high deposition intensity. On the other hand, as the value of (d) reduces, the deposition intensity reduces, resulting in increasing the obtained relative density of samples. Moreover, Fig. 7 shows that when low relative densities are required, the concept of constant HD should be adopted. This is due to the high sensitivity of the density to the value of HD at the early stages of pluviation. Therefore, it is important to avoid any variation of HD during the deposition process.

For Sand A, Fig. 7(a) shows that the critical HD ranges from 20 cm at d = 10 mm to 35 cm at d = 2 mm. For the range of sieve

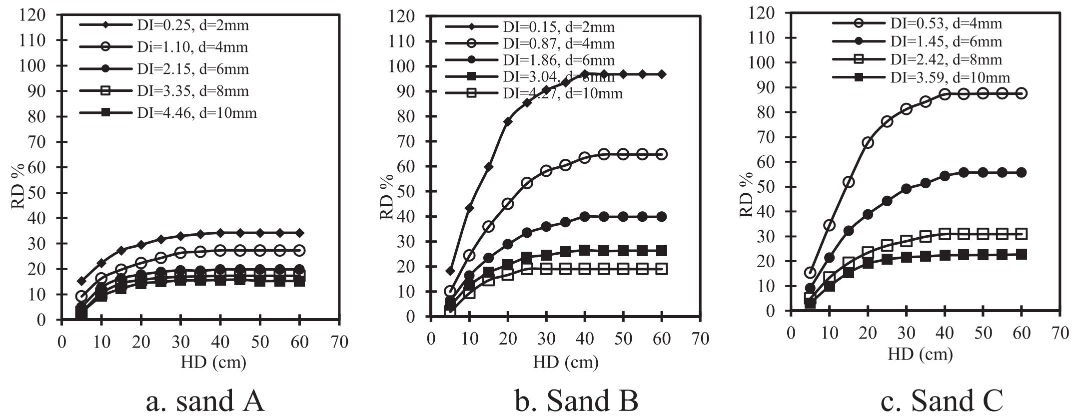


Fig. 7. Effect of the height of the drop on the relative density.

opening size adopted, it is noted that the range at which the relative density changes is small (3% at HD = 5 cm to 35% at HD = 35 cm). In other words, medium or dense samples can not be obtained for this type of sand using the current pluviation technique. Moreover, the results suggest that, even by reducing the rate of flow, the relative density can not be increased to more than 35%. The limited influence of the height of the drop and deposition intensity on the obtained relative density can be attributed to the nature of very fine particles of Sand A. Similar results were observed by (Khari et al., 2014) for samples of fine sand and by (Hakhamaneshi et al., 2016) when the mesh diameter exceeded 2 mm.

The importance of including coarser particles of sand to obtain a wide range of relative density can be shown clearly in Fig. 7(b) and Fig. 6(c) for the remaining two samples (B and C), respectively. The wider range of RD is achieved when Sand B was used in the experiments (RD = 5%–97%). Also, for Sand B, it can be seen that at d = 2 mm, the obtained RDs are in the range of 18% to 97%. This is to say that the desired state of density for this type of sand can be achieved by changing the HDs only without giving much attention to the deposition intensity. On the other hand, the maximum RD obtained by Sand C is 87%. It should be pointed out that the arching phenomenon has appeared in Sand C after a few times of pluviation through the smallest sieve opening (d = 2 mm), leading to an interruption of sand flow. This is why the curve of d = 2 mm does not appear in Fig. 7(c). The blocking or non-continuous flow of sand for lens-shaped openings is expected, especially when relatively coarse sand is used in conjunction with the small opening size of the sieve. One of the methods used to overcome arching phenomena is vibrating the sieving system. However, this method needs an additional apparatus to be attached to the main frame, making the procedure more complicated. The vibration applied to the system needs to be conducted very carefully so that the same vibration energy is applied for each sample. Manual vibration cannot be adopted as this process is not easy to control. Therefore, the vibration process has been ignored for the samples' preparation.

Fig. 8 depicts the variation of relative density obtained at various values of deposition intensity. It can be seen that the rate at which the relative density decreases with increasing the value of DI is not the same for each height of the drop. The figure shows the great influence of the deposition intensity on the value of relative density obtained, especially for sands of coarse fraction due to the high impact of their particles.

Fig. 9 illustrates CPT test results for the three samples of sand. Considering the test result at the center of the sample as a reference, a slight variation of results can be observed at all other test points. This variation can be attributed to the boundary interaction effect and also to the disturbance that occurs when the same sample is penetrated many times during the CPT test. In general, it can be seen that the measured penetration resistance increased with the increase of penetration depth as a result of soil discharge.

The penetration resistance-depth relationships for Sand A show a slight curvature with curves concave downwards for both values of RD (Fig. 9(a) and (b)). For Sand B, it can be seen from Fig. 9(c) and (d) that the measured penetration resistance keeps, almost linearly increasing with the depth of penetration. The results of Sand C with RD = 76% show that the penetration resistance is increasing

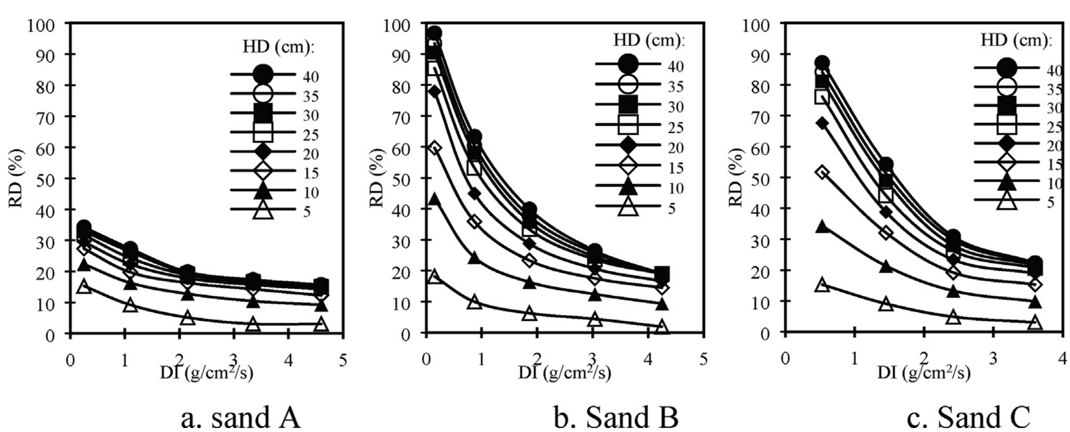


Fig. 8. Variation of DR at various values of DI.

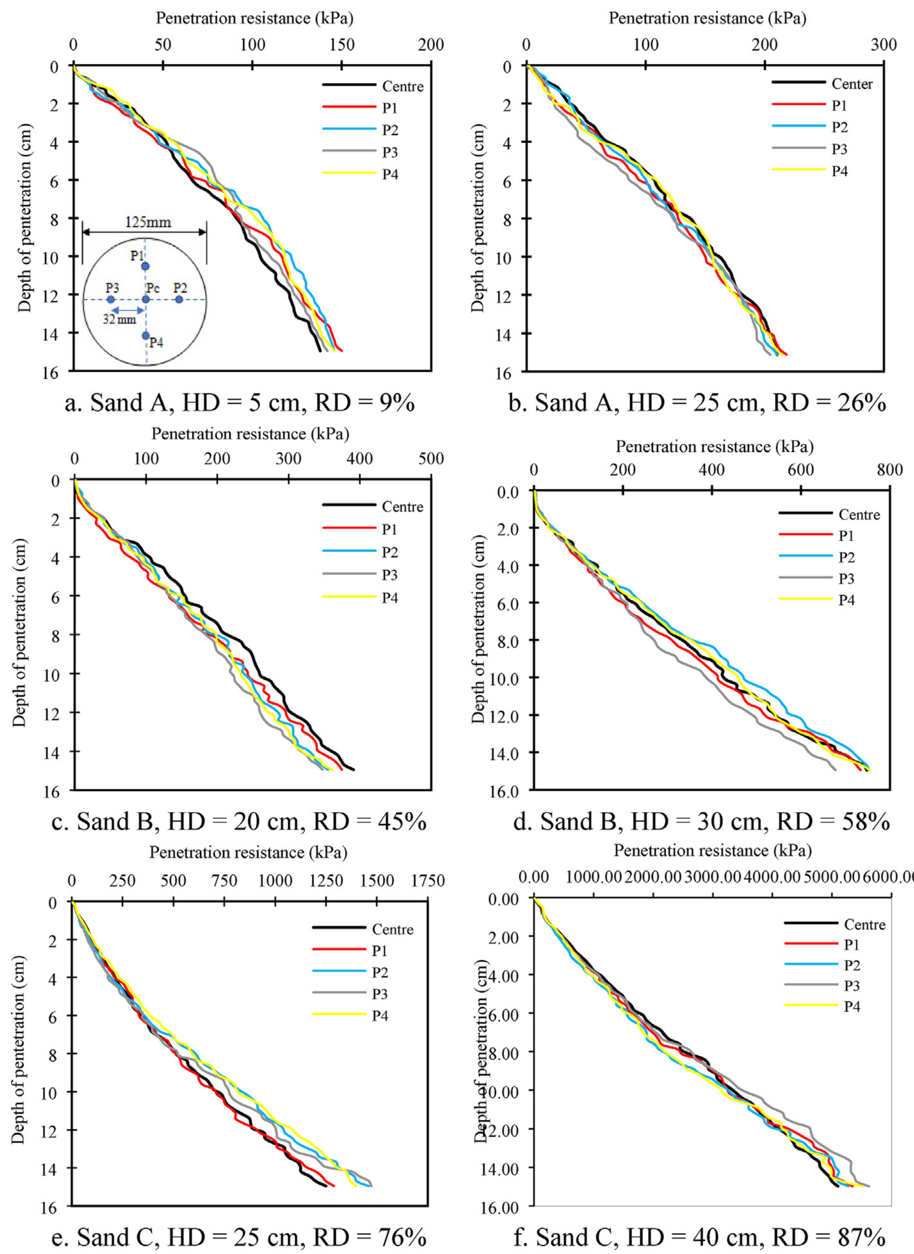


Fig. 9. CPT test results.

with a slightly nonlinear rate against the penetration depth (Fig. 9 (e)). On the other hand, this sand showed an almost linear relationship at RD = 87% (Fig. 9(f)). However, the difference in CPT values measured at every RD value for all samples is recognizable.

In general, CPT results for the three samples of the sand show three different trends of results; a slightly nonlinear relationship with curves concave downward for Sand A, a linear relationship for Sand B, and a linear to a slightly nonlinear trend with curves concave upward was noticed for Sand C. Theoretically, the penetration resistance of homogenous sand should increase linearly throughout the depth (Baghdadi et al., 1990). This expected behavior is due to the uniform discharge load caused by the soil density, which is assumed to be the same over the specimen's depth. However, this ideal response is difficult to obtain experimentally due to different reasons. The small specimens used with shallow penetration depth might be the main reason. In large-scale experiments, this depth is usually ignored in presenting results. Another reason is the sensitivity of the load cell used to measure the resisting force. The recorded resisting force at shallow depths is very small compared to the high capacity of the load cell used, causing the signal reading to fluctuate. Human errors could be one of the sources of this variation of penetrometer readings. Furthermore, boundary effects may play an important role in obtaining incorrect results. Finally, if all possible reasons mentioned above are checked, the most likely reason will be the non-uniformity of the sand bed. Most of the available research in the literature has shown some variation of obtained results from the ideal response expected theoretically (Al-Shibli 1996, Aldefae 2019, Gade and Dasaka 2016). The relationships obtained were nonlinear, with curves concave slightly to extremely upward or downward.

For the purpose of comparison, CPT test results at the center of each sample prepared at different values of RD are presented in Fig. 10.

Another set of tests was carried out to investigate the effect of layering on the uniformity of the sample. The sand was poured into the mold in the form of layers with a thickness of 5 cm per layer. After the completion of pouring a layer, the sand container was raised up 5 cm, and the raining was started again. The process

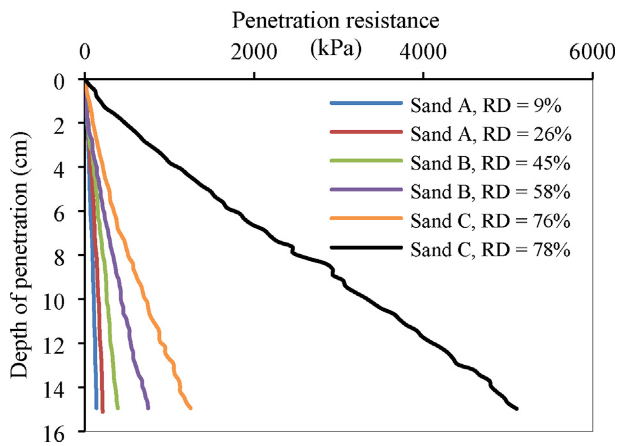


Fig. 10. CPT test results of Sand samples measured at the center.

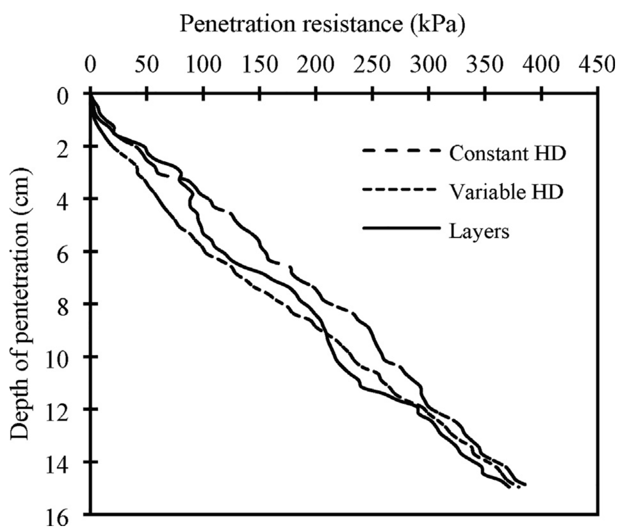


Fig. 11. Effect of the pluviation method on the uniformity of samples.

was repeated until filling the mold. As the total depth of the mold is 175 mm, the top layer had a thickness of 25 mm. The tests were carried out with an initial value of HD of 20 cm. A sample of Sand B poured through the sieve of 4 mm opening size was used in this test. The results of the layering effect were compared with the results of two cases, which are the constant HD and the variable HD. In the case of variable HD, the sand container was fixed in its position without lifting it up to follow the sand rising in the collecting mold as in the case of variable HD.

Fig. 11 shows the influence of layering, constant HD, and variable HD on the penetration results. It can be seen that the case of constant HD gives higher values of penetration resistance (i.e., density) compared to the other two cases. This response can be attributed to the continuous rising of the sand container during the pluviation process. In the case of variable HD, while the thickness of the sand deposit builds up inside the collecting mold, the density decreases gradually from bottom to top. On the other hand, the non-uniformity of penetration resistance values involved in layering test results can be clearly observed, especially at the successive layers interface.

5. Conclusion

This paper describes a newly designed and fabricated air pluviation apparatus used to reconstitute small specimens of dry sand. Three types of sand were rained using five different sieve opening sizes positioned at various heights of drops. On the basis of the results and discussion shown previously, the following conclusions can be drawn:

- In order to obtain a wide range of relative densities, the sand used should be selected carefully. A calibration study can be carried out on a number of sieved samples to choose the most suitable sample which can give the desired relative density. It is found that Sand B gives a wider range of relative density (5 – 97%) compared to others.
- The obtained relative density is found to be a function of the rate of deposition, the height of the drop, and grain size distribution. High values of RD are obtained when small sieve opening sizes are used (i.e., at small values of DI). On the other hand, the RD-HD relationship consists of three distinct zones; an early linear variation followed by a nonlinear relationship and finished with a constant relative density even with the continuous increase of HD.
- When loose to very loose samples are desired, fine sands with relatively large sieve opening sizes can be used without much attention to the height of the drop.
- Results showed that adopting the constant HD concept can increase the sand density obtained compared to the case of variable HD.
- More uniform samples can be obtained using the constant HD concept. However, the uniformity index (CPT test results) for this concept showed a slight variation for some types of sand from the ideal response. Based on the CPT test results of the current study, with results available in the literature, the uniformity of poured sand can be classified into four states; linear uniformity, nonlinear uniformity, fluctuated uniformity, and non-uniformity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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