Multi-scale calibration of a line-style sand pluviator

Yang, Yifan; de Lange, Dirk A.; Wang, Huan; Askarinejad, Amin

DOI
10.12989/gae.2024.37.5.431

Publication date
2024

Document Version
Final published version

Published in
Geomechanics and Engineering

Citation (APA)
Yang, Y., de Lange, D. A., Wang, H., & Askarinejad, A. (2024). Multi-scale calibration of a line-style sand pluviator. *Geomechanics and Engineering*, *37*(5), 431-441. https://doi.org/10.12989/gae.2024.37.5.431

Geomechanics and Engineering, *Vol. 37, No. 5 (2024) 431-441*
https://doi.org/10.12989/gae.2024.37.5.431

Multi-scale calibration of a line-style sand pluviator

Yifan Yang*[1,2], Dirk A. de Lange[1,3a], Huan Wang[1,4b] and Amin Askarinejad[1,5c]

[1]*Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands*
[2]*Department of Civil and Environmental Engineering, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208, United States*
[3]*Geo-Engineering Unit, Deltares, Boussinesqweg 1, 2611 HD Delft, The Netherlands*
[4]*Department of Offshore Energy, Norwegian Geotechnical Institute, Sandakerveien 140, N-0484 Oslo, Norway*
[5]*Swiss Federal Office of Energy, Pulverstrasse 13, 3063 Ittigen, Switzerland*

(*Received September 18, 2023, Revised April 7, 2024, Accepted April 19, 2024*)

Abstract. A newly developed line-style sand pluviator has been calibrated to prepare repeatable sand specimens of specific statuses of compactness and homogeneity for laboratory tests. Sand is falling via a bottom slot of a fixed hopper, and by moving the sample container under the slot, the container is evenly filled with sand. The pluviator is designed with high flexibility: The falling height of sand, the hopper's opening width and the relative moving speed between the hopper and the sample box can be easily adjusted. By changing these control factors, sand specimens of a wide range of densities can be prepared. A series of specimen preparation was performed using the coarse Merwede River sand. Performance of the pluviator was systematically evaluated by exploring the alteration of achievable density, as well as checking the homogeneity and fabric of the prepared samples by CT scanning. It was found that the density of prepared coarse sand samples has monotonic correlations with none of the three control factors. Furthermore, CT scanning results suggested that the prepared samples exhibited excellent homogeneity in the horizontal direction but periodical alteration of density in the vertical direction. Based on these calibration test results, a preliminary hypothesis is proposed to describe the general working principles of this type of pluviators *a priori*, illustrating the mechanisms dominating the non-monotonic correlations between control factors and the relative density as well as the vertically prevalent heterogeneity of specimens. Accordingly, practical recommendations are made in a unified framework in order to lessen the load of similar calibration work.

Keywords: geotechnical CT-scanning; sand pluviation; sand specimen preparation

1. Introduction

Small-scale laboratory testing, either at the normal gravitational or a centrifugal acceleration field, is one of the most important research strategies in geotechnical engineering. These tests are usually designed to simulate large-scale geotechnical problems in prototypes with much smaller models in the laboratory (Schofield 1980). Preparation of standardized model specimens is a prerequisite to obtain reliable results from laboratory tests on sands, since any subtle alteration of pre-designed physical modelling parameters (e.g., the relative density for sand specimens) could result in unacceptable deviation in the test results (Madabhushi *et al.* 2006).

It is well-known that the mechanical behaviour of cohesionless soil is dependent on the features of both particles themselves (e.g., roughness and roundness) and the fabric of granular assemblages (e.g., compactness and alignment of particles) (see e.g., Oda 1972a, b). Features of particles are generally fixed for a typical sand, leaving fabric the main factor affecting the behaviour when only a single type of sand is considered. Research in the passing decades has indicated that among all fabric features, the compactness of particles is one of the most crucial factors controlling the mechanical behaviour of sand (see e.g., Lee 1965, Lade *et al.* 2009, Khatri *et al.* 2017), which can be quantified by the index "relative density" (D_r).

Currently, there are mainly two different categories of methods for sand specimen preparation for a specific relative density (Butterfield and Andrawes 1970). In the first category, the target density is achieved by either shoveling, tamping, or vibrating loose sand packing, after the process of deposition. When using these methods, the inclination of sand particles is relatively more random (see e.g., Arulanandan 1978, Sze and Yang 2014), and this configuration does not accord with that of natural deposition (Mamen and Hammoud 2021, Garcia *et al.* 2022, Ferrick *et al.* 2022). Alternatively, the other category of specimen preparation methods controls the density of sand samples during the process of deposition, by controlling the falling height and volumetric flow rate of falling sand grains (Kolbuszewski 1948, Kolbuszewski and Jones 1961). Sample preparation methods proposed following this concept are generally categorized as the "sand pluviation method". Over the past decades, various sand pluviators have been developed by numerous institutions worldwide (see e.g., Garnier and Cottineau 1988, Lo Presti *et al.* 1993, Fretti *et al.* 1995, Madabhushi *et al.* 2006, Lagioia *et al.*

*Corresponding author, Master's Student
E-mail: yifan.yang@northwestern.edu
[a]Researcher
[b]Postdoctoral Scholar
[c]Associate Professor

ISSN: 2005-307X (Print), 2092-6219 (Online)

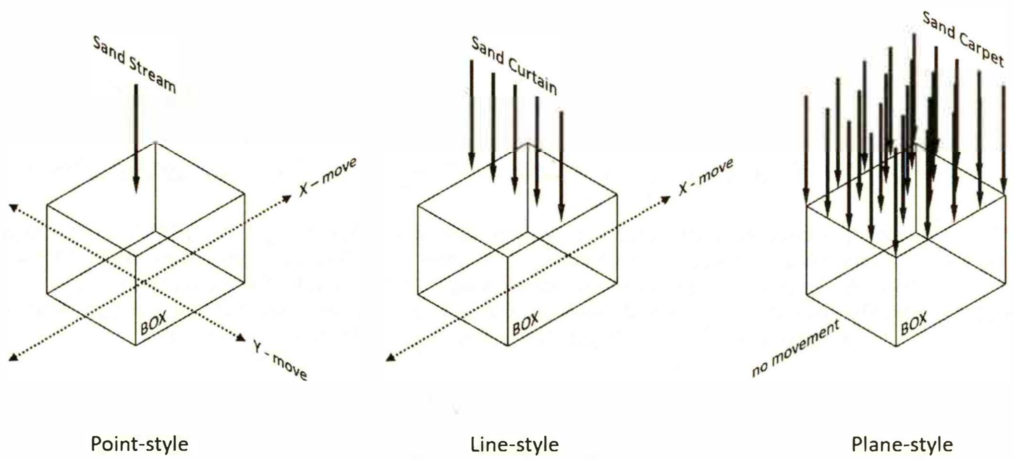

Fig. 1 Point-, line- and plane-style sand pluviation concepts

2006, Choi *et al.* 2010, Dave and Dasaka 2012, Hakhamaneshi *et al.* 2016, Hariprasad *et al.* 2016, Zhang and Chian 2022, Jamil *et al.* 2022). The previous studies have proved that the relative density of prepared sand samples can be well controlled by the sand pluviators, showing the sand pluviator method conceptually promising.

The key step of the sand pluviation method is to rain sand grains into the sample box from a certain height. The sand grains usually go through an aperture or a set of sieves, or both to form a relatively steady and continuous flow. According to the mode of sand flow, the existing sand pluviators can be categorized into three types, namely "point-style", "line-style", and "plane-style", respectively, as illustrated in Fig. 1. For the "point-style" pluviator, the sand grains are rained into the sample box through a hole whose scale is significantly smaller than that of the box (larger than sand grains however). To fill the box, relative movement between the sand stream and the sample box in both X- and Y- directions on the horizontal plane is indispensable. Therefore, a significant limitation of "point-style" pluviators is that the traveling route of sand hoppers varies (Zhao *et al.* 2006). This traveling route is difficult to quantify and can be very subjective, making the post-processing work of calibrating tests more difficult, and consequently less likely to make the formal execution work normative. For the "plane-style" pluviator, the sand grains are rained into the model box through a sieve (or a set of sieves) whose area is larger than that of the model box. The falling sand grains form a "sand carpet" with substantially no horizontal movement relative to the model box (Choi *et al.* 2010). In this case, the size of pluviators must match the size of corresponding sample boxes. Therefore, one specific "plane-style" pluviator is not versatile for boxes of a large range of sizes, unless designed redundantly cumbersome, which is uneconomical. The limitations of "point-style" and "plane-style" pluviators inspired the development of "line-style" pluviator (Stuit 1995). For this type of pluviators, a long-strip (slot) shaped opening gap is designed at the bottom of the sand hopper with the strip thickness adjustable. The sand grains flow through the strip-gap and then form a "sand curtain". Compared with the "plane-style" pluviators, the sand hopper can be designed much smaller, at least in one certain direction, and still capable of covering a large pluviating area by moving the sand hopper. Compared with the "point-style" pluviator, the travelling route of the sand hopper is fixed, since it can only move in one horizontal direction at a certain speed. Therefore, the "line-style" sand pluviator has avoided disadvantages of the other two, and can be considered as a hybrid of them.

In light of preceding discussions, a new "line-style" sand pluviator was developed at Delft University of Technology (TU Delft) to prepare sand specimens for standardized small-scale laboratory tests. Multi-scale calibration work for this new machine was carried out. To be more specific, the first step is to study the range and repeatability of achievable bulk (average) relative density by executing the apparatus with various combinations of control factors (e.g., falling height of particles). Subsequently, the scope was zoomed in: Fields of relative density and microstructures of pluviated sand particles were obtained from computed tomography at two different subscales by scanners of distinct resolutions, respectively. Based on this detailed scrutiny, technical execution's influences were investigated. In particular, aside from fundamental observations and summarizations, a preliminary hypothesis was proposed to explain the effects of three key factors of technical manipulations on sample density and local layering in a unified framework. In the end, some general rules concerning sand sample preparation (e.g., how to adjust technical variables to obtain the most favorable specimens) were also discussed in this research.

2. The TU Delft sand pluviator

The TU Delft sand pluviator is an automatic line-style pluviator. Various components and the schematic working principle of this machine are presented in Fig. 2. This device has a triangular-prism shaped sand hopper to store the sand temporarily. A slot located at the bottom ridge of the sand hopper can be opened manually, and the opening width (i.e., slot thickness) can be adjusted by a spiral

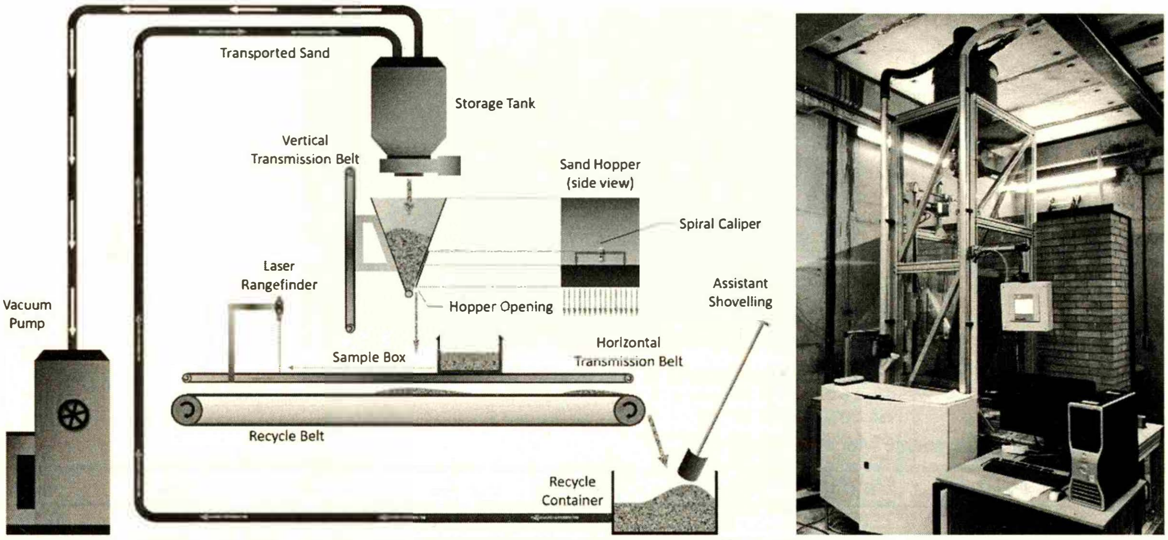

Fig. 2 Sketch and photograph of the TU Delft sand pluviator

Table 1 Technical variables of the TU Delft sand pluviator

	Controlling method	Max. value	Min. value	Accuracy
Falling Height	Servo motor belt	1080 mm	*	1 mm
Opening Width	Spiral caliper	25 mm	0	1μm
Box Speed	Servo motor belt	90 mm/s	0	1 mm/s

* The minimum value of falling height should be determined by the height of sample boxes

caliper. The thickness of the "sand curtain" can be controlled by screwing the spiral caliper to change the bottom gap. This thickness is positively correlated with the sand grains' raining intensity (i.e., volumetric flow rate) (Lo Presti *et al.* 1993, Bolouri Bazaz *et al.* 2018). Meanwhile, the height of the sand hopper can also be adjusted by driving a pair of vertical transmission belts.

When preparing the sand specimen, the sample box goes through the aforementioned "sand curtain" back and forth at a controlled speed, driven by a pair of horizontal transmission belts. During this process, fallen sand grains deposit in the box. A pre-calibrated laser rangefinder is installed above the moving routine of the model box to measure the height of accumulated sand packing periodically. As the deposition process loops, sand grains accumulate in the sample box layer by layer until the target height of the sand body is reached. It is noteworthy that, driven by the vertical transmission belts, the height of the sand hopper is increased dynamically after each deposition loop to compensate for the loss of falling distance due to sand's accumulation, and the compensation height can be automatically calculated according to the measurements by the laser rangefinder. It should also be noted that not all the falling grains can be deposited in the sample box. Therefore, a wide recycle belt is installed beneath the horizontal transmission belts to collect the sand grains falling outside the model box and then transport them into a recycle container. The collected sand grains will subsequently be sucked upwards to refill the sand hopper using an electric vacuum pump, with an approximate power of 8 kW.

According to previous research on the similar line-style sand pluviators by Stuit (1995), there are three technical variables of the pluviator that control the density of prepared samples, namely: the width of the opening gap at the bottom of the sand hopper, referred to as the "opening width", the height between the hopper bottom and the sand surface in the model box, referred to as the "falling height", and the horizontal moving speed of the sample box, referred to as the "box speed". The accuracy, maximum, and minimum values of the three variables and their controlling methods are summarized in Table 1. It is worth mentioning that there exist some factors (e.g., fullness of sand hopper) that challenge the repeatability of sand specimens' relative density (see e.g., Hakhamaneshi *et al.* 2016). These factors are not set as technical variables, since they cannot be simply controlled during the tests, but are required to be noticed by the executors nevertheless.

3. Experimental programme

3.1 Sand material

The coarse Merwede River sand was used in this study. The mean grain size of the sand is 0.73 mm with maximum and minimum void ratios of 0.72 and 0.50, respectively. Some other basic properties of the sand are summarized in Table 2, and a photograph of this sand is presented in Fig. 3. This coarse sand is specifically focused because, against two finer sands whose mean diameters are 0.14 and 0.26 mm, respectively, extensive calibration work has been

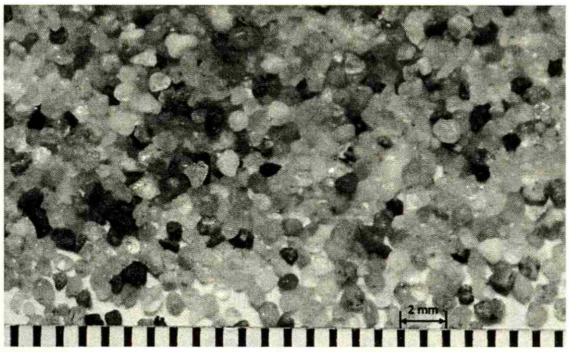

Fig. 3 Photograph of the coarse Merwede River sand

Table 2 Properties of the coarse Merwede River sand

G_s	D_{60} (mm)	D_{50} (mm)	D_{30} (mm)	D_{10} (mm)	C_u	C_c	e_{max}	e_{min}
2.65	0.78	0.73	0.65	0.54	1.44	1.00	0.72	0.50

Table 3 Control variates for repetitive pluviation tests

Variable name	Number of values	Values
Falling Height	8	18 cm, 24 cm, 33 cm, 48 cm, 63 cm, 78 cm, 93 cm, 108 cm
Opening Width	3	2 mm, 3 mm, 5 mm
Box Speed	2	15 mm/s, 30 mm/s

earlier done on a structurally similar but less automatic pluviator at TU Delft (Stuit 1995). This historical research has significantly different results showing the influence of the box speed, with some more recent analogous research (see e.g., Bolouri Bazaz *et al.* 2018, Zhang and Chian 2022) using a larger range of sands. To investigate the reasons, this research takes precedence focusing on a coarse sand as an extension of the domestic pioneering work (Stuit 1995).

The shape of the coarse Merwede River sand was rigorously quantified, since it influences the sand behaviour significantly (see e.g., Altunbas *et al.* 2021). To this end, morphological images of 300 particles were captured from the micro-scale computed tomography (micro-CT), see e.g., Fig. 7, and then analysed. The sphericity, which is the eccentricity of the ellipses having the same second-moments as the actual shapes of particles, has an average value of 0.72 for the coarse Merwede River sand, indicating the existence of distinct longest axes of sand particles, since the eccentricity of a circle is 0 and that of an ellipse can never exceed 1. Meanwhile, the angularity of the sand is also considered: According to the computational algorithm by Zheng and Hryciw (2015) which is based on the concept of Wadell (1932, 1935), the index of average roundness is slightly less than 0.5. Therefore, the sand can be classified as "subrounded" according to the roundness scale proposed by Powers (1953). It is also noteworthy that indicated by the rather low coefficient of uniformity C_u and coefficient of curvature C_c, this coarse Merwede River sand is considered poorly graded (single-sized).

3.2 Repetitive pluviation test programme

Following the control variates method, a series of sand pluviation tests were performed to study the influence of falling height, opening width, and box speed on the relative density of prepared samples. For these three variables, 8, 3, and 2 different values were investigated respectively, as summarized in Table 3. Therefore, a total of 48 variable combinations were studied. It should be noted that for each combination of variables, at least two repetitive pluviation tests were performed to ensure the reliability of the test results.

3.3 Multi-scale CT scanning programme

Experimental results in existing studies, such as cone penetration tests (e.g., Corté *et al.* 1991, Fretti *et al.* 1995, Jamil *et al.* 2022), lamel ring container tests (Stuit 1995) and mold sampling tests (e.g., Choi *et al.* 2010) suggested that sand samples prepared by the pluviation method are not always ideally homogeneous, especially in the vertical direction. It is readily understood that the homogeneity checking methods mentioned above (e.g., cone penetration tests) disturb the fabrics of sand specimens and hence inevitably include errors or assumptions when quantifying the local relative density of sand packing. In this study, the non-disturbing computed tomography (CT) method was adopted. Existing studies have proved that there is a positive linear correlation between the radiographic density and the density of sand packing (see e.g., Desrues *et al.* 1996, Safdar *et al.* 2022). For a typical sand, the particle density, maximum, and minimum void ratios can be considered constant. Then it is reasonable to qualitatively evaluate the local relative density distribution inside the prepared samples based on the radiographic density from CT scanning.

A Siemens Somatom medical CT scanner (referred to as the macro-CT) and a Phoenix-Xray CT scanner (referred to

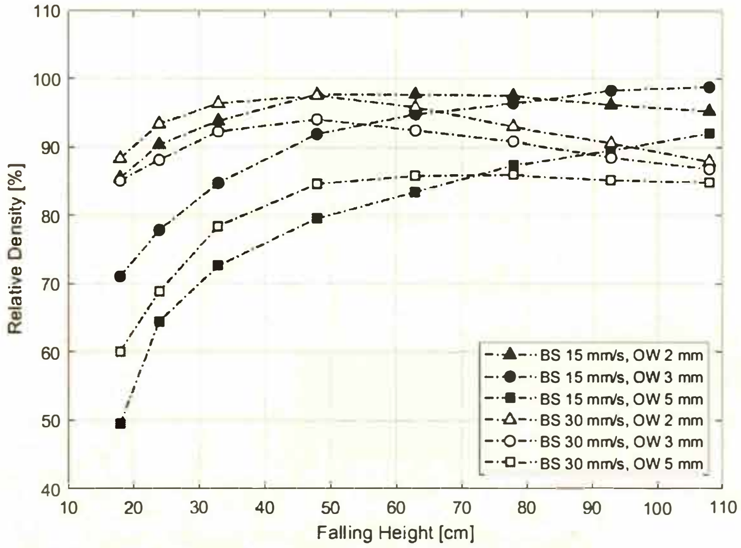

Fig. 4 Relative density test results for the coarse Merwede River sand

Table 4 Information of samples for CT scanning tests

	Falling Height	Opening Width	Box Speed	D_r	Number of layers	Layer thickness
V-1	24 cm	3 mm	15 mm/s	80%	6	~ 14 mm
V-2	48 cm	5 mm	15 mm/s	81%	3	~ 31 mm

as the micro-CT) of TU Delft were used in this work. It is obviously uneconomical to systematically scan all the specimens prepared in the repetitive pluviation test programme with these costly apparatus, and hence appropriate choices must be made. It has been indicated by various previous research that the same bulk relative density can be achieved by different combinations of technical variables such as falling height and box speed, and therefore, the heterogeneity of those nominally identical samples naturally becomes the privileged ones to be investigated.

According to the results of the repetitive pluviation test programme (to be introduced in the next section), two specimens, namely V-1 and V-2 were selected to be scanned by the macro-CT. These two samples have almost the same bulk relative density but were prepared with different technical approaches, and their detailed information is summarized in Table 4. After the macro-CT scanning process, the sample V-1 was saturated and then slowly frozen to get a small part of it sampled by a borehole drill without disturbance. The borehole sample was subsequently scanned by the micro-CT to observe the microstructure of sand particle assemblage.

4. Interpretation of the results

4.1 Relative density of pluviated specimens

The relative densities of prepared samples are plotted in Fig. 4. It can be seen that by adjusting the falling height (FH), box speed (BS), and opening width (OW), sand samples of various relative densities (approximately ranging from 50% to 100%) can be prepared. As expressed in Fig. 4, in general, the experimental results in this study are consistent with previous research works: The sand sample tends to be summarily denser when the falling height increases or the opening width decreases (see e.g., Lo Presti *et al.* 1993, Lagioia *et al.* 2006, Madabhushi *et al.* 2006, Hariprasad *et al.* 2016). Despite that, one interesting observation from this study is that under certain conditions, the relative density of the prepared sample may decrease with an increase of falling height, and the curves of test series "BS 30 mm/s, OW 2 mm" and "BS 30 mm/s, OW 3 mm" in Fig. 4 are two significant examples. Besides, it can be concluded that the relative density of sand has shown a salient sensitivity to the variable opening width. For example, when increasing the opening width from 2 mm to 5 mm, the relative density of the prepared sample decreases from 85% to 50% with the same falling height of 18 cm and the same box speed of 15 mm/s. On the contrary, the variable falling height has a much less significant effect on the relative density, especially when the opening width is small: for an opening width of 2 mm, the relative density of the prepared sand sample is always larger than 80% even when the falling height decreases from around 110 cm to 20 cm.

The influence of the variable box speed has a more significant non-monotonic feature. For this coarse Merwede River sand, as shown in Fig. 4, when falling height is smaller than 50 cm, the relative density is positively correlated with box speed, while the correlation would become negative in several cases when the falling height is larger than 50 cm. This conclusion could mediate the

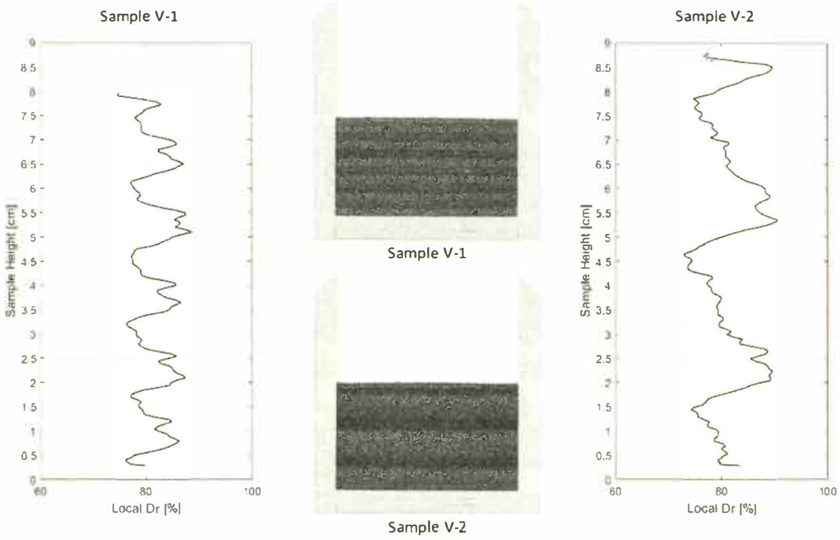

Fig. 5 Homogeneity check by macro-CT scanning tests

contradictory results from previous papers which held the views that the relative density is negatively and positively correlated with the moving speed of the sample box, respectively. To be more specific, Stuit (1995) suggests that the relative density decreases as the box speed increases. Conversely, other scholars such as Bolouri Bazaz *et al.* (2018) and Zhang and Chian (2022) argue that higher box speeds actually result in an increase in the overall relative density of the specimens. Based on the results of this study, the influences of both opening width and moving speed are coupled with that of falling height, and none of them on the relative density is necessarily monotonic. Complicated mechanisms dominating these non-monotonic features may be clarified by tracking kinematic movement of sand grains, and are introduced in Section 5.

4.2 Homogeneity of pluviated specimens

The reconstructed images of samples V-1 and V-2 are shown in Fig. 5. It can be observed that the inhomogeneity in the horizontal direction is minor when compared with that in the vertical direction. For example, for the sample of V-2, the relative density of the densest layer varies between 88% and 91% in the horizontal direction, and 72% and 74% for the loosest layer, while the vertical difference is rather more significant. Similar patterns apply to the sample of V-1. It is noteworthy that the opening width for sample V-2 (5 mm) is significantly larger than that for sample V-1 (3 mm). That is why the thickness of each single deposited layer is larger for V-2. To be more specific, sample V-2 consists of only 3 layers (approx. 31 mm each) but has a slightly higher body than that of V-1, which consists of 6 thinner layers (approx. 14 mm each). The number of layers is also be clearly indicated by the periodically altering curves in Fig. 5. Besides, in the sample V-1, the value of local relative density varies more frequently than that of V-2 in the vertical direction. What is more, the calculated coefficient of variation of the sample V-1 (0.0012) is obviously smaller than that of the sample V-2 (0.0021). According to the comparison between V-1 and V-2, it can be concluded that sand specimens of the same bulk relative density may have different degrees of homogeneity. In terms of the coefficient of variation of relative density, sample V-1 is relatively more uniform than V-2, and might be a better approximation if the sample is designed to be ideally homogeneous. On this occasion, a "many-thin-layer" strategy is generally more recommended than a "few-thick-layer". It should also be noted that the surface of a specimen is looser than the average, and this phenomenon agrees with previous studies (e.g., Fretti *et al.* 1995, Choi *et al.* 2010).

Stratification is inevitable during the process of pluviation, and these uniformity differences among nominally identical specimens bring up challenges in standardized physical modelling projects. Despite that, since naturally deposited sand bodies are not ideally homogeneous either, according to the *in situ* profiles to be physically simulated, this feature of stratification also introduces a positive effect that sand specimens may be prepared *ad hoc*. For example, although sample V-2 is less homogeneous than V-1, it might be of greater value if its relative density profile agrees more with the *in situ* data that are obtained from site investigations. No matter whether the specimens are needed to be more uniform or closer to the stratified profile *in situ*, the working principles and executing techniques of sand pluviators must be well understood, and further investigations on this point are given in the next section.

5. Principles of line-style sand pluviators: A hypothesis

Plenty of calibration tests have been introduced in the previous sections. By referring to the test results of the bulk relative density and homogeneity of the prepared specimens, researchers may select the most satisfying sample according to the requirements of the corresponding physical modelling projects. However, the previous

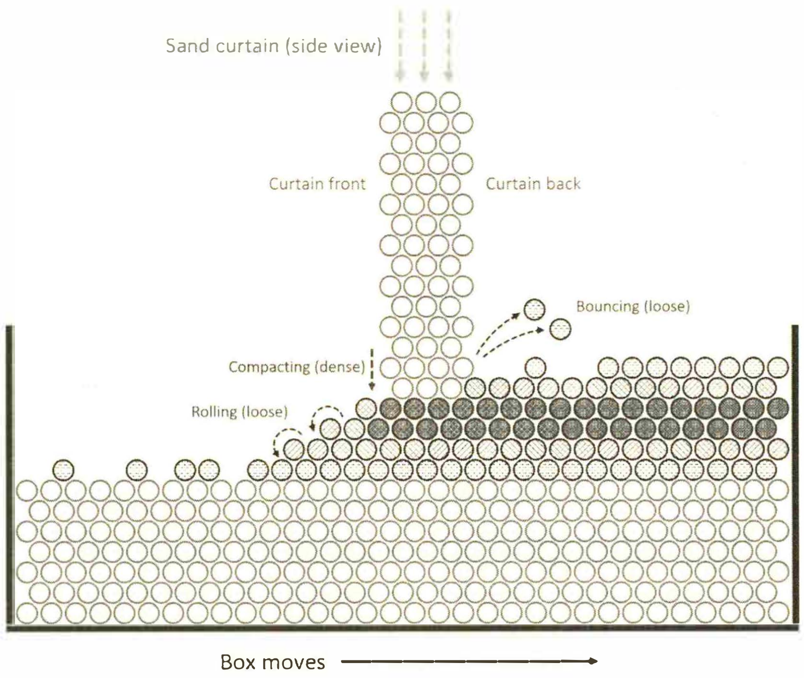

Fig. 6 Sketch of the line-style pluviation process and its mechanisms

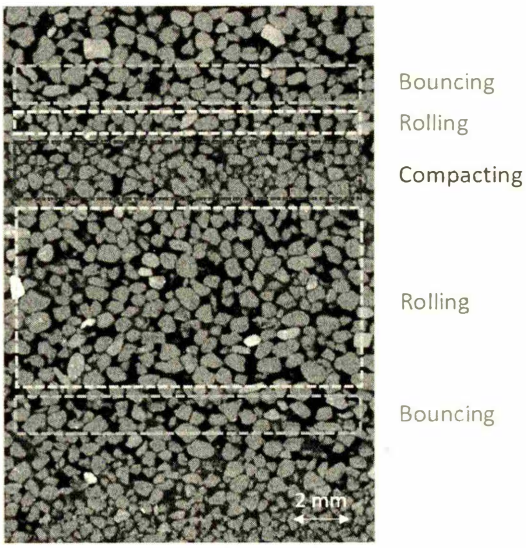

Fig. 7 Fabric of sample V-1

discoveries only work for the TU Delft sand pluviator with the coarse Merwede River sand. Similar heavy systematic calibration work would still be inevitable for a new pluviator, a new sand, or possibly even a new box. Also, the spatial inhomogeneity of specimens can hardly be systematically understood solely based on experimental observations. Furthermore, the reasons for the historically contradictory conclusions on the correlation between the relative density and the box speed remain nebulous. Therefore, it is meaningful to explore the general rules for the technical variables' influences on the density and homogeneity of pluviated specimens to understand the performance of the line-style sand pluviator family *a priori*.

For this reason, the kinematic displacement and rotation of sand grains of the line-style sand pluviation process were observed by scrutinizing photographs shot by a high-speed (50 frames per second) camera, and then these recorded microscopic movement of particles can be summarized to reveal the mechanisms governing the properties (e.g., bulk relative density, homogeneity) of the pluviated specimens. Since some details, such as the collision-induced deformation of particles and the field of air drag can hardly be tracked by means of the current apparatuses, the condensed working principles of the sand pluviator are limited to a partially substantiated hypothesis. According to photographic observations, an instantaneous but

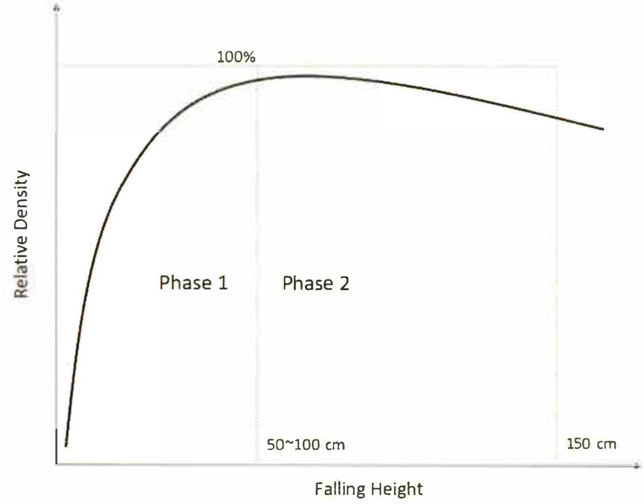

Fig. 8 Falling-height dependent relative density: A general rule

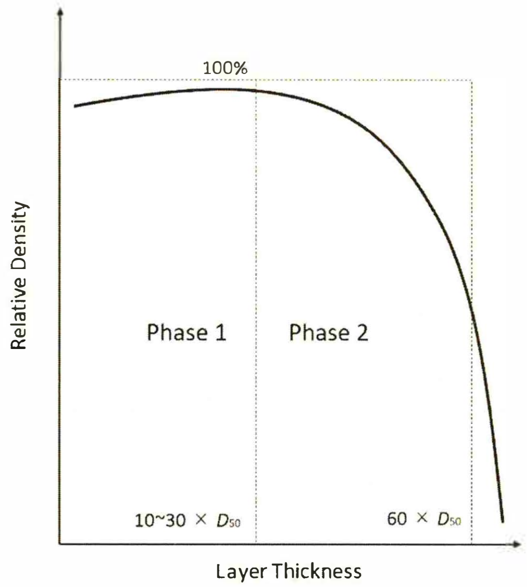

Fig. 9 Layer-thickness related relative density: A general rule

representative state of the pluviated sample box (side view) is sketched in Fig. 6. As can be seen, the falling sand grains exhibit different kinematic behaviour. Inspired by the similar but incomplete concepts proposed by Stuit (1995) and Cresswell *et al.* (1999), the behaviour of sand grains can be categorized into three different mechanisms, namely: "bouncing", "rolling", and "compacting", as marked in Fig. 6.

For a new layer of sand, a slope usually forms due to the relatively slow horizontal movement of the sand curtain. In this slope region, the "rolling" mechanism is the dominant one. Sand governed by the "rolling" mechanism slides along the slope, losing kinetic energy, and can hardly be compressed either. As a result, these particles will be deposited in a loose state (Stuit 1995, Zhang and Chian 2022). The "rolling" mechanism can also be found on the back-side of the sand curtain, although not as manifest as that on the front-side.

As the box moves, the generated slope from rolling particles is then densified by the following falling particles due to the dynamic impulse, as well as the infiltration of segregated finer grains (see Fig. 7 "compacting" box, also Zhang and Chian 2022). Based on the observation from the micro-CT scanning in Fig. 7, this series of influences cannot uniformly densify the whole loose layer but the upper part mainly. In fact, the void ratio of the downer part remains substantially unchanged unless the underlying loose packing is as thin as several particles (Cresswell *et al.* 1999). On this occasion, a relatively thin and dense layer forms at the top of the sand slope (i.e., middle of the whole new layer), governed by the "compacting" mechanism. Aside from the "rolling" and "compacting" mechanisms, some sand grains also exhibit a "bouncing" mechanism, as shown in Fig. 6. The bouncing-off particles on the front-side of the curtain form the base layer of the rolling slope, while those particles on the back-side form the top cover of the new sand layer.

Moreover, the fabric of sample V-1 was further analysed using the micro-CT, and the altering degree of compactness of one pluviated layer can be clearly seen in Fig. 7, which provides additional information to the proposed three mechanisms. Generally, sand packing governed by the "compacting" mechanism is distinctively denser than that governed by the other two mechanisms. In other words, the "rolling" and "bouncing" mechanisms have a similar effect to make the pluviated sand packing relatively loose.

The bulk relative density and homogeneity of a prepared sand sample are determined by the ultimate thicknesses of these relatively dense or loose layers that are governed by either the "compacting", the "rolling", or the "bouncing" mechanism. For instance, a specimen tends to become denser when layers governed by the "compacting" mechanism take a more significant thickness proportion, and more uniform when all the three types of layers are thinner: Since distinctions among them are inevitable, a relatively high frequency of periodic appearance compensates to the loss of homogeneity to a certain degree. The exact thickness is influenced by various technical variables (i.e., falling height, opening width, and box speed) through rather complicated processes. Based on the results of the relative densities of pluviated samples (i.e., Fig. 4), as well as the three proposed mechanisms of particle deposition, fundamental principles that dominate the relations among the thickness of different layers are summarized in the following two subsections. Then the influences of technical variables on the sand specimens' relative densities and uniformities can be explained through two representative patterns referring to which the performance of line-style sand pluviators can be predicted based on a small number of pilot pluviation tests.

5.1 The influences of falling height

Although the influence of air drag is not ignorable, the terminal velocity of a single falling sand particle (especially when diameter > 0.4 mm) is positively correlated with the height of falling in the interval 0-1 m (Vaid and Negussey 1984, Chian *et al.* 2010). Besides, the kinetic energy of one sand grain is positively correlated to its terminal velocity. Therefore, the kinetic energy of a falling sand grain monotonically increases with its falling height, although not necessarily linearly.

Based on the previously proposed mechanisms, the top part of the loose (see e.g., downer boxes marked by "bouncing" and "rolling" in Fig. 7) sand packing is hammered to be denser by falling grains with relatively higher kinetic energy. Consequently, a sand specimen's relative density increases with the falling height in certain intervals, as can be seen in Fig. 4. However, when the falling height further increases to a critical value, the high kinetic energy of the falling sand particles would force themselves to bounce off after hitting the existing sand layer. In this case, the "bouncing" mechanism, which results in a loose state, becomes more dominant than other mechanisms. As a result, the density of the specimen will decrease, as shown in Fig. 4 (e.g., when falling height is larger than 50 cm for the curves of test series "BS 30 mm/s, OW 2 mm" and "BS 30 mm/s, OW 3 mm").

In summary, for specimens prepared by the line-style sand pluviators using a certain type of sand, especially a poorly-graded coarse sand, the relative density has a certain representative pattern of relationship with the variable falling height, and varying values of opening width and box speed do not change this pattern essentially. This pattern is shown in Fig. 8. As can be seen, the correlation between the relative density and the variable falling height is not monotonic: It is positive in Phase-1 ("compacting" featured) and negative in Phase-2 ("bouncing" featured).

For fine sands, Phase-2 is sometimes a plateau, since the grains' kinetic energy does not increase as significantly as that of coarse sand due to the air drag (Zhang and Chian 2022). Besides, macro-CT scanning results suggested that specimens prepared in Phase-2 can be more homogeneous than those having a comparable density in Phase-1, since the bouncing effect may make the difference between loose "rolling" layers and dense "compacting" layers smaller. Therefore, so long as feasible and controllable, a large value of falling height is practically recommended if sample are required to be relatively uniform.

5.2 The influences of opening width and box speed

Experimental results suggested that the thickness of each single deposited layer increases with a larger opening width of hopper gap or a lower moving speed of the box. According to the observation from a high-speed camera, the main growth of thickness mentioned above is for the layers governed by the "rolling" mechanism which are naturally loose. This explains the decrease in density of prepared samples with a larger opening width or a lower box speed. However, on the other side, if the loose layer governed by the "rolling" mechanism is considerably thin, and meanwhile the kinetic energy of falling grains is significantly large (due to large falling height), the dense layers which could have been governed by the "compacting" mechanism will start bouncing off because of the lack of loose cushion layers. Since the dense "compacting" layers are transformed into the loose "bouncing" state in this case, the relative density decreases eventually.

In whatever way, the correlation between the relative density and the opening width is generally not monotonic, neither is that for the box speed. To be more specific, the relative density has a certain representative pattern of relationship with the layer thickness (directly governed by opening width and box speed), and varying values of falling height do not change this pattern essentially, as shown in Fig. 9. It is eye-catching that the correlation is positive in Phase-1 (indicating less and less "bouncing" effects) and negative in Phase-2 (indicating more and more "rolling" effects). The macro-CT scanning results suggested that in Phase-2, the specimens become more heterogeneous with the increase of layer thickness, since only a small top portion of the loose rolling layers can be densified then. Therefore, for practical execution, in order to prepare uniform samples, the moving speed of the sample box should be as large as possible, as long as the pluviated sand packing is not disturbed by the high horizontal acceleration. Besides, the thickness of the sand curtain should be as small as possible, so long as the particle flow is steady. More specifically, based on this premise of high box speed and small opening width, one may adjust the value of falling height to obtain specimens of various densities. However, if the minimum achievable relative density is larger than the target value, a lower box speed and a larger opening width may be selected for new attempts.

The aforementioned representative patterns and technical recommendations shall stand for any similar line-style sand pluviators, extra cautions should be taken, however, when significantly finer grains are prevalent in the chosen sands, because some basic assumptions (e.g., relatively unified sizes and a consistent falling speed of particles) of the proposed hypothesis of pluviation principles may alter then.

6. Conclusions

A line-style sand pluviator has been developed at TU Delft, after multi-scale calibration work, the following conclusions are drawn.

• The repetitive sand pluviation tests suggested that the line-style sand pluviator of TU Delft is capable of preparing sand samples of controllable bulk relative density. By controlling the execution parameters falling height, opening width, and box speed, specimens with relative density ranging from 50% to 100% can be prepared using the coarse Merwede River sand. With certain non-monotonicity though, in general, the relative density of pluviated specimens increases with falling height and decreases with the opening width in their most common intervals. The influence of box speed on the relative density, however, is significantly non-monotonic.

• Macro-CT scanning tests suggested that stratification is obvious in the specimens prepared by the line-style pluviation method. For all the prepared sand specimens, the local relative density varies periodically along the sample depth, but stays relatively constant in the horizontal direction in each layer.

• Mainly based on the observations from the high-frame-rate photographs, a partially substantiated hypothesis was proposed. It illustrates the working principles of the line-style sand pluviation process and the influencing mechanisms of the three variables (i.e., falling height, opening width, and moving speed) on the relative density and homogeneity of the prepared sample. Based on this hypothesis, representative patterns of these variables' influences have been summarized. Consequently, practical technical recommendations are made to help study the line-style sand pluviator family *a priori*, simplifying the potential calibration work.

• Future studies focusing on the performance of line-style pluviators on well-graded sands are recommended since the current results engage better for poorly-graded sands. Considering the difficulties of observing and tracking fine grains through image analyses, numerical simulations such as those by the discrete element method (DEM) are also encouraged to be introduced in the following research.

Acknowledgments

The authors would like to thank Paul Vermeulen, Kees van Beek, Karel Heller, Roland Klasen, Marc Friebel, Jens van den Berg, Ellen Meijvogel-de Koning, Joost van Meel, and Wim Verwaal for their technical support for this study.

References

Altunbas, A., Soltanbeigi, B. and Cinicioglu, O. (2021), "DEM modelling of retained backfill: Influence of particle shape for different stress paths and densities", *Geomech. Eng.*, **27**(3), 273-290. https://doi.org/10.12989/gae.2021.27.3.273.

Arulanandan, K. (1978), "A directional structure index related to sand liquefaction", *Proceedings of the ASCE Geotechnical Engineering Division Specialty Conference*.

Bolouri Bazaz, J., Zadehmohamad, M. and Hashemi, S.S. (2018), "Developing a portable curtain sand pluviator for reconstitution of soil models (in Persian)", *Modares Civil Eng. J.*, **18**(1).

Butterfield, R. and Andrawes, K.Z. (1970), "An air activated sand spreader for forming uniform sand beds", *Géotechnique*, **20**(1), 97-100. https://doi.org/10.1680/geot.1970.20.1.97.

Chian, S.C., Stringer, M.E. and Madabhushi, S.P.G. (2010), "Use of the automatic sand pourers for loose sand models", *Proceedings of the 7th International Conference on Physical Modelling in Geotechnics*, 7th ICPMG '10.

Choi, S., Lee, M., Choo, H., Tumay, M.T. and Lee W. (2010), "Preparation of a large size granular specimen using a rainer system with a porous plate", *Geotech. Test. J.*, **33**(1), 45-54. https://doi.org/10.1520/GTJ101634.

Corté, J.F., Garnier, J., Cottineau, L.M. and Rault, G. (1991), "Determination of model soil properties in the centrifuge", *Proceedings of the International Conference on Geotechincal Centrifuge Modelling*.

Cresswell, A., Barton, M. and Brown, R. (1999), "Determining the maximum density of sands by pluviation", *Geotech. Test. J.*, **22**(4), 324-328. https://doi.org/10.1520/GTJ11245J.

Dave, T.N. and Dasaka, S.M. (2012), "Assessment of portable traveling pluviator to prepare reconstituted sand specimens", *Geomech. Eng.*, **4**(2), 79-90. https://doi.org/10.12989/gae.2012.4.2.079.

Desrues, J., Chambon, R., Mokni, M. and Mazerolle, F. (1996), "Void ratio evolution inside shear bands in triaxial sand specimens studied by computed tomography", *Géotechnique*, **46**(3), 529-546. https://doi.org/10.1680/geot.1996.46.3.529.

Ferrick, A., Wright, V., Manga, M. and Sitar, N. (2022), "Microstructural differences between naturally-deposited and laboratory beach sands", *Granular Matter*, **24**(1), 9. https://doi.org/10.1007/s10035-021-01169-4.

Fretti, C., Lo Presti, D. and Pedroni, S. (1995), "A pluvial deposition method to reconstitute well-graded sand specimens", *Geotech. Test. J.*, **18**(2), 292-298. https://doi.org/10.1520/GTJ10330J.

Garcia, F.E., Andò, E., Viggiani, G. and Sitar, N. (2022), "Influence of depositional fabric on mechanical properties of naturally deposited sands", *Géotechnique*, **74**(3), 250-264.. https://doi.org/10.1680/jgeot.21.00230.

Garnier, J. and Cottineau, L.M. (1988), "La centrifugeuse du

LCPC: moyens de préparation des modèles et instrumentation", *Proc. Centrifuge 88*, 83-90.

Hakhamaneshi, M., Black, J.A., Cargill, A., Cox, C.M. and Elmrom, T. (2016), "Development and calibration of a sand pluviation device for preparation of model sand bed for centrifuge tests", *Proceedings of the 3rd European Conference on Physical Modelling in Geotechnics*.

Hariprasad, C., Rajashekhar, M. and Umashankar, B. (2016), "Preparation of uniform sand specimens using stationary pluviation and vibratory methods", *Geotech. Geol. Eng.*, **34**, 1909-1922. https://doi.org/10.1007/s10706-016-0064-0.

Jamil, I., Ahmad, I., Ullah, W., Junaid, M. and Khan, S.A. (2022), "Uniform large scale cohesionless soil sample preparation using mobile pluviator", *Geomech. Eng.*, **28**(5), 521-529. https://doi.org/10.12989/gae.2022.28.5.521.

Khatri, V.N., Debbarma, S.P., Dutta, R.K. and Mohanty, B. (2017), "Pressure-settlement behaviour of square and rectangular skirted footings resting on sand", *Geomech. Eng.*, **12**(4), 689-705. https://doi.org/10.12989/gae.2017.12.4.689.

Kolbuszewski, J.J. (1948), "An experimental study of the maximum and minimum porosities of sands", *Proceedings of the Second International Conference of Soil Mechanics and Foundation Engineering.*

Kolbuszewski, J.J. and Jones, R.H. (1961), "The preparation of sand samples for laboratory testing", *Proceedings of the Midland Soil Mechanics Foundation Engineering Society*.

Lade, P.V., Yamamuro, J.A. and Liggio Jr, C.D. (2009), "Effects of fines content on void ratio, compressibility, and static liquefaction of silty sand", *Geomech. Eng.*, **1**(1), 1-15. https://doi.org/10.12989/gae.2009.1.1.001.

Lagioia, R., Sanzeni, A. and Colleselli, F. (2006), "Air, water and vacuum pluviation of sand specimens for the triaxial apparatus", *Soils Found.*, **46**(1), 61-67. https://doi.org/10.3208/sandf.46.61.

Lee, K.L. (1965), "Triaxial compressive strength of saturated sand under seismic loading conditions", PhD dissertation, University of California, Berkeley.

Lo Presti, D., Berardi, R., Pedroni, S. and Crippa, V. (1993), "A new traveling sand pluviator to reconstitute specimens of well-graded silty sands", *Geotech. Test. J.*, **16**(1), 18-26. https://doi.org/10.1520/ GTJ10263J.

Madabhushi, S.P.G., Houghton, N.E. and Haigh, S.K. (2006), "A new automatic sand pourer for model preparation at University of Cambridge", *Proceedings of the 6th International Conference on Physical Modelling in Geotechnics*.

Mamen, B. and Hammoud, F. (2021), "Microstructural observations of shear zones at cohesive soil-steel interfaces under large shear displacements", *Geomech. Eng.*, **25**(4), 275-282. https://doi.org/10.12989/gae.2021.25.4.275.

Oda, M. (1972a), "Initial fabrics and their relations to mechanical properties of granular material", *Soils Found.*, **12**(1), 17-36. https://doi.org/10.3208/sandf1960.12.17.

Oda, M. (1972b), "The mechanism of fabric changes during compressional deformation of sand", *Soils Found.*, **12**(2), 1-18. https://doi.org/ 10.3208/sandf1972.12.1.

Powers, M.C. (1953), "A new roundness scale for sedimentary particles", *J. Sedimentary Res.*, **23**(2), 117-119. https://doi.org/10.1306/D4269567-2B26-11D7-8648000102C1865D.

Safdar, M., Newson, T. and Waseem, M. (2022), "Fiber orientation distribution of reinforced cemented Toyoura sand", *Geomech. Eng.*, **30**(1), 67.

Schofield, A.N. (1980), "Cambridge geotechnical centrifuge operations", *Géotechnique*, **30**(3), 227-268. https://doi.org/10.1680/geot.1980.30.3.227.

Stuit, H.G. (1995), "Sand in the geotechnical centrifuge", PhD dissertation, Delft University of Technology.

Sze, H. and Yang, J. (2014), "Failure modes of sand in undrained cyclic loading: impact of sample preparation", *J. Geotech. Geoenviron. Eng.*, **140**(1), 152-169. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000971.

Vaid, Y.P. and Negussey, D. (1984), "Relative density of pluviated sand samples", *Soils Found.*, **24**(2), 101-105. https://doi.org/10.3208/sandf1972.24.2_101.

Wadell, H. (1932), "Volume, shape, and roundness of rock particles", *J. Geol.*, **40**(5), 443-451. https://doi.org/10.1086/623964.

Wadell, H. (1935), "Volume, shape, and roundness of quartz particles", *J. Geol.*, **43**(3), 250-280. https://doi.org/10.1086/624298.

Wijewickreme, D., Sriskandakumar, S. and Byrne, P. (2005), "Cyclic loading response of loose air-pluviated fraser river sand for validation of numerical models simulating centrifuge tests", *Can. Geotech. J.*, **42**(2), 550-561. https://doi.org/10.1139/t04-119.

Zhang, Z. and Chian, S.C. (2022), "Layering effects of sand samples prepared by travelling pluviators", *Int. J. Phys. Model. Geotech.* ,https://doi.org/10.1680/jphmg.20.00061.

Zheng, J. and Hryciw, R.D. (2015), "Traditional soil particle sphericity, roundness and surface roughness by computational geometry", *Géotechnique*, **65**(6), 494-506. https://doi.org/10.1680/geot.14.P.192.

GC