



DEVELOPMENT OF AN AIR PLUVIATION METHODOLOGY FOR PREPARING UNIFORM MODEL GROUND USING SAND

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ABSTRACT: Laboratory model tests are extensively employed to examine soil behavior and validate numerical analyses. However, the preparation of dense, uniform and reproducible model grounds continues to pose difficulties, particularly when utilizing basic laboratory apparatus with space constraints. Recent studies have established various pluviation techniques utilizing air, water, or vacuum to reconstruct soil models. This paper presents a simple air-pluviation technique for creating dense and highly uniform model ground in laboratory settings with limited overhead space. The procedure entails determining the correlation among drop height, flow rate, and relative density within a small container, subsequently applying these findings to the actual container dimensions to prepare the model ground for experimentation. The system comprises a portable air pluviator equipped with a funnel, flow-control sieves, a fabric hose, and a supporting crane system to produce uniform model ground utilizing Toyoura sand. The developed system-generated model grounds had a coefficient of variation under 5%, indicating excellent uniformity, well within acceptable parameters for laboratory studies. The research indicates that relative density increases nonlinearly, with a progressively diminishing rate, as drop height rises, while flow rate influences relative density linearly. An empirical equation is presented to estimate the relative density as a function of drop height and flow rate for a fine-sand model substrate.

Keywords: Compaction, Model Ground, Air Pulviator, Relative Density, Model Ground Uniformity

1. INTRODUCTION

Laboratory model experiments offer a regulated approach to examine soil behavior under many loading circumstances, involving static, dynamic, and seismic stresses [1]. These studies are conducted to analyze soil behavior, calibrate constitutive models, and validate numerical simulations [2]. The outcomes of these assessments are extensively utilized in both research and engineering applications.

Consistent model ground preparation is crucial for achieving dependable experimental outcomes. Physical modeling centrifuges, calibration chambers, or 1g model boxes necessitate the preparation of soil deposits under regulated circumstances [3]. Sandy soils exhibit remarkable sensitivity to fluctuations in relative density (D_r), where minor alterations in deposition can result in substantial differences in the observed stress-strain behavior of the soil and the anticipated performance of geotechnical structures [4-5].

Different methods have been developed to reconstitute sand specimens, including tamping, vibration, and pluviation processes utilizing air, water, or vacuum [6-11]. Among these methods, air

pluviation is extensively utilized due to its ability to produce soil beds with a broad spectrum of relative densities, little particle segregation, and excellent repeatability [12-13]. Air pluviators are frequently utilized in model foundation investigations [14], centrifuge research [15-16], calibration chamber trials [17], and shaking table analyses [18].

Despite their advantages, contemporary air pluviators have limitations. Stationary pluviators often fail to provide uniform depositional intensity across large soil beds, whereas portable, mobile, and robotic devices can be complex and difficult to operate [17, 19]. Furthermore, inaccuracies in sand bed preparation can directly influence experimental outcomes. For instance, estimates of pile bearing capacity may vary by up to 20% when employing inconsistent hand pouring processes, in contrast to less than 8% inaccuracy associated with better regulated pluviation systems [3].

To address these issues, researchers have consistently enhanced pluviation devices, from small-scale laboratory configurations to mobile and motorized systems capable of preparing extensive soil beds. Recent research has produced mechanized moving pluviators [13], biaxial mechanical systems [22], and mechatronic-assisted devices that provide

precise regulation of deposition parameters [3]. These advancements have enhanced the consistency of model ground preparation. However, these pluviators necessitate greater overhead clearance for installation to facilitate the preparation of the model ground.

This study presents a newly constructed air pluviator that efficiently prepares dense, homogeneous model grounds for fine-grained soils in laboratory testing, while accommodating restricted overhead space. This technique, in contrast to prior studies, achieves ideal outcomes for uniform, dense ground within the 60 cm overhead installation space limitations. This study investigates the correlations between drop height (H_d), flow rate (F_r), and the relative density of Toyoura sand to establish uniform model grounds in laboratory testing.

2. RESEARCH SIGNIFICANCE

Air pluviation is a simple technique introduced in this study for constructing model grounds in the laboratory. The new air pluviator enables the production of uniform, homogeneous sand beds with precise control of relative density and flow rate to ensure consistency and repeatability in physical model investigations under overhead space constraints. This is an important part of the procedure. If the variation in specimen preparation is reduced, the repeatability of laboratory test results for foundations, retaining structures, and other geotechnical systems tested at 1g is enhanced. This discovery provides a more accurate assessment of soil behavior and significantly enhances the utility of 1g model testing as a real-world research tool.

3. MATERIALS

Toyoura sand was used in this study because of its uniform grading and widespread use in geotechnical laboratory testing. Key physical properties of Toyoura sand [9] utilized in this research are summarized in Table 1.

Table 1. Key physical properties of Toyoura sand [9]

Property	Value
Specific gravity, G_s	2.651
Mean particle size, D_{50} (mm)	0.20
Maximum void ratio, e_{max}	0.977
Minimum void ratio, e_{min}	0.597

4. EXPERIMENTAL SETUP

The drop height and flow rate (depositional

intensity) are useful for achieving the desired relative density and uniformity in reconstituted sand model grounds. In this study, the relationships between drop height, flow rate, and relative density were studied using a smaller experimental setup. These relationships were then applied to prepare a model ground in a larger container, using a mobile air pluviator, to verify and ensure the uniformity and homogeneity of the prepared model ground [8, 9, 11]. Both experimental setups are discussed below.

4.1 Relationship Between Relative Density, Fall Height, and Flow Rate

A small setup was used to study the relationship between relative density, drop height, and flow rate. This setup included a model container, a funnel, flow-control sieves, a fabric hose, and a crane system.

A transparent acrylic container was used, as shown in Fig.1. The container measured 40 cm in diameter and 30 cm in height, with a wall thickness of 1 cm. The wall was marked every 10 cm, and the total height was divided into three equal sections.

The funnel was a cylindrical-conical component made of HDPE, with the top and bottom sections cylindrical and the middle section conical. The top cylindrical part had a diameter of 40 cm and a height of 4 cm, while the bottom cylindrical part had a diameter of 10 cm and a height of 7 cm. The height of the central conical section was 10 cm, as shown in Fig.2.

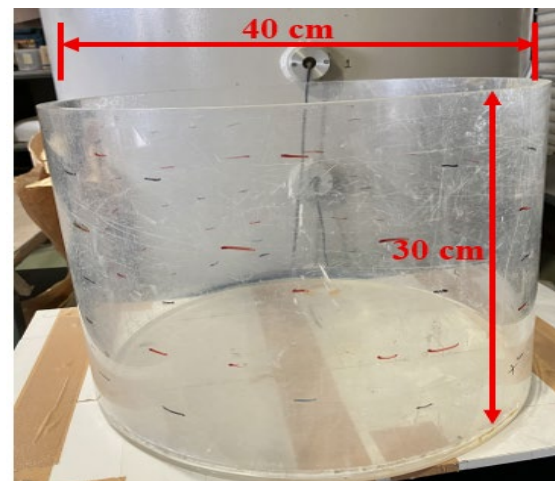


Fig.1 Model container for fall height - relative density relationships

Three small stainless-steel containers, each with a diameter of 6 cm and a depth of 2 cm, were modified by drilling 2.8-mm holes in their bases to serve as sieves to control the flow rate of sand. These

sieves are called “Head A,” “Head B,” and “Head C,” as shown in Fig.3. The sand flow rates through Head A, Head B, and Head C were 20 g/sec, 15 g/sec, and 30 g/sec, respectively. These heads were glued to the fabric hoses, which were clamped to the bottom of the funnel, as shown in Fig.4. A 2.8-ton-capacity “Street Overhead Crane” was used to lift the sand-filled funnel to the required height for container filling during sand pouring, as shown in Fig.4.

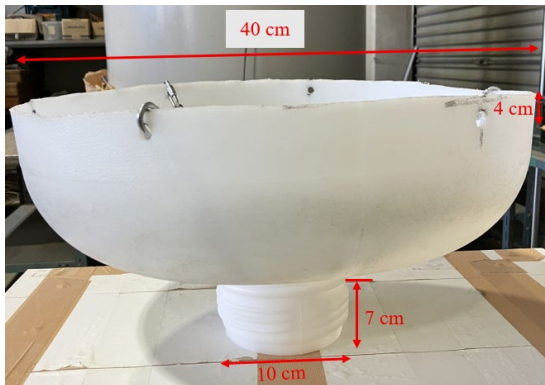


Fig.2 Cylindrical-conical for sand pouring

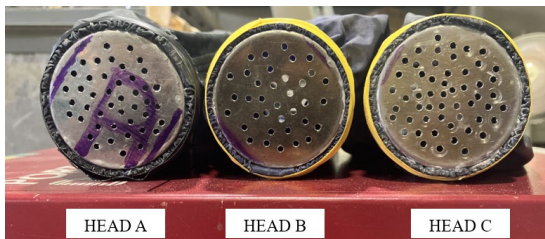


Fig.3 Sieve heads to control the flow rate of sand

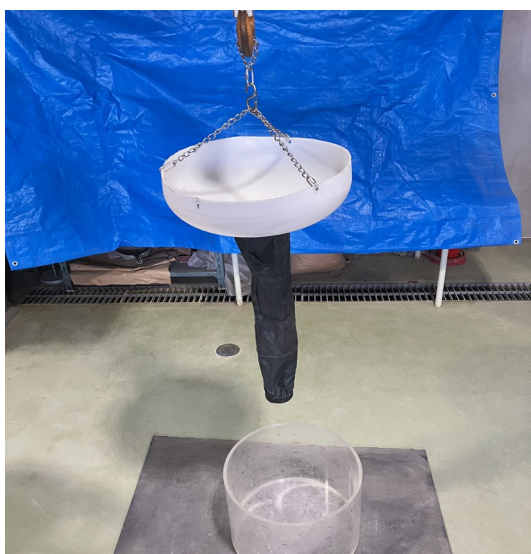


Fig.4 Experimental setup for drop height ~ relative density relationship

4.2 Uniformity of Model Ground

A steel container with a diameter of 100 cm and a height of 113 cm was used to create the model ground. A guide rail system was designed to move the funnel horizontally over the container during sand pouring to the required height, as shown in Fig.5. The funnel hung from the guide rails via chains and a hook, and its height was adjusted to the required fall height using a small chain.

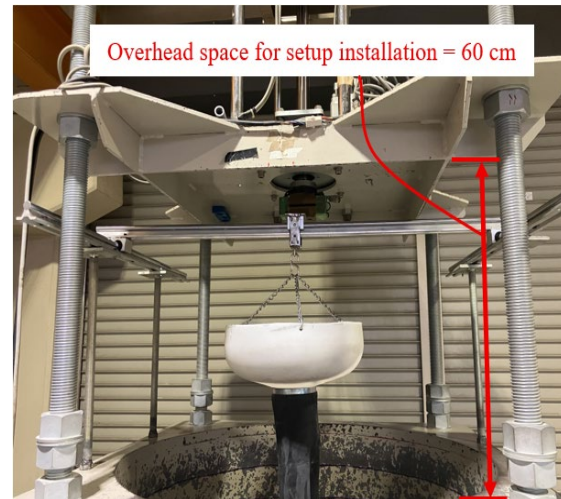


Fig.5 Experimental setup for ground uniformity verification

5. DETAILED WORKING METHODOLOGY

The overall methodology consisted of two stages: (i) establishing the relationships between relative density, drop height, and flow rate in a small container and (ii) preparation of homogeneous dense model ground in a large container using the developed relationships.

Before testing, the flow rate of each sieve head and drop height were verified. The flow rate of each sieve head (Head A, Head B, and Head C) was determined by allowing dry Toyoura sand to discharge freely for 60 seconds and measuring the discharged mass. This activity was repeated five times for each head to obtain an average value. The drop height was verified before each test using a steel measuring tape. The mass of sand used in density calculations was measured with a digital balance to an accuracy of 0.01 g.

To establish the relationship between relative density, drop height, and flow rate, the pluviator funnel was filled with a measured amount of Toyoura sand. Then, the funnel was suspended using a crane. While filling the funnel with sand and hanging it with the crane, plastic tape was applied to

the bottom of the sieve heads to prevent the sand from flowing out prematurely.

Next, the 40 cm diameter model container was positioned below the pluviator, and the height of the pluviator was adjusted to the desired drop height as shown in Fig. 4. In this study, considering the limited overhead space available for the bigger model container, i.e., 60 cm, drop heights ranging from 10 cm to 60 cm were used at 10 cm intervals to develop the relationships between relative density, flow rate and drop height. Then, sand was allowed to fill the container at each specified drop height. The mass of sand needed to fill the container was recorded, and the density was calculated from the mass and volume of the container.

By using maximum and minimum sand densities, the relative density of the model ground was measured at different drop heights. The same procedure was applied with different sieve heads to examine the effects of sand flow rate on the relative density. Relationships among drop height, sand flow rate, and relative density were established after a series of three tests for each drop height and flow rate.

To evaluate the uniformity of the model ground, each layer was prepared using established relationships among drop height, flow rate, and relative density in a 100-cm-diameter container. A system comprising a funnel, fabric hose, and sieve head was suspended from guide rails installed on the container. The container was divided into 10 equal sections, each 10 cm long. Initially, the target relative density was set to 80 % for the first 70 cm and 45 % for the remaining 30 cm, with fall heights determined from the established relationships. The amount of sand needed for a 10 cm thick layer was calculated for 80 % relative density and poured into the container using the funnel, with the appropriate drop height and sieve head. The model ground was built up in layers, reaching the 7th layer at 80 % relative density. Afterward, the soil mass required for a 10 cm layer at 45 % relative density was calculated and added layer by layer using the corresponding drop height and sieve head for the remaining 30 cm of model ground.

After preparing the model ground, its uniformity was assessed using two different methods.

In the first method, the uniformity of the ground model was assessed by measuring the relative density at various sampling points. For this, 14 small steel containers with specified dimensions and weights were used. These containers were placed at 14 points on the base of the model before pouring the sand, as shown in Fig.6. Then, sand was poured into the model container from the corresponding drop height and sieve head to achieve 80 % relative

density. After filling each small container with sand, its weight was recorded. Using the volume of each container and the weight of sand inside, the bulk density at each point was calculated. Next, the relative density at each point was determined using the minimum and maximum void ratios of Toyoura sand, along with the void ratio of the sand in each container.

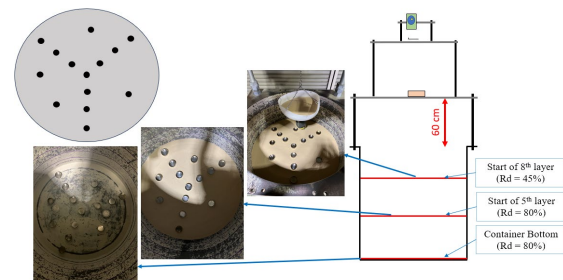


Fig.6 Ground uniformity verification at 42 sampling points by mass-volume relationships

The same procedure was used to find the relative density at 40 cm height (start of the 5th layer) and 70 cm (start of the 8th layer), as shown in Fig.6. After that, the Coefficient of Variation (COV) was calculated by determining the percentage variation of the calculated relative density from the target relative density at each point, both horizontally and vertically.

In the second method, a 0.4 cm diameter, 60 cm long needle attached to a load cell was used, as shown in Fig.7. The needle was inserted into the model ground at various points. A displacement transducer recorded the needle penetration. During insertion, the load required to penetrate the needle versus depth was recorded using a data logger. The load versus depth was then plotted for all points, and variations in the curves indicated the non-uniformity of the model ground.

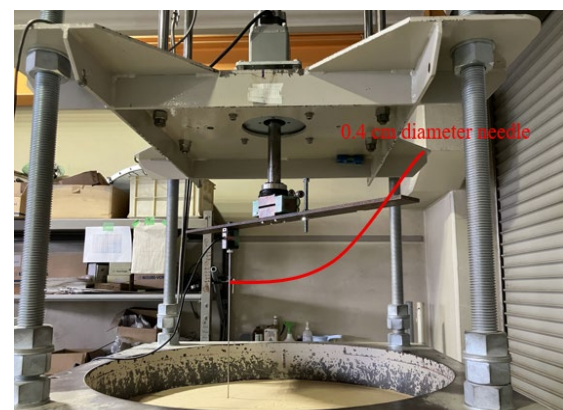


Fig.7 Ground uniformity verification by a 0.4 cm diameter needle

6. RESULTS AND DISCUSSION

6.1 Effect of Variation of Drop Height on Relative Density

A 40 cm diameter model container was filled with Toyoura sand with various drop heights ranging from 10 cm to 60 cm, in 10 cm increments. The relative density of the model ground was then calculated using mass-volume relationships for each drop height. Figure 8 shows the relationship between the relative density and the corresponding drop height for different sieve heads.

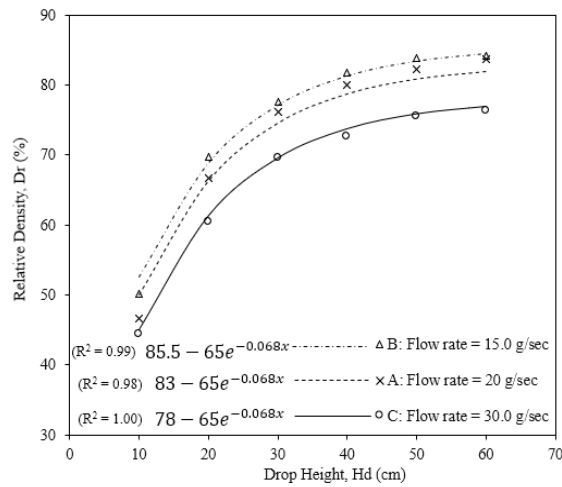


Fig.8 Relationship between drop height (cm) and relative density (%) for different flow rates

Figure 8 shows that the relative density increases nonlinearly with drop height. The increase in relative density with increasing drop height can be attributed to the higher impact energy of sand particles during free fall. This higher energy helps the particles rearrange into a denser packing. However, the increase becomes small at larger drop heights because the particles have already reached a relatively dense packing state; i.e., at a flow rate of 15.0 g/sec, the rate of increase is 39.1 % from drop height 10 cm to 20 cm, and it drops to 0.6 % from drop height 50 cm to 60 cm. A similar trend was reported by Gade and Dasaka [13], who observed that the increase in relative density becomes negligible once the fall height exceeds a certain limit.

The relationship between drop height (cm) and relative density (%) can be expressed in equation form as follows:

$$D_r = A - 65e^{-0.068H_d} \quad (1)$$

Where D_r represents the relative density in percent, H_d represents the drop height in cm, and A

is a constant that depends on the flow rate (F_r) and is 85.5, 83, and 78 for flow rates of 15 g/sec, 20 g/sec, and 30 g/sec, respectively.

6.2 Effect of Variation of Flow Rate on Relative Density

The relationship between the sand flow rate and relative density at different drop heights is shown in Fig.9. It has been observed that relative density decreases linearly with increasing flow rate. The reduction in relative density with flow rate can be explained by higher particle interference at higher flow rates during deposition. At higher flow rates, more particles are deposited simultaneously, resulting in a looser packing structure, whereas lower flow rates allow better particle rearrangement and denser packing. Similar effects of deposition on specimen density have been reported in previous studies [4, 12, 13, 19]. It has also been observed that the relative density decreases by 8-13% when the flow rate is doubled.

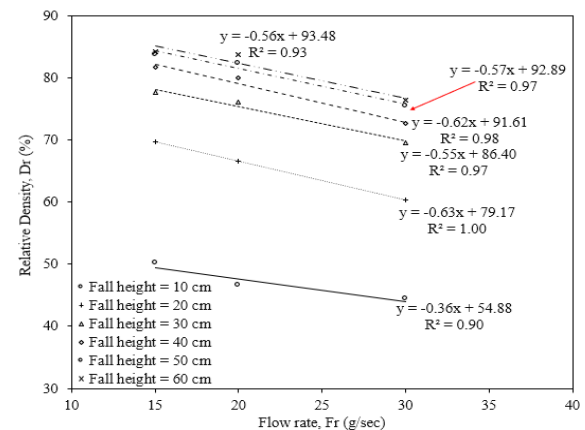


Fig.9 Relationship between relative density and flow rate for different drop heights

The relationship between the relative density and flow rate can be expressed in an equation as follows:

$$D_r = -BF_r + C \quad (2)$$

Where D_r represents the relative density in percentage, F_r represents the flow rate in g/sec, and B and C are constants that depend on the drop height (H_d) as shown in Fig.9.

Furthermore, the change in relative density with different flow rates is examined for various drop heights and found to be consistent across all heights, as shown in Fig. 10.

As constant A in Eq. (1) is a function of flow rate,

it can be evaluated empirically as follows, which is based on the relations provided in Fig.10.

$$A = -0.0074F_r + 1.1138 \quad (3)$$

So, the combined equation to calculate the relative density (%) with change in drop height (cm) and flow rate (g/sec) is expressed as follows:

$$D_r = -0.634F_r - 65e^{-0.068H_d} + 95.787 \quad (4)$$

The above equation is valid for fine-grained soils to estimate the relative density of the model ground for the corresponding drop height and flow rate. However, more studies are needed to incorporate the effects of particle shape, gradation, funnel diameter, hose length, humidity, and container boundary effects.

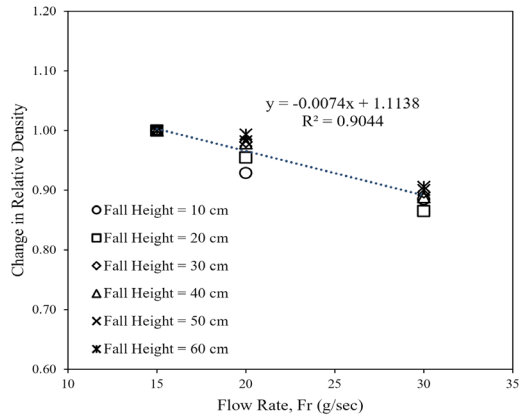


Fig.10 Relationship between change in relative density and flow rate for different drop heights

6.3 Ground Uniformity Verification by Mass-Volume Relationship

The uniformity of the large model ground is quantitatively confirmed using mass-volume relationships for small containers at 14 horizontal points and 3 vertical levels. The target relative density of the prepared model ground is 80 % at level 1 (at the base of the container) and level 2 (at the start of the 5th layer), and 45 % at level 3 (at the start of the 8th layer). The relative density at all points across the three levels is illustrated in Fig.11. Relative density was calculated at 14 horizontal points and at three vertical levels as shown in Fig. 6. The percentage variation of the calculated relative density at 42 sample points per batch from the target relative density is represented by the Coefficient of Variation (COV) and is shown in Fig.12. Three trials were conducted to achieve an average value of calculated relative density at 42 sample points.

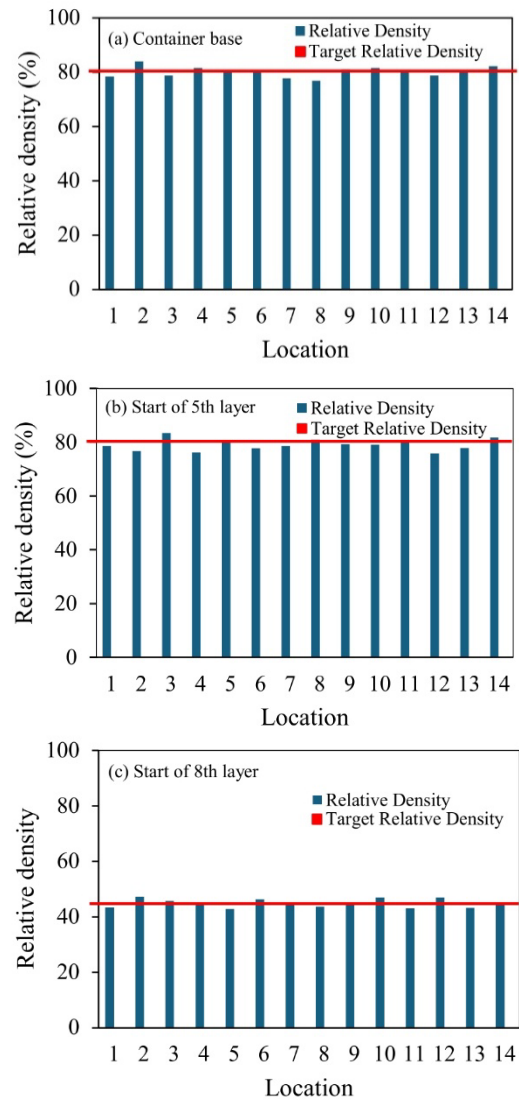


Fig.11 Relative density (%) of model ground at 14 horizontal points each at three levels: (a) at base of container, (b) at start of 5th layer, (c) at start of 8th layer

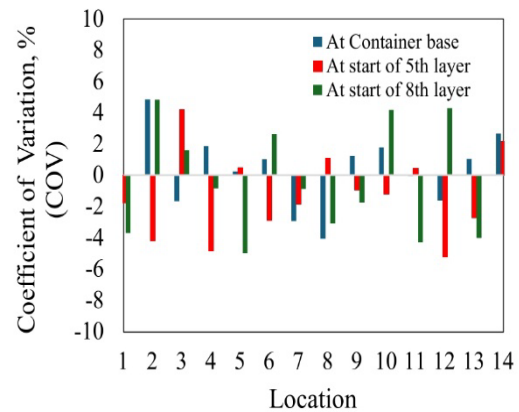


Fig.12 Coefficient of Variation (COV) of the prepared model ground

The coefficient of variation obtained in this study was below 5%, indicating a highly uniform deposit. Hariprasad [4] reported that COV values below approximately 7% are generally considered acceptable for laboratory model ground preparation. The results indicate that the developed pluviator can produce dense, uniform, and repeatable sand deposits, even where overhead space is limited.

6.4 Ground Uniformity Verification by 4 mm Needle

Ground uniformity was also evaluated using a 60 cm long needle with a diameter of 0.4 cm. The needle was inserted into the model ground up to a depth of about 48 cm at seven different locations. Needle penetration load and penetration depth were recorded with a data logger. The relationship between penetration load and depth at various points is shown in Fig.13. Similar penetration curves indicate a uniform soil deposit.

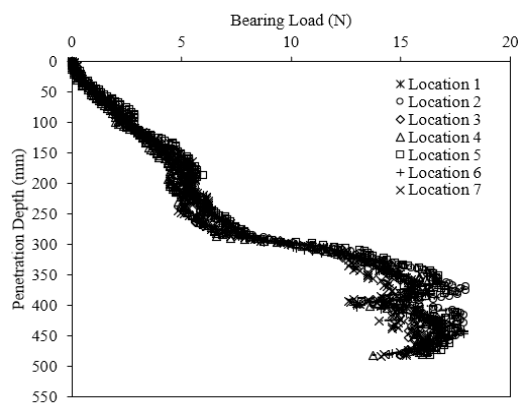


Fig.13 Qualitative assessment of ground uniformity by 0.4 cm diameter needle

These results indicated that the proposed methodology involves establishing the relationship between drop height, flow rate, and relative density in a small container, then applying this to the actual container size to prepare the model ground for experiments, along with a mobile air pluviator that consists of a funnel, flow-control sieves, a fabric hose, and a crane system.

7. CONCLUSIONS

This study presented the design and performance of an air pluviator for model ground preparation. The pluviator's performance has been tested using Toyoura sand at various flow rates, leading to the following conclusions:

- The relative density of sand increases nonlinearly

with the drop height. The rate of increase in relative density drops sharply once the drop height exceeds 40 cm.

- For a given drop height, increased depositional intensity (flow rate) leads to looser deposits, showing a linear relationship. The experiments revealed about a 10 % decrease in relative density when the flow rate doubled.
- An empirical equation (Eq. 4) is proposed to estimate the relative density of the model ground for fine sand for the corresponding drop height and flow rate. However, future studies are needed to investigate the effects of particle shape, gradation, funnel diameter, hose length, humidity, and container boundary effects.
- The developed pluviator achieved a COV of $\leq 5\%$ in relative density across horizontal and vertical sampling points. The results confirm that the proposed procedure can be used to prepare uniform and repeatable model grounds in laboratories with limited overhead space.
- The proposed methodology was validated using Toyoura sand. Further studies should evaluate its applicability to other sand types and investigate its performance for large-scale laboratory and centrifuge model tests.

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