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An automatic sand pourer for the preparation of loose and dense samples for physical modelling

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ABSTRACT: Preparation of consistent sand densities around scaled models in physical modelling is a challenge. Manual sand-pouring techniques require a significant amount of time, are difficult to control, and yield unreliable results. The new device utilises a moving hopper and custom-designed tip allowing control over the sand discharge rate, drop height, traversing speed, sieve mesh size, and pouring spacing. To assess the impact of each of these factors on the relative density, extensive calibration tests were conducted. The calibration results are presented in this paper. Tests were also conducted on a pile with sand poured around the pile to demonstrate sample repeatability and uniformity. The findings revealed that sand discharge rate, drop height, and traversing speed are primary controls on relative density, while pouring spacing influences layer thickness uniformity. Both dense and loose samples can be reliably prepared by appropriate parameter selection or by removing sieves for loose deposition. Repeatability checks confirm that the automated system can produce uniform, reproducible samples suited for soil–structure interaction studies. This work contributes to improving the effectiveness and reliability of geotechnical testing by providing valuable insights into optimising automated sample preparation for physical modelling applications.

1 INTRODUCTION

Physical modelling in geotechnical engineering is a useful tool for replicating prototype behaviour under controlled conditions and validating proposed solutions. When geotechnical problems are modelled at a reduced scale, whether through 1-g testing or centrifuge testing, accurate sample preparation is required for reliable results.

In air pluviation, dry sand is poured from a fixed hopper, funnel, or diffuser, allowing particles to fall freely through the air and settle under gravity, as shown in Figure 1. Density is primarily controlled via drop height, flow rate, hopper geometry, and sieve mesh configurations (Gade and Dasaka, 2016, Srinivasan et al., 2016, Hossain and Ansary, 2018). In manual air pluviation systems, these are qualitatively controlled, rarely instrumented, or quantifiable. Operators typically adjust the height manually and maintain flow by shaking/tapping the hopper, or by adjusting the funnel discharge aperture size. Sometimes performed in a raster pattern (moving the hopper by hand across the box) or in layers at varying heights. These issues lead to poor repeatability between tests, increased uncertainty in initial soil conditions, and reduced reliability in interpreting soil–structure interaction responses. Although widely used, non-automatic pluviation therefore presents clear limitations for modern physical modelling, particularly where reproducibility and quantifiable control over sample density are required.

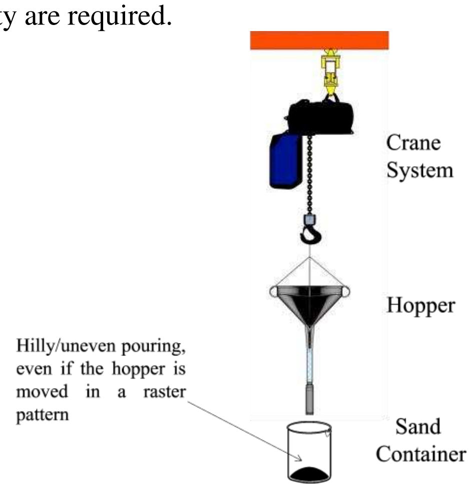

Figure 1. Sample preparation using manual air pluviation.

2 THE AUTOMATED AIR PLUVIATION TECHNIQUE

Air pluviation systems can be automated with mechanical actuation, enabling precise control of the hopper's movement over the sand-depositing area. This enables quantifiable, repeatable sample preparation, where parameters for achieving a target density can be systematically adjusted, logged, and consistently reproduced. By maintaining a constant flow and consistent coverage of the sand container, automated systems enhance density uniformity and minimise the impact of operator variability. Both loose and dense samples can be poured by controlling how sand is deposited during the fall. Previous literature largely focused on the impact of sand discharge rate and drop height (Zhao et al., 2006, Chian et al., 2010, Gade and Dasaka, 2016, Wu et al., 2021, Al-Salih and Al-Abboodi, 2023). This study also examines how the traversing speed, pouring spacing, and sieve mesh size affect the properties of the poured samples. The automatic sand pourers used for preparing samples for model testing at the University of Nottingham campuses are shown in Figures 2 and 3.

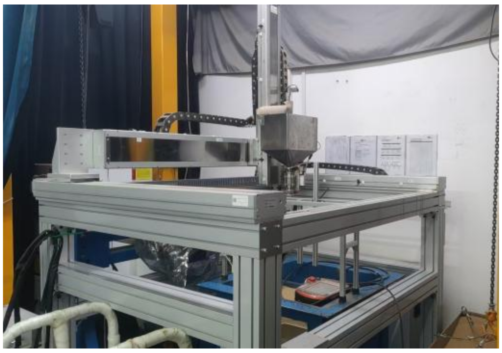

Figure 2. Automatic sand pourer at the University of Nottingham, Ningbo Campus, China.

Figure 3. Automatic sand pourer at the University of Nottingham, University Park Campus, UK.

3 METHODOLOGY

3.1 Automatic sand pourer design

The automatic sand pourer used in this study is shown in Figure 4. A hopper holding the sand is moved over an area horizontally using motor-controlled axes. After each layer of sand is poured, the thickness is measured using an LVDT distance sensor, and the hopper is automatically raised to maintain a constant drop height throughout the sample preparation process.

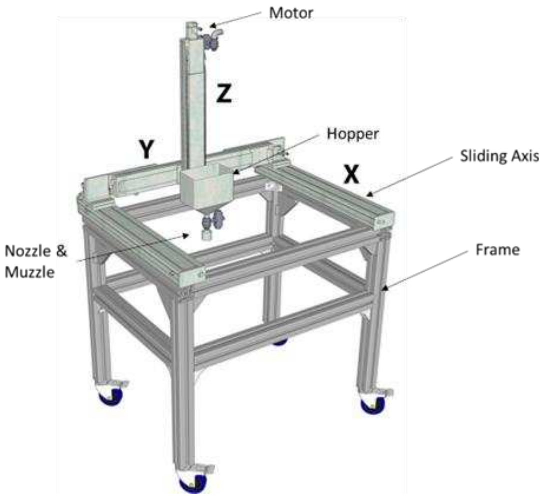

Figure 4. Automatic sand pourer design.

An acrylic nozzle was designed to hold the orifice plate. The nozzle is connected to the hopper discharge, and the hole diameter on the plate is adjusted to control the sand discharge rate. A muzzle with sieves can be connected to the nozzle to spread the sand over an area and encourage particle rearrangement. The nozzle, muzzle, and orifice plates used are shown in Figure 5. The transparent body allows the operator to easily notice if the sieves are clogged during the sand-pouring process.

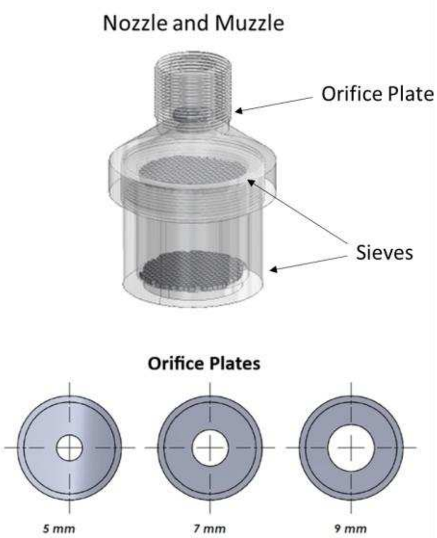

Figure 5. Nozzle, Muzzle, Orifice Plates.

The path along which the nozzle is moved over the calibration box is shown in Figure 6. A layer consists of two passes, one vertical and one horizontal, to fully cover the calibration box. The changes in direction along the defined path must be outside of the box boundary, as the area under which the pourer turns will evidently accumulate more sand as the actuators slow down to change the direction. After each layer is poured, the hopper must also be raised outside the box's boundary to prevent accumulation in a single area of the sample.

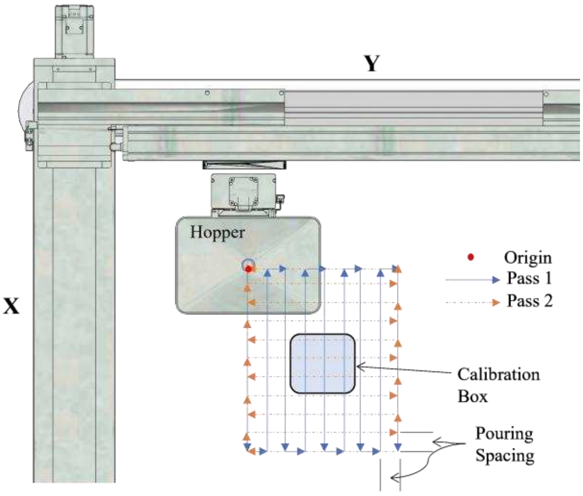

Figure 6. Pouring Path.

3.2 Sand properties and calibration boxes

Table 1. Sand properties.

Property	Specification	
Sand Name	Henan Sand	
ϕ_{cr}	36.5	Degrees
D_{10}, D_{50}, D_{60}	0.43, 0.50, 0.56	mm
C_U	1.21	-
γ_{min}	12.90	kN/m^3
γ_{max}	15.32	kN/m^3
e_{min}	0.729	-
e_{max}	1.054	-
G_s	2.65	-

A clean, dry, poorly graded silica sand was used in this study. The properties of the sand are tabulated in Table 1.

Two boxes of different sizes were used for the calibrations. The box was filled with water to calculate its volume through the water mass. The volume of the calibration boxes is tabulated in Table 2. The box has a sharp edge that prevents accumulation at the edge and prevents sand particles from bouncing into the sample being prepared. A photo of a calibration box during pouring is shown in Figure 7.

Table 2. Calibration box size.

Calibration Box	Volume	
Small	1493.0	cm^3
Big	3650.7	

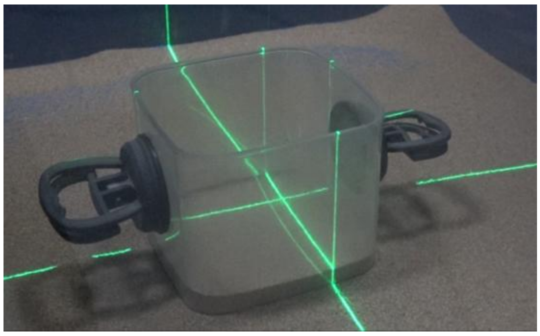

Figure 7. Photo of the calibration box during pouring.

3.3 Calibration tests

48 calibration tests and 4 checks were carried out to investigate the influence of the parameters on the sample's density. The test schedule is shown in Table 3. The sand discharge rate using different orifice plate hole sizes is first quantified, followed by an examination of how the relative density changes at various drop heights and sand discharge rates. The study then extends into the traversing speed, pouring spacing, sieve mesh size, and pouring without sieves.

Table 3. Calibration tests schedule.

Test No.	Test	No of Calibrations
1(a)	Change in sand discharge rate using orifice plates with different hole sizes	3 *2
1(b)	Change in relative density at different drop heights and discharge rates	9 *2
2	Change in relative density at different traversing speeds	3 *2
3	Change in relative density at different pouring spacing	3 *2
4	Change in relative density using different sieve mesh sizes	3 *2
5	Change in relative density without sieves	2 *2
6(a)	Repeatability check using different calibration box sizes	2 *2
6(b)	Repeatability check using the lateral loading of pile models	2 *2

Finally, samples were poured using the presented device into the two calibration boxes and around piles that were laterally loaded to showcase sample repeatability and uniformity.

In the calibration tests, the mass of the sample poured was measured using an electronic balance, and the corresponding relative density calculated. The equations used for the calculations are shown below

$$M_s = M_{af} - M_c \quad (1)$$

where M_s (g) is sand weight, M_c (g) is the box weight, and M_{af} (g) is the weight after the sample is poured.

$$\rho = M_s/V \quad (2)$$

where ρ (g/cm^3) is the density of the sample, and V (cm^3) is the volume of the calibration box.

$$e = \frac{G_s}{\rho/\rho_w} - 1 \quad (3)$$

where e is the void ratio and ρ_w is water density.

$$D_r = \frac{e - e_{max}}{e_{max} - e_{min}} \times 100 \quad (4)$$

where D_r (%) is the relative density of the sample.

4 RESULTS

4.1 Overview

The results of the calibration testing are presented in this section. The influence of key controllable parameters on the resulting relative density and layer thickness in automated air pluviation was systematically examined. First, the effects of sand discharge rate and drop height were evaluated to establish their primary role. The traversing and pouring spacing were then assessed to investigate how sand delivery per unit area affects density uniformity and layer thickness. The contribution of sieve mesh size to the sample's density was also assessed. Samples were then poured to demonstrate that the system can prepare loose samples.

Finally, repeatability tests were conducted to verify that the calibrated pouring technique yields consistent sand samples suitable for physical modelling applications.

4.2 Influence of sand discharge rate and drop height

The variation in sand discharge rate with increasing orifice plate hole diameter is shown in Figure 8. The flow rate increased with increasing hole diameter, rising from approximately 0.10 kg/min for the 5 mm plate to approximately 0.70 kg/min for the 9 mm plate. The increase exhibited a nonlinear trend that was consistent in form with previously reported discharge data for similar sands, although the absolute values were lower than those reported by Chian et al. (2010). The sand used in this study had a larger grain size. The orifice plate hole diameter in this experimental design governed the sand discharge rate during pouring, and relatively small changes in hole size resulted in substantial changes in mass flux.

The influence of drop height on the resulting relative density for the three orifice configurations is presented in Figure 9. For all orifice plate hole diameters, the relative density increased with increasing drop height from 20 cm to 60 cm, indicating that higher heights allow for greater particle rearrangement and densification of the sample during deposition. At a constant drop height, a slower sand discharge rate produced the highest relative densities (71.5–87.9 %).

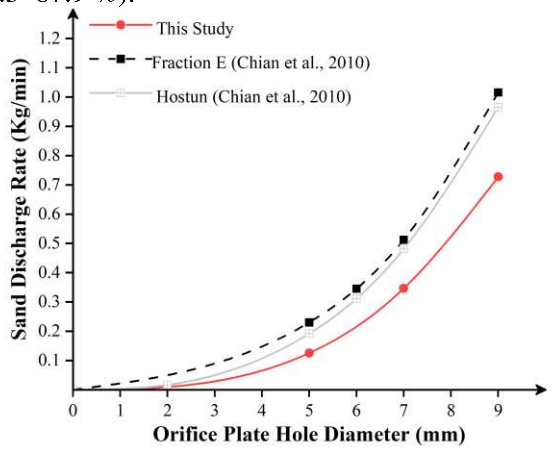

Figure 8. Change in sand discharge rate with increasing orifice plate hole diameter.

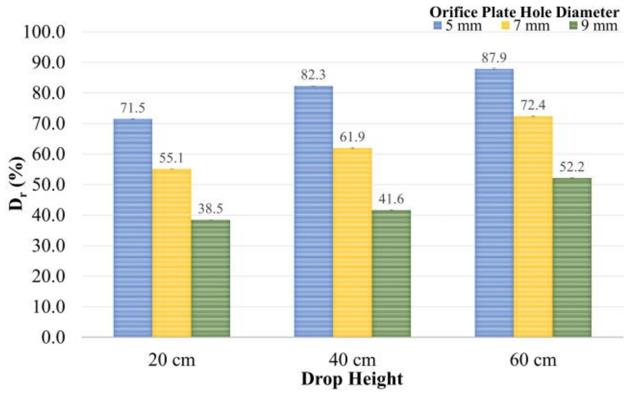

Figure 9. Change in relative density at different drop heights and sand discharge rates.

A faster discharge rate reduced particle organisation during deposition, yielding progressively looser specimens. Control of both flow rate and drop height is therefore required to achieve target density states during sample preparation.

4.3 Influence of traversing speed

The influence of traversing speed on the resulting relative density is shown in Figure 10. Increasing the traversing speed from 20 mm/s to 50 mm/s increased the relative density from 42.4% to 55.1%. This trend indicated that faster hopper movement reduced the volume of sand deposited per unit area, producing a looser pour by mass but ultimately yielding a denser deposit once settled.

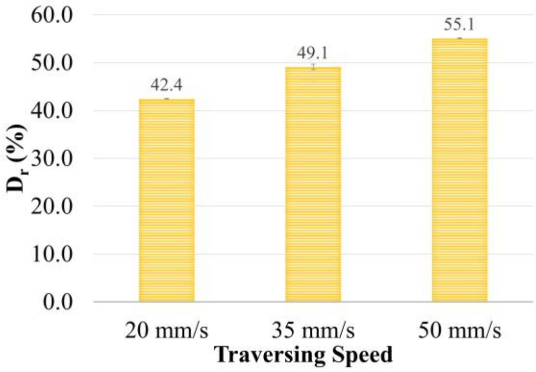

Figure 10. Change in relative density for increasing traversing speeds.

The effect of traversing speed on the layer thickness is shown in Figure 11. Layer thickness decreased noticeably with increasing traversing speed, reducing from approximately 22 mm at 20 mm/s to approximately 9 mm at 50 mm/s. The combined observations showed that the traversing speed directly controlled the sand delivery rate per pass and, therefore, influenced both the layer thickness and the achieved relative density. A higher traversing speed is beneficial, as it improves local density uniformity. Thinner layers during pouring prevent particles from rolling down the edge of the poured area.

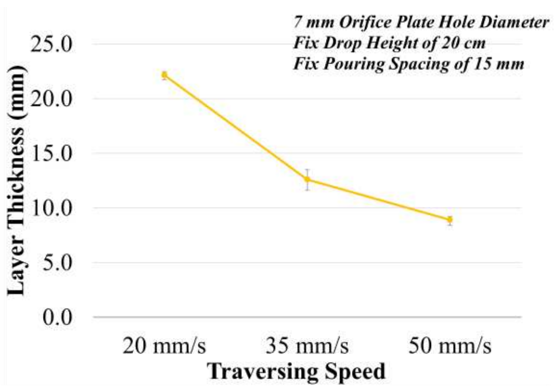

Figure 11. Change in the poured layer thickness for increasing traversing speeds.

4.4 Influence of pouring spacing

The influence of pouring spacing on the achieved relative density is shown in Figure 12. Reducing the spacing between adjacent pouring lines slightly increased the relative density, with values of 55.1%, 50.5%, and 48.6% recorded for spacings of 15 mm, 20 mm, and 25 mm, respectively. Under otherwise constant pouring conditions, closer spacing resulted in greater sand coverage per pass and produced denser deposits after settling.

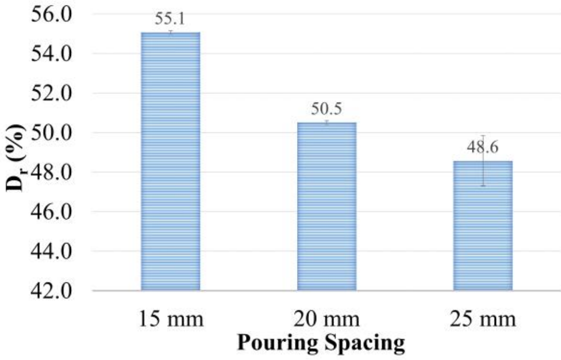

Figure 12. Change in relative density for increasing pouring spacing

The corresponding layer thickness for each spacing is presented in Figure 13. Layer thickness decreased from approximately 9 mm at a spacing of 15 mm to approximately 5.5 mm at a spacing of 25 mm. The results showed that widening the pouring spacing creates gaps between adjacent pouring lines. The sand can partially flow into the gaps as it reaches the surface. While this reduces the layer thickness, it is undesirable as it affects the local density within the sample. This indicates that the pouring spacing must be smaller than the discharge muzzle diameter to prevent local density variations.

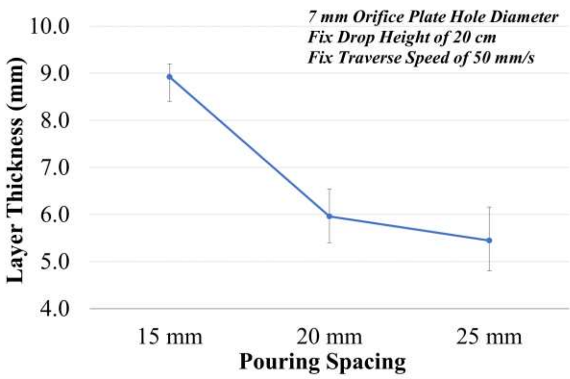

Figure 13. Change in the poured layer thickness for increasing pouring spacing.

4.5 Influence of mesh size

The effect of the mesh size on the denser samples is shown in Figure 14. Variations in mesh size, ranging from 2.5 mm to 3.5 mm and 4.5 mm, produced only minor changes in relative density at a high pouring height. This indicates that mesh size had a minor influence on the sample's density.

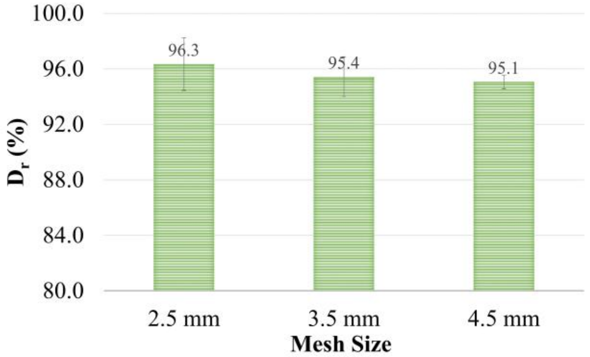

Figure 14. Change in relative density for different mesh sizes at a high drop height.

The corresponding layer thicknesses are shown in Figure 15. Although the layer thickness showed some variability, it was consistently thin across the tested range. It is, however, necessary that the discharge rate is slow enough, or the mesh size is large enough, to allow sufficient time for the sand to spread through the mesh without clogging it.

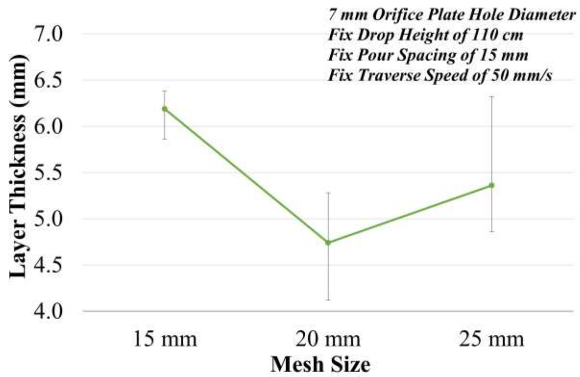

Figure 15. Change in the poured layer thickness for different mesh sizes at a high drop height.

4.6 Pouring of loose sand samples

A lower drop height is ideal for producing loose sand samples. However, in most practical cases, the hopper must operate above sand containers so that the turn along the pouring path remains outside the container. This constraint can be accommodated by removing the sieves from the muzzle, enabling higher drop heights without creating overly dense deposits. As shown in Figure 16, loose samples were successfully prepared at a drop height of 110 cm and a pouring spacing of 15 mm.

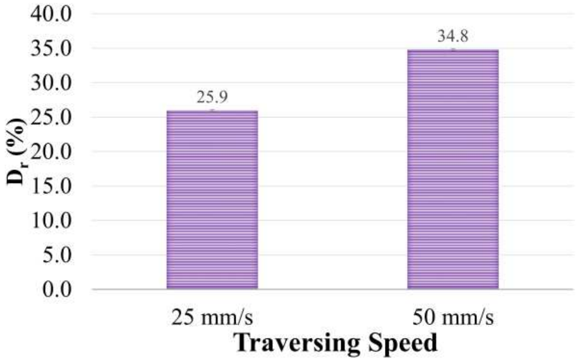

Figure 16. Preparation of loose samples at a high drop height.

The corresponding layer thicknesses are plotted in Figure 17. Traversing speed can be used to provide flexibility in achieving the target relative density.

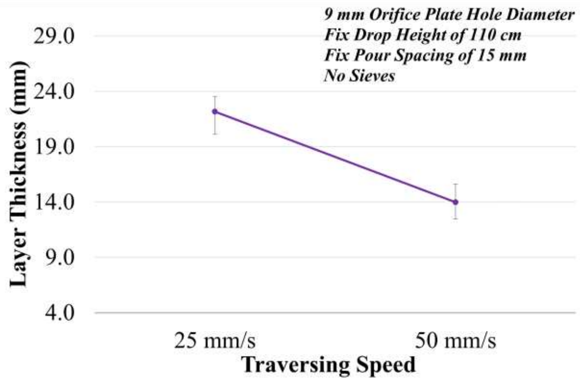

Figure 17. Poured layer thickness of the loose samples.

4.7 Repeatability testing

4.7.1 Different calibration box size

The repeatability of the samples was tested using different calibration box sizes, and the results are shown in Figure 18. Under identical pouring conditions, the relative densities obtained in the small and big calibration boxes were 38.45% and 38.01%, respectively.

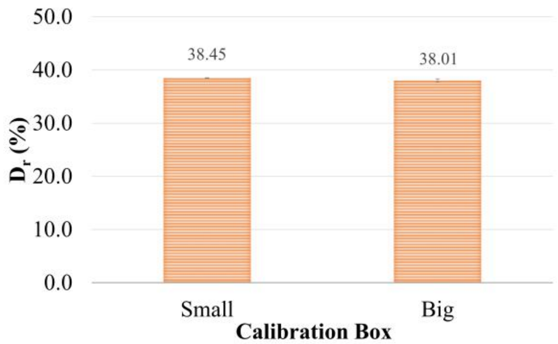

Figure 18. Repeatability check in relative density for different calibration box sizes.

Measured layer thicknesses were approximately 19.15 mm in the small box and 19.06 mm in the big box, again indicating little variation between the two cases. This shows that the deposition was consistent across the two calibration boxes, and the automated air pluviation technique yielded satisfactory repeatability essential for physical model testing.

4.7.2 Pushover tests of pile models

Repeatability of the sample preparation technique was also assessed by laterally loading a model pile into sand prepared with the automated pluviation device. Two sets of tests were conducted on single piles: one whole and one split in half, designated FMS and HMS, respectively, each repeated twice. The sand is poured around the pile using the method, as shown in Figure 19, and the resulting load-displacement-rotation responses are shown in Figure 20. The pile was clamped rigidly to the sandbox after the layers beneath it were poured. The hopper moves above the pile during the pouring process, and the sand dropped at the pile location is caught and removed using a cup placed inside the pile.

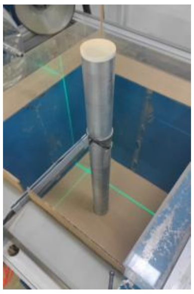

Figure 19. Sand pouring around a model pile.

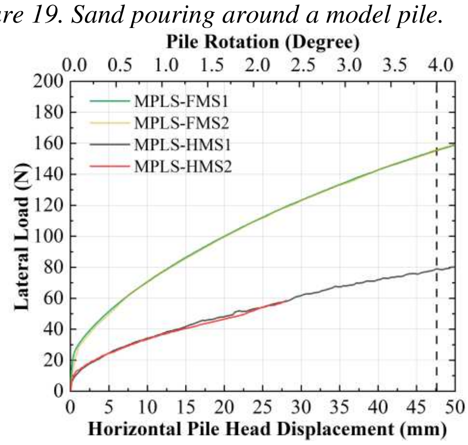

Figure 20. Repeatability check by pile lateral loading.

In both configurations, the repeated lateral loading tests showed close agreement across the loading range, with nearly overlapping curves for both pairs. The consistency observed between repeated runs demonstrates that the automated pluviation technique can produce sand beds with good repeatability for subsequent physical model testing.

5 CALIBRATION PROCESS FOR SAMPLE PREPARATION USING THE AUTOMATED AIR PLUVIATION TECHNIQUE

The calibration process for preparing sand samples using automated air pluviation followed the workflow shown in Figure 21.

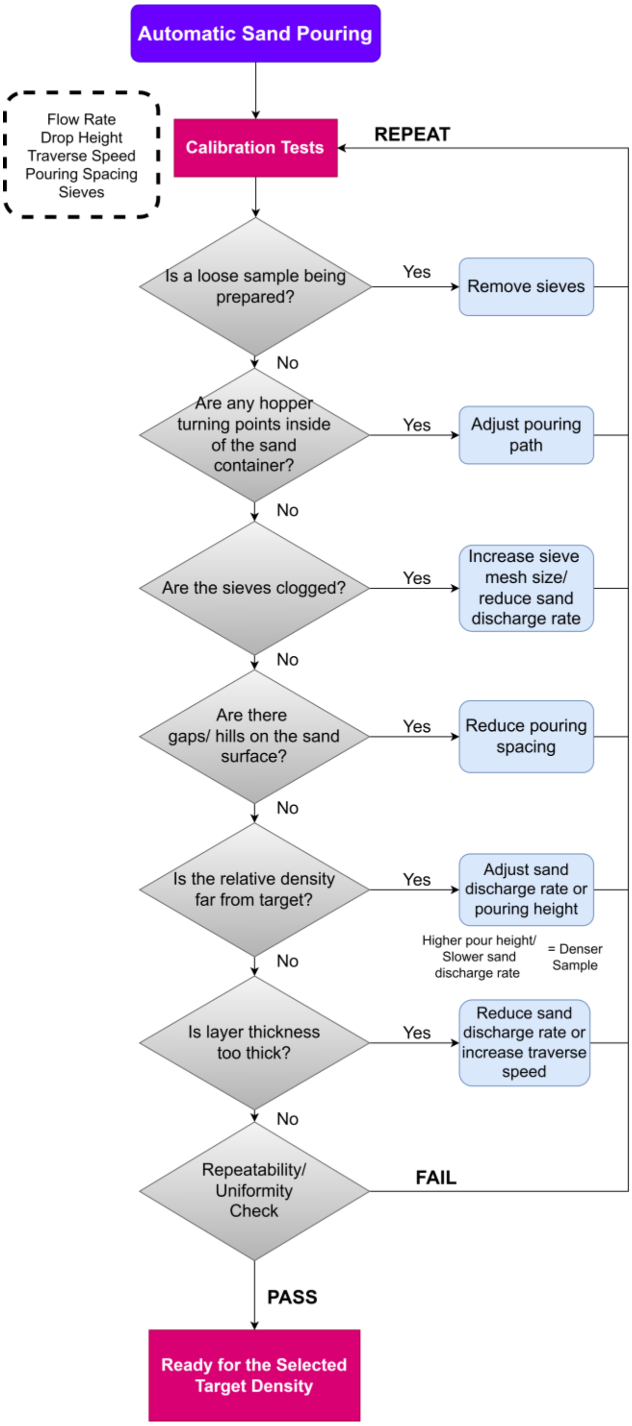

Figure 21. Automated air pluviation calibration process.

The procedure consists of a series of tests in which the key controllable parameters—namely sand discharge rate, drop height, traversing speed, pouring spacing, and sieve configuration—are adjusted to characterise their influence on density and optimise layer thickness. For loose samples, the sieves are removed to reduce particle rearrangement, which promotes densification. The pouring path is then examined to ensure that hopper turning points remain outside the boundaries of the sand container. During pouring, if used, sieves are monitored for clogging. Surface irregularities such as gaps or ridges are addressed by adjusting the pouring spacing. If the measured relative density during calibration deviates from the target value, the parameters are adjusted accordingly. After these adjustments, repeatability and sample uniformity are checked.

6 CONCLUSIONS

This study demonstrates that automated air pluviation provides a reliable method for preparing sand samples for physical modelling. It addresses the limitations associated with manual pouring, vibration, and tamping methods. The calibration tests carried out revealed that sand discharge rate, drop height, and traversing speed are the primary controls affecting relative density, while traversing speed and pouring spacing help adjust layer thickness and sample uniformity. There was a minor influence on the relative density for the sieve mesh tested at high drop heights. The study also shows that both dense and loose samples can be prepared, making it suitable for modelling various geotechnical scenarios. Repeatability checks confirmed that the method consistently reproduces target densities and yields uniform samples suitable for soil–structure interaction studies. Furthermore, a chart is included to assist new operators in navigating the calibration process for this device. The broader adoption of automated pluviation systems is anticipated to bolster confidence in physical modelling results and support the development of more robust geotechnical solutions.

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