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A CALIBRATION OF AN AIR PLUVIATION SYSTEM USED TO RECONSTITUTE LARGE SPECIMENS OF SAND

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ABSTRACT: In physical modeling of geotechnical problems, the difficulty in preparing uniform deposits of granular soil or simulating the in-situ soil conditions increases as the size of the testing box increases. Special care should be provided to the soil preparation process in order to maintain trusted results in a repeated manner. In addition to striving to obtain reliable results, the method used, including the time spent and human effort expended, must be taken into consideration. In this study, a carefully designed and fabricated air pluviation apparatus is used to rain the sand uniformly and homogeneously over the area of the box. Many distinctive features were adopted in the design of the apparatus, such as emptying the box and restoring the sand automatically and getting rid of the dust outside the testing room, which both contribute positively to the health and productivity of the workers and to the quality of the job. In order to prepare a calibration database for a specific type of sand, a series of calibration tests was carried out to measure the density of sand with respect to the height of drop (HD) and the opening size of the perforated plate. It is found that the value of critical HD that achieves the maximum density depends on the porosity of the perforated plate, with a direct relationship between them. The porosity is also the critical factor that determines the density of sand at a certain value of HD. The obtained density can be increased by reducing the opening sieve size for a specific drop height.

Keywords: Sand pluviation; Sand density, Laboratory tests, Height of drop; Uniform samples.

1. INTRODUCTION

One of the major difficulties that geotechnical researchers face when conducting laboratory tests is obtaining the required density of sand in the testing box. The challenge increases when this density is to be maintained in a repeated manner for all parameters that are planned to be investigated. The accurate preparation of sand deposit leads to a precise prediction of the response of model tests in both 1-g and centrifuge modelling. A variety of procedures were suggested to control the soil density in laboratory tests. In order to gain a high level of confidence in results, the design of the density control apparatus should meet the following requirements:

- The ability to distribute the sand evenly and uniformly over the whole area of the box.
- A wide range of the desired densities or natural states of sand is guaranteed.
- It is preferable that the whole process or, at least, some important steps should be performed automatically and, as much as possible, free of human errors. Experiments that involve repeatedly filling and emptying a test box with sand are stressful for laboratory workers, which may increase the possibility of human errors.

Filling and emptying the testing box for repeated tests should be carried out within a short time and a minimum of human effort.

In addition, simplicity in the design of the apparatus is desired. Although several studies have been performed taking into account most of the above requirements, literature indicates that no standard method for sand preparation with a specific procedure has yet been adopted. However, air pluviation is one of the most widely used techniques to reconstitute granular soil [1-5]. This is due to its ability to provide the important components required for a successful sand preparation system. In this method, sand with a predetermined gradation is allowed to be poured from a constant or variable height into the container. Authors in [6] showed that the pluviation method is preferable when compared to the tamping technique when triaxial samples are required. Literature shows that the air pluviation can be classified into three distinguished procedures:

- A nozzle or a funnel with a certain diameter is used to pour the sand over the area of interest [7-9].
- A curtain moves back and forth continuously until the testing box is filled [10, 11].
- A sieve or a set of sieves rain the sand evenly over the cross-sectional area of the box [12, 13].

The sand fall height can be fixed, changed manually or changed automatically while the sand deposit is built up.

A general view of the previous research shows that extreme densities (very loose and very dense) can be achieved more easily than any other density in between. For example, a simple funnel with a little height of drop can be used for very loose sand. On the other hand, any pluviation method with a relatively large height of drop can offer sand in dense to very dense state.

Several attempts have been carried out to understand the factors influencing the resulting sand density. The majority of these attempts have focused on preparing small specimens of sand for triaxial and shear box tests [14-16]. Only limited studies have considered filling large boxes with sand [17, 18]. Large specimens are required when preparing, for example, soil-foundation interaction tests in both 1-g and centrifuge models. Although preparing small or large specimens shares, at most, the same influencing factors, it is known that manufacturing the raining system and controlling the whole process becomes more difficult as the specimen size increases. The effort and time required to fill and empty the testing box repeatedly are serious challenges in this kind of tests.

Regarding the height of sand drop (HD) which defines as the distance measured from the sieve or nozzle to the top surface of sand inside the box, raining systems can be divided into three categories:

- Stationary height of drop, in which the sieve or nozzle is set at a fixed level during the whole process of raining [19]. Although this procedure is time saving, uniform samples of a large size can not be guaranteed as the HD continues to decrease during the pluviation process, making the density decreases gradually as we move to the top of the box. However, this procedure can be successively used when the maximum possible density is required, in which the value of the HD adopted is greater than a critical value, which will be discussed later.
- The height of the drop is automatically lifted up at the same rate that the sand deposited in the box is increased [20]. This technique ensures unchanging the HD, which leads to more uniform samples. This procedure can be adopted relatively easily when small specimens are required. However, for large specimens, providing the automatic motion of the pluviator is difficult and makes the manufacturing of the apparatus more complicated.
- The height of the drop is adjusted manually by repeatedly shifting its position up after a certain height of the sand is pluviated inside the box. Although layers can be built, reasonable results can be achieved compared to the method of a stationary height of drop.

It is known that soil density is related to the volume of voids in a soil sample. Raining the sand can control the volume of voids with the proper selection of raining intensity and drop height. Three physical principles contribute to this result of the sand raining process, which are: particle rearrangement, settling under gravity and dynamic compaction.

Authors in [21] have divided the sand pluviated through the raining process into three layers starting from the base of the container as: settled sand, energetic layer which is affected by the upcoming sand particles, and top turbulence zone. However, the scenario of raining starting from leaving the sand particles the perforated plate until the resting of particles in their final position inside the testing box contains different stages of energy losses [22]. One of the major losses in this short journey is due to the collisions of the different-sized sand particles along the falling path under air resistance. The energy losses resulting from this collision are not equal in magnitude across the projected cross-sectional area of the falling sand, as the air turbulence generated by the falling sand differs in intensity and effect according to its location. The influence of collisions continues after the initial resting, where other upcoming particles cause rearrangement of already deposited particles. In addition, loose sand tends to densify as the upcoming particles build layers work as an overburden pressure resulting in an increase in the compaction energy that applies to the bottom layers [23].

In the current study, a versatile sand pluviation apparatus named (G-TA), which refers to Geotechnical Testing Apparatus, is designed and manufactured to carry out geotechnical tests and to densify the sand inside a relatively large testing box. The essential control parameter to calibrate the apparatus is its ability to produce a uniform rate of sand flow over the testing box. The calibration was performed by measuring the density of sand collected by small molds placed inside the box.

In addition to the above review, the article includes a detailed description of the sand pluviation apparatus used, including its parts, specifications and how to use. Moreover, the experimental results section assesses and calibrates the results by measuring the density of sand falling from various heights into nine molds distributed over the cross-sectional area of the box.

2. RESEARCH SIGNIFICANCE

The significance of this research lies in considering some aspects that have been neglected in designing sand raining apparatus in previous studies. It is believed that factors such as changing the drop height continuously during sand raining, reducing human efforts and speeding up the filling-emptying process are pretty important in both academic research and practical geotechnical engineering applications. Most of the previous studies have not specifically focused on these factors.

3. DESCRIPTION OF THE APPARATUS

As shown in Fig. 1, the apparatus (G-TSP) consists mainly of four parts which are: the testing box, the main frame, the perforated plate and the rigid sand hopper.

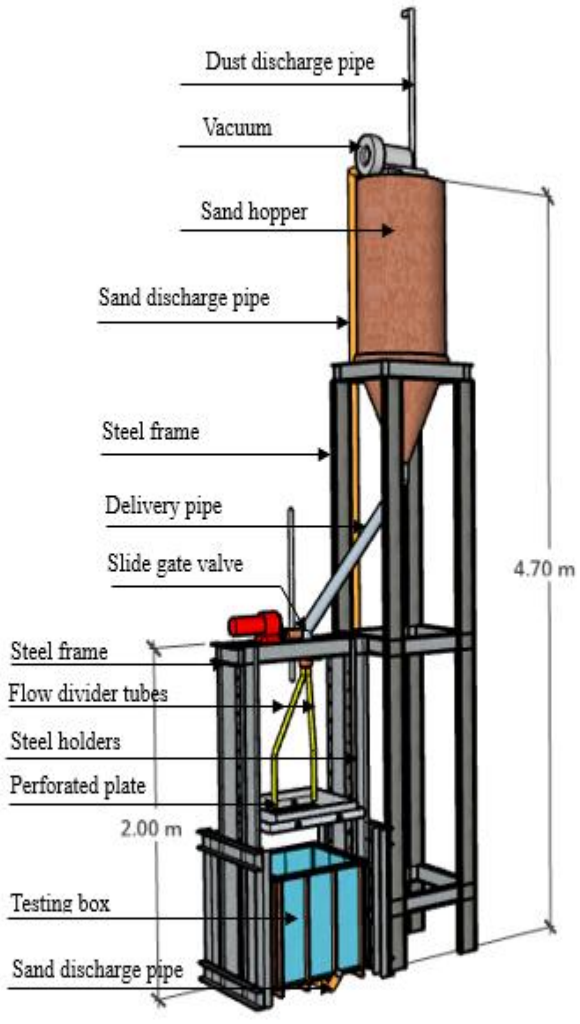


Fig. 1 Main parts of the apparatus (G-TA)

The testing box was made of a steel frame with clear Perspex Acrylic sheets of 10 mm thickness on four side walls and a bottom base. The internal dimensions of the box are 600 × 600 × 600 mm. A circular hole was made at the base of the box and connected to a discharge pipe (Fig. 2). By using a vacuum motor placed at the top of the sand hopper, an effective sand discharge system was created that allows the sand to be automatically recycled from the box and returned to the hopper within 30–35 minutes. The vacuum motor used has a power of 2.2 kW and a maximum air flow of 265 m^3/hr. An air entrance pipe was added to avoid clogging of the discharge pipe by sand, as shown in Fig. 2. This technique ensures that the discharge process is carried out without human effort and in a relatively short time. In fact, the effort expended in the process of emptying the box and then restoring the sand into the hopper and the time spent in this process are two critical factors when this process is performed manually, especially when repeated tests are required. Moreover, this technique involved user safety considerations.

The main frame, which consists of four columns connected by transverse beams, was designed to accomplish two functions: to work as a reaction frame and to hold the perforated plate by means of steel holders (see Fig. 1). The holders were welded to the steel columns at equal intervals (100 mm) along their height. Therefore, the height of drop can be adjusted by increasing it up every 100 mm of sand deposition thickness. In this manner, the drop height is held unchanged and the sand is allowed to rain until 100 mm of the box is filled with sand. Subsequently, the perforated plate is manually shifted up to the next level and the sand is allowed to rain again. This process is repeated until the box is filled to the desired height. It is important to mention that when there is a need to start the filling process from a small height (less than the height of the box), the perforated plate can be inserted inside the box, where it can be fixed at the required height using four temporary steel legs. Holes are made in the steel legs spaced 100 mm apart, with an ability to reduce the spacing to 50 mm when required. The steel legs are removed when the perforated plate reaches the top edge of the box.

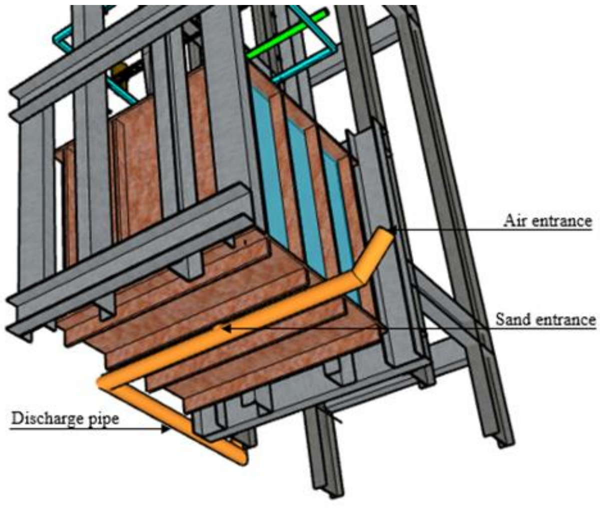


Fig. 2 Discharge pipe details (a view from the bottom of the box)

The perforated plates were made of steel plates of 3 mm thick and 570 × 570 mm in cross section with different diameters of holes, *d* (4, 6, 8 and 10 mm). Literature showed that these values of diameter may produce a wide range of sand densities. An external metal frame of depth 100 mm was made and welded to each perforated plate, as shown in Fig. 3. From now onwards, the perforated plate with its frame is referred as the sieve.

The sand hopper was formed from a cast iron plate with circular and conical cross sections at its top and bottom, respectively, and can store 0.35 m^3 of sand.

The hopper was mounted on 4-leg steel frame with a total fixed height of 4.5 m. To deliver the sand freely from the hopper, a semi-rigid outlet reinforced pipe of 50 mm in diameter was installed at the bottom of the sand hopper. The pipe is split into two flexible tubes, which in turn distribute the sand into the sieve. A steel plate stopper in the form of a slide gate valve was inserted at the end of the delivery pipe to control sand flow.

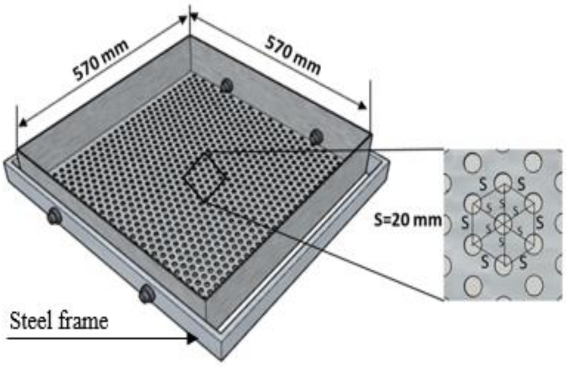


Fig. 3 The perforated plate

It is worth noting that the dust associated with the sand that is restored in the hopper is removed by pulling it out of the testing room using the vacuum and a pipe with outlet diameter of 50 mm that are illustrated in Fig. 4.

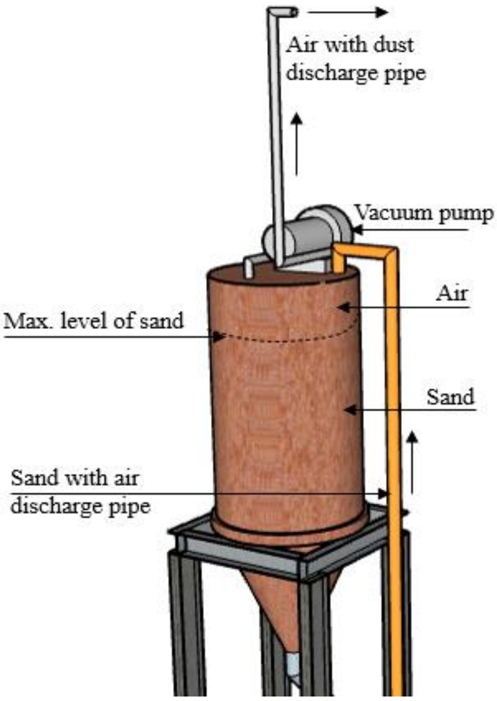


Fig. 4 Dust Discharge Details

This procedure helps to reduce the dust that consists as a result of the abrasion of sand particles throughout the different stages of sand raining. As questions can be raised about the safety of laboratory workers, reducing the sand powder is essential for the personal health of workers. In addition, this procedure may contribute to maintaining, as much as possible, the original gradation of sand.

The following steps were applied to fill the box with sand, starting from an empty box. The four temporary steel legs are inserted inside the box, and then the sieve is set at the required height inside the box by bolting the external frame of the perforated plate to the temporary steel legs. A flexible plastic stopper is set to cover the whole area of the perforated plate prior to the sand being allowed to flow to fill the sieve. After filling the sieve, the stopper, then, is quickly removed manually in order to allow the sand to rain inside the box uniformly. As mentioned previously, the steps above are performed only when the required height of the sieve is located within the depth of the box. Otherwise, the sieve is fitted above the box by means of the steel holders welded to the main frame. The same process is repeated until the testing box is filled with sand. A schematic flow diagram summarizing sand circulation is shown in Fig. 5.

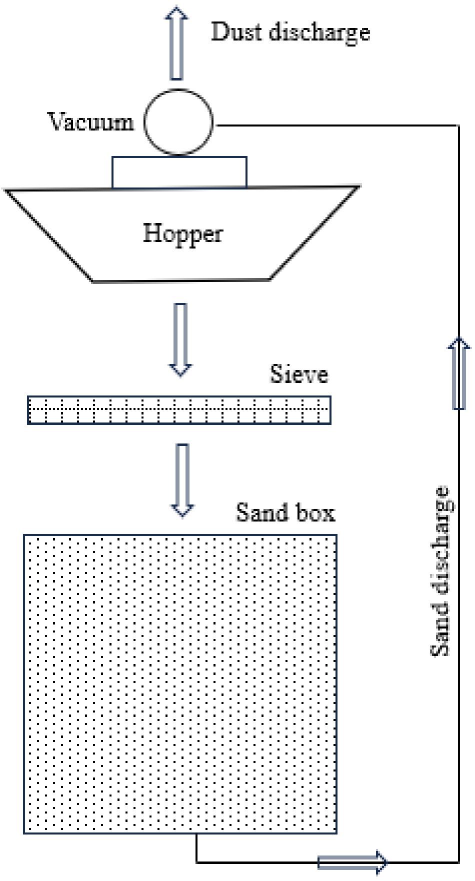


Fig. 5 Flow diagram summarizing sand circulation

4. RESULTS AND DISCUSSION

Measuring the density of the sand at various locations over the cross-sectional area of the box is the factor that determines the uniformity of the sand being poured. Previous studies have reported a number of techniques used to assess the uniformity of sand in both vertical and horizontal directions of the testing box. These techniques can be found in [2] and [24]. The most easily and widely used method is collecting the poured sand in molds that are placed at a certain level inside the box, and in the current study this method is adopted to measure the sand density by using 9 molds of 285 cm^3 volume each (Fig. 6).

Fig. 6 Locations of molds used to measure sand density

Each test was repeated three times and the average weight of the sand that was poured into the molds is considered in the calculations of density. The molds were placed at equally spaced positions and filled during each run. After every test, molds were emptied, cleaned, and repositioned to minimize positional bias.The grain size distribution and physical properties of sand used in the tests are illustrated in Fig. 7 and Table 1, respectively.

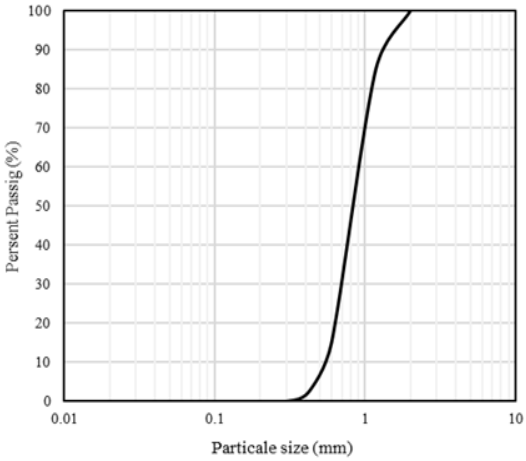


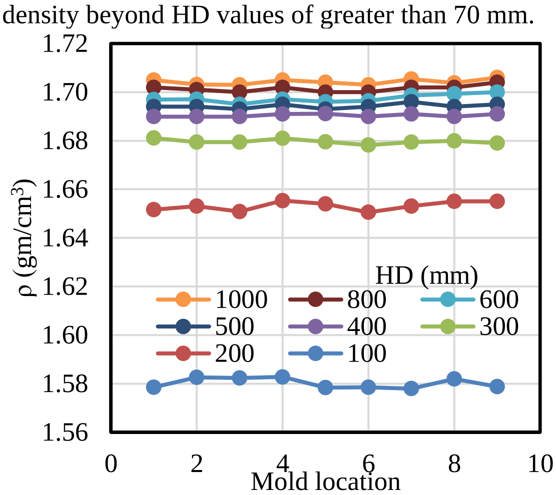
Fig. 7 Particle size distribution of the sand

Figure 8 shows the relationship between the height of drop (HD) and the produced density of sand collected by the 9 calibration molds using 4 different opening size of the perforated plates, i.e., (4, 6, 8 and 10 mm). It can be seen that the difference in the measured horizontal densities is small, with a maximum variation of 1%. This result indicates that the horizontal homogeneity of the reconstituted sample is achieved. Moreover, it can be seen that the rate of increasing density with increasing the HD decreases as the HD increases.

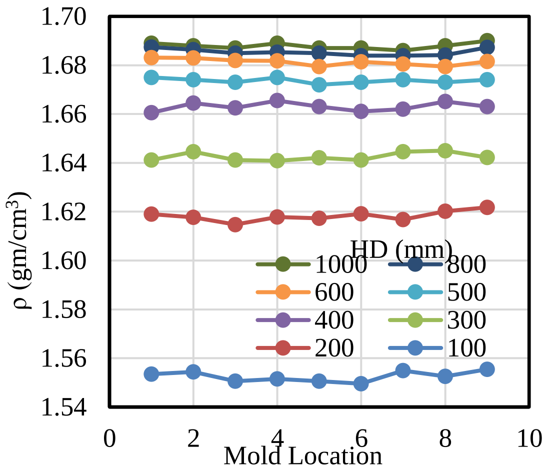
Table 1. Properties of the sand

Parameter	Value
D_{10} (mm)	0.60
D_{30} (mm)	0.72
D_{50} (mm)	0.83
D_{60} (mm)	0.90
C_u	1.56
C_c	1.32
ρ_{min}	0.58
ρ_{max}	0.76
G_s	2.65

In other words, the height of the drop gradually loses its control over the obtained density as its value increases. This trend can be seen clearly in Fig. 9 for *d* = 4 and 6 mm, as there is no significant increase in density beyond HD values of greater than 70 mm.

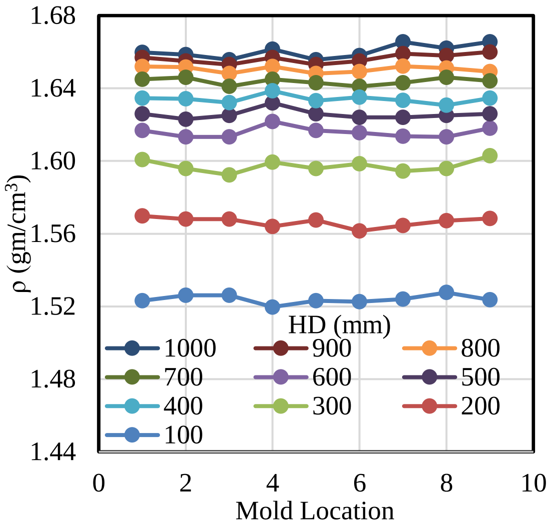


(a) *d* = 4 mm

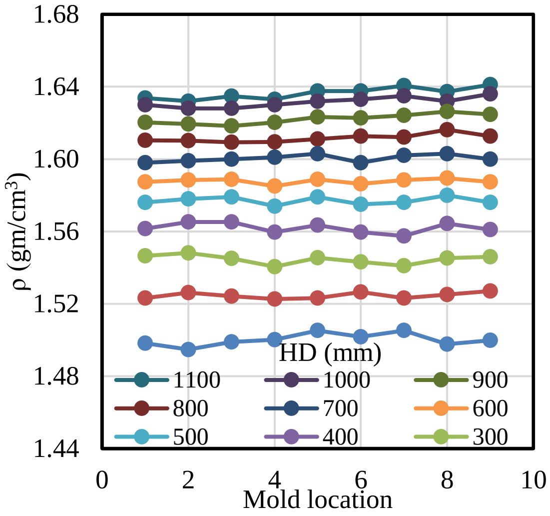


(b) *d* = 6 mm

Fig.8a,b Variation of sand density in the horizontal direction at different HD



(c) *d* = 8 mm



(d) *d* = 10 mm

Fig.8c,d Variation of sand density in the horizontal direction at different HD

The value of HD beyond which a constant density is achieved is known as the critical HD. This finding supports previous studies which linked terminal velocity, which is the maximum velocity that soil particles reach during the raining path, to the value of critical HD [25, 26]. On the other hand, as the sieve opening size increases, the value of critical HD required to gain a constant density increases. However, the graphs of $d = 8$ and 10 mm did not show a constant density in the range of tested HD (up to 1000 mm). The pronounced effect of HD at greater sieve porosity can be observed by comparing the results of $d = 4$ and 6 mm against the results of $d = 8$ and 10 mm in Fig. 9. Fig. 9 shows, also, that the obtained density can be increased by reducing the opening sieve size for a specific drop height. This can be attributed to the time taken to pluviate the sand. It is known that less time is required to rain a quantity of sand when using coarse sieve sizes compared to fine ones. Therefore, with the use of a large opening size of the sieve, the particles that exist in the energetic zone do not take enough time to reposition to fill the voids [21].

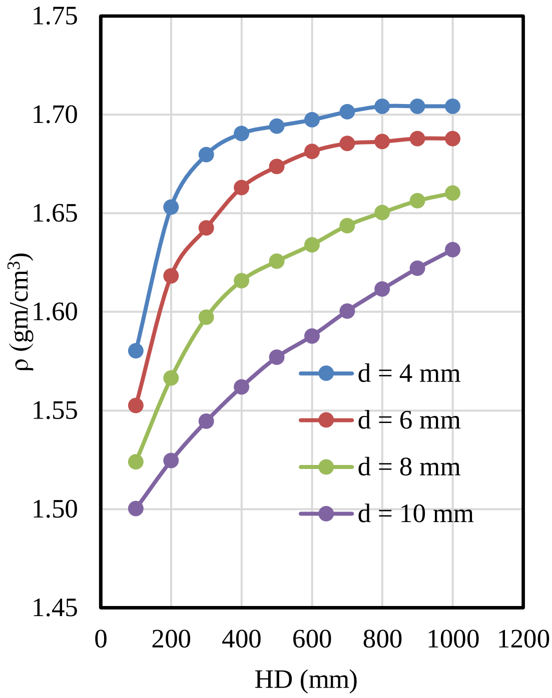


Fig. 9 Effect of HD on sand density for different values of *d*

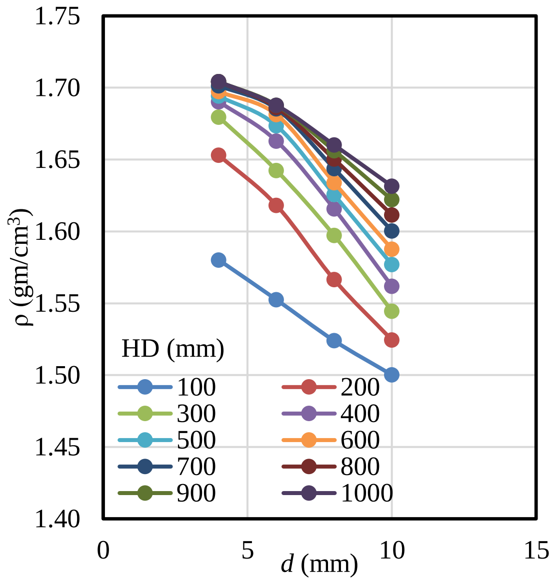


Fig. 10 Variation of sand density with *d* at different values of HD

The variation of density with the value of *d* is illustrated in Fig. 10. It can be seen that the rate at which the density increases with reducing the value of *d* is not constant for each value of the height of drop. However, the relationship is almost linear for the range of *d* lies between 6 and 10 mm. Once a smaller value of d is considered (i.e., $d = 4$ mm), this linearity is not guaranteed.

5. CONCLUSION

In the current study, a sand pluviation apparatus has been designed, manufactured and calibrated to investigate its capability to prepare uniform large-scale samples of sand. The apparatus was developed taking into account some requirements that seem to be important for quickly carrying out the tests and reducing the human effort and health hazards. An automatic vacuum system was used to empty the box and restore the sand inside the hopper. Moreover, as an attempt to reduce the health hazards that workers can face, the apparatus was designed to get rid of dust that results from crushing and friction of sand particles. The calibration was conducted by measuring the density of sand falling into small molds distributed over the cross-sectional area of the box. The horizontal homogeneity of the reconstituted sample was achieved as there was no considerable difference in the magnitudes of density measured. The required density can be achieved by choosing the diameter of the sieve opening and the height of drop, which are the main factors that control the value of density for a specific type of sand. However, the study provides additional evidence that no further increase in the density is obtained beyond a critical height of drop. The value of critical HD that achieves the maximum density depends on the porosity of the perforated plate with a direct relationship between them. The porosity is also the critical factor that determines the density of sand at a certain value of HD. The obtained density can be increased by reducing the opening sieve size for a specific drop height.

It is important to mention that the presented calibration is specific to the tested sand. Future works can be extended to include sands of different grading to generalize calibration. However, the observed trends of results can guide calibration for other sands after similar verification.

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