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Development of a sand-pluviation test stand to investigate pluviation considering air-resistance and (partial) vacuum-conditions

N. Heim, S. Henke
Helmut Schmidt University, Hamburg, Germany, heimn@hsu-hh.de, sascha.henke@hsu-hh.de

ABSTRACT: To investigate influencing factors on the sand-pluviation method, the developed sand-pluviation test stand needs to be variable in multiple aspects. This includes falling height, deposition intensity (which can be controlled by different sieves), as well as the general set-up. The falling height must also be adjustable during the experiment to maintain consistent conditions for the entire test. All these requirements could be met by the developed test stand.

Because the discussed experimental equipment was created to specifically investigate the influence of (partial) vacuum-conditions on the pluviation process, a vacuum bell was built to encase the entire experimental set-up. The vacuum bell was developed such that the set-up is visible during the whole pluviation process. This allows for observation of irregularities during the pluviation process. However, the vacuum bell requires that the entire pluviation set-up has to be operated from the outside. Specifically, that includes the slide damper for the opening of the sand silo, the linear motor for the upwards movement of the apparatus, and the scraper for sample levelling after the pluviation process.

Specific difficulties in the development and construction of the pluviation stand were the design of the slide damper, the generation and maintenance of the vacuum, and contamination of several components with sand during the test. All these aspects require a thorough cleaning of the entire experimental set-up between each experiment. Specifically, sliding parts are very sensitive to sand grains and helpful adjustments to the pluviation stand have been developed and will be discussed in this paper.

1 BACKGROUND

Currently, the professorship for geotechnics at Helmut Schmidt University in cooperation with the Federal Waterways Engineering and Research Institute in Germany and the Technical University of Munich are developing a large-scale pressure container for investigation of laboratory CPT-tests of for example non-cohesive soils.

To create the necessary large-scale sample, the sand-pluviation method is supposed to be used. This method has already proven to be able to create homogenous samples of this size with different bulk densities by varying set-up, falling height and deposition intensity (Gade and Dasaka, 2017) (Dastpak et al., 2021) which is for example necessary to guarantee reproducible and predictable test conditions during the planned model scale CPT-tests in the pressure chamber . The developed experimental stand is therefore able to offer insight into the required variability of the large-scale apparatus, as well as possible mechanical challenges, such as the design of the slide damper, can be identified and improved at small-scale.

2 REQUIREMENTS FOR THE TEST STAND

Beside the influences of deposition intensity, the falling height and the set-up on the reached soil density of a sand-pluviated sample, other factors to be investigated are the properties of the sand itself and the flow resistance due to air pressure. These influencing factors have been identified during first experiments at the professorship, as well as with experimental set-ups found in literature (Vaid and Negussey, 1984) (Lagioia et al., 2006).

To investigate the afore mentioned influences separately, the developed test stand must be variable not only considering these factors but has to also create consistent conditions during the entire pluviation process. Therefore, the pluviation apparatus needs to be adjustable in height during the pluviation process to maintain a constant falling height. The movement of the pluviation box needs to be variable in speed to account for different deposition intensities.

The effect of (partial) vacuum on sand pluviation is an important point of interest. Previous experiments of the authors showed that especially with larger deposition intensities and smaller grain sizes negative effects of turbulence and air resistance on bulk densities and particle separation dominated the pluviation results. This confirmed findings of previous publications (Lagioia et al., 2006), where performing sand-pluviation in a partial vacuum increased both, uniformity of the samples as well as the achieved bulk densities. To maintain the adjustability of the pluviation apparatus, partial vacuum was to be created using an encasement of the pluviation as opposed to creating a new test stand.

Finally, to observe different processes during the pluviation, the pluviated sand has to be visible during the whole experiment. This requirement severely limited possible choices of materials, especially for the vacuum bell.

3 FIRST DESIGN AND CONSTRUCTION

The first construction of the sand-pluviation test stand was designed based on the above-described requirements. The basic design, which has been maintained up to this day, consists of two parts: the main pluviation set-up and the vacuum bell. These parts can operate independently, to perform experiments both in partial vacuum as well as in normal atmospheric pressure.

3.1 Main pluviation apparatus

The main apparatus consists of a silo, a slide damper, a chamber with calming trays, a sieve, diffusor sieves, and a sample tank with a sample scraper, as seen in figure 1. Excluding the base, the test stand has an approximate height of 1.90 m. Due to the vacuum-bell, the entire set-up had to be able to be contained in a cylinder with a diameter of 0.50 m.

The silo, which contains the sand before the start of pluviation, needs enough capacity to guarantee a completely filled sample at the bottom. Due to sand compaction during the pluviation process, an increased volume is necessary. The necessary volume at test start was based on the lowest and highest packing density of a natural sand. The minimal volume increases therefore are calculated as shown in equation (1).

$$V_{silo} = V_{sample} * \frac{\rho_{d,max}}{\rho_{d,min}} \qquad (1)$$

Underneath the silo, a slide damper is located. The construction of the slide damper is a self-constructed metering valve with the openings of the sliding plates organized in a checker pattern. In the first construction, it was opened using a stepper motor located on one side of the sliding plates. That meant that the force applied to open the slide damper did not act centrically and therefore created torque. This increased constraining forces on the sliding plates and made the opening of the slide damper more difficult.

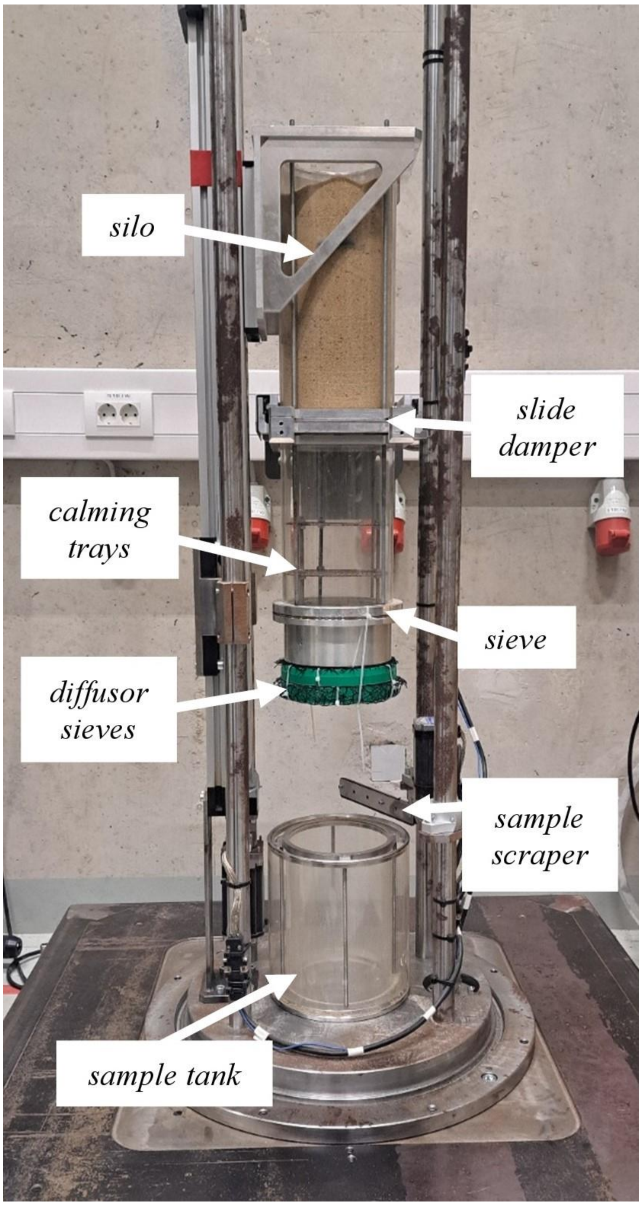

Figure 1: Pluviation apparatus with diffusor sieve

Beneath the slide damper another chamber with two calming trays, each consisting of a sieve with a very high permeability, are arranged. Their primary purpose is to equally distribute the sand over the lower sieve. However, they also avoid segregation of the sand into different size-fractions. This was especially evident in the silo, where the filling led to creation of visible layers. This is no longer an issue underneath the calming trays. The comparison of grain size segregation between silo and calming trays can be seen in figure 2.

Figure 2: Separation of grains in the silo (left) and mixed sample over sieve (right)

Underneath the calming trays a sieve is attached. The sieve is exchangeable to achieve different deposition intensities based on the sieve's permeability. The diameter of the sieve openings is also variable, to allow for experiments with different grain sizes. If the diameter of the openings is smaller than approximately twice the largest grain size of a natural, medium graded sand, pre-tests showed that the openings are easily plugged. However, using sieves with more openings but same permeability generally allows for a more equal distribution of sand across the sample surface.

The attachment of the sieves also allows for the possibility to attach multiple diffusor sieves. Diffusor sieves are supposed to create a uniform sand flow over the entire sample surface, to allow for homogenous compaction (Gade and Dasaka, 2017) (Rad and Tumay, 1987).

The last component of the pluviation apparatus is the sample tank which is constructed out of an inner and outer cylinder. The inner cylinder is the actual sample tank with a diameter of 14 mm and a height of 200 mm, while the outer catches dropout such that it does not contaminate the experimental stand. The outer cylinder is also used to catch sand displaced through the scraper, which can be used to level the sample. This is especially important in tests with closed vacuum bell, because manual sample smoothing after removal of the vacuum bell after the test is assumed to lead to an unwanted compaction of the sample. The sample tank is centred on the base of the test stand.

The base of the test stand forms the connection between the pluviation apparatus and the vacuum bell. Furthermore, it also creates the necessary stability for the test stand during the test as well as attachment and removal of the vacuum bell.

3.2 Vacuum Bell

The original vacuum bell (figure 3, left) was constructed to fit over the pluviation set-up. Due to a failure of the original vacuum bell it had to be reconstructed (figure 3, right). Both the original and the reconstructed vacuum bell consist of a skeleton of metal rings and bars inside of a transparent cylinder consisting of acryl glass. The metal skeleton reinforces the acryl glass against stress from the negative pressure due to vacuum creation. Furthermore, it connects the top and bottom of the vacuum bell to remove stresses from the acryl glass. Connections between all components were constructed airtight with ring seals on the upper and lower ends. Another ring seal was used to create an airtight connection between the vacuum bell and the base of the experimental stand.

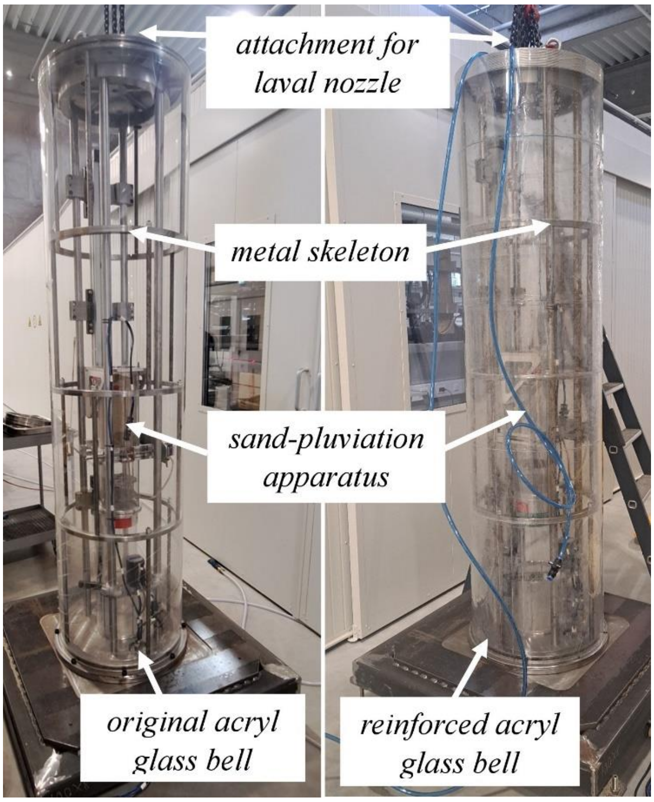

Figure 3: Original vacuum bell (left) and reconstructed vacuum bell (right)

Vacuum is created using a laval nozzle with connections placed on top of the vacuum bell. The minimum air pressure inside the original vacuum bell that could be achieved was approximately 0.1 bar, which equals a vacuum of 90 %. The partial vacuum was achieved after approximately 4 minutes. This vacuum was not repeated in the reconstructed vacuum bell, however, here a minimal air pressure of 0.50 bar has been achieved.

3.3 Electrical components

Next to the mechanical components, the electrical components are of equal importance for the pluviation test stand. This specifically includes the motors, one linear actuator and two stepper motors, and the electrical feedthrough.

The linear actuator is connected to the upper part of the pluviation apparatus and lifts it between and during the pluviation process. This motor needs to be powerful due to the weight of the mechanical components together with the test sand. It also needs to allow for a wide range of possible speeds, to be adjustable regarding the speed at which sand is deposited in the sample tank. The approximate range for the necessary speed can be calculated using the maximum and minimum deposition intensity DI ($g/(s*m^2)$) as well as the maximal and minimal bulk density $\rho_{d,max}$ and $\rho_{d,min}$ (g/m^3) as shown in equation (2) and (3).

$$v_{min} = \frac{DI_{min}}{\rho_{d,max}} \qquad (2)$$

$$v_{max} = \frac{DI_{max}}{\rho_{d,min}} \qquad (3)$$

The stepper motors are powering the slide damper and the scraper respectively. While the stepper motor for the scraper does not need to be particularly powerful, due to the construction of the slide damper, the stepper motor used during the first construction was not powerful enough to open reliably such that it had to be replaced by a more powerful one.

Due to the vacuum bell, all motors need to be operated from the outside of the sand-pluviation stand. Therefore, an electrical connection between inside and outside of the vacuum bell was necessary. For this, an electrical feedthrough specifically for vacuum was built into the base of the pluviation stand. Choosing this component, the specifics for the electrical equipment inside the vacuum need to already be known. Otherwise, the connections of the electrical feedthrough may not be suitable. This also makes later adjustments of the electrical components difficult.

3.4 Test procedure

To perform a pluviation experiment under air pressure, the appropriate sieve as well as diffusor sieves need to be selected and attached to the pluviation set-up. Afterwards, the sand sample is filled into the silo, and an appropriate speed to lift the pluviation apparatus maintaining a consistent falling height is selected. To begin the experiment, the slide damper is opened, and the linear actuator lifts the pluviation apparatus maintaining a constant falling height with respect to the height of the sample. After the entire sample material is deposited, the scraper is used to level the sample. Then, the sample container can be removed, and the sample is examined.

If a pluviation experiment is performed under vacuum, the vacuum-bell is attached after the silo is filled by lifting it over the entire pluviation apparatus and fixing it air-tight to the base. Then vacuum is created until steady-state conditions are reached. After the sample is levelled by the scraper, the vacuum bell is removed.

4 DIFFICULTIES AND ADJUSTMENTS

During (continuing) experiments several difficulties regarding the original set-up were discovered. These were contamination of the components with sand, rusting of parts of the set-up, the vacuum bell and spilling of sand next to the sample tank.

4.1 Contamination with sand particles

The first problem that showed was contamination of different components with sand. This became especially problematic considering the moving components, specifically the slide damper.

Due to the construction and movement of the slide damper, it was possible for grain particles smaller than 0.5 mm to penetrate between the sliding plates, leading to high resistance while opening. That meant that in this case, the stepper motor was not powerful enough to reliably open at the start of the experiment.

The first solution was to reduce the number of openings in the metering valve. Unfortunately, that also reduced the flow rate of sand from the silo. This led to a too small flow out of the silo during experiments with high deposition intensities, as the sieve was not always entirely covered. This created an unequal deposition across the sample surface.

Additionally, to avoid problems with small sand grains, a small portion of the sample was sieved to particles > 1 mm, which was then placed in the opening of the slide damper. Due to the larger size, these particles could not penetrate between the slider plates, and the slide damper could open completely. After the silo was emptied, no more sand particles could end up between the slider plates, the slide damper closed without problems.

However, these solutions were only temporary fixes, and the slide damper had to be reconstructed. The new construction (figure 4) consists of a significantly stronger stepper motors, which is centrically attached on the slider plate with a joint. This allows for a reliable slide damper, which opens even if the silo is filled with grains < 0.5 mm, even without reducing the number of openings. Nevertheless, the slide damper should be continuously improved, to achieve a reliable and durable component.

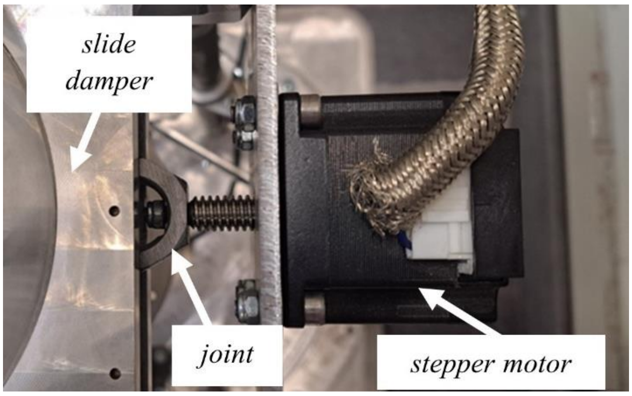

Figure 4: New design for stepper motor attachments to sliding plate

4.2 Rusting

The next problem which showed itself during the use of the experimental stand was rusting of certain components, an example of which can be seen in figure 5.

This rusting was the result of a combination of high humidity due to shared laboratory space, handling of certain components with bare hands and material choice. It was determined that specifically different steels used for the test setup were susceptible to rusting, while the aluminium alloys have not shown any sign of rusting at this point.

However, until this time, the rusting has not led to issues considering the execution of experiments and has apparently not affected operation or stability of the test stand.

Figure 5: Rusting of the sand pluviation test stand

4.3 Vacuum Bell

The vacuum bell proved to be the most difficult part of the construction. During the second test with the original vacuum bell, the bell suffered a catastrophic failure at 0.1 bar leading to full destruction of the vacuum bell. The results are shown in figure 6. Therefore, it had to be redesigned and reconstructed.

Figure 6: Failure of the original vacuum bell

The new vacuum bell had the same requirements as the original vacuum bell, specifically concerning the visibility of the pluviation apparatus, however, it had to be reinforced to guarantee higher stability especially at high vacuum levels. This means, that the acryl glass used in the construction was arranged in a double layer, and the two layers were connected with acryl glue. Further, as outermost layer a protective foil was applied, to both protect the vacuum bell from outside damage, as well as to protect the environment from shards should another failure occur.

In addition to the reconstruction, it was decided that the pressure inside the vacuum bell would initially be limited to 0.5 bar for the first test series. The air pressure will also be lowered slower compared to the case with failure.

Until this time the new vacuum bell could both hold vacuum as well as withstand the stresses caused by vacuum generation. However, the new vacuum bell will be continuously monitored to prevent another catastrophic failure.

4.4 Spilling of sand

Spilling of sand next to the sample tank during the pluviation was an expected side effect during experiments. Due to partially elastic impacts of the sand grains, they are “reflected” from the sample surface and out of the sample tank. This effect becomes stronger with increasing deposition intensity and falling height, as well as with decreasing grain size.

However, in certain set-ups, specifically with certain diffusor sieves, many of the sand particles are also deflected sideways, which means that a large amount of sand spills. In these cases, the silo is not large enough to fully fill the sample tank, due to the sideways losses, and that the entire base needs to be cleaned after every experiment. Furthermore, the spilled sand often contained a larger fraction of small particles compared to the original material. This means that with continuing spilling, the sample composition changes over time, which again significantly influences the pluviation results. This may lead to inhomogeneity in large-scale samples if the wrong version of diffusor sieves in chosen, with larger grain sizes closer to the centre and smaller to the outside of the sample. Furthermore, the grading curve of the samples will need to be continuously monitored.

5 PRELIMINARY RESULTS

During preliminary experimentation it was determined that all the previously described factors as well as the grain size distribution and grain roughness had a significant influence on the sample density. In figure 7, an example of medium sand at a falling heigt of 800 mm at different air pressures with two different deposition intensities is shown. The slight increase in bulk densities with decreasing air pressure is comparable with results from literature (Lagioia et al., 2006).

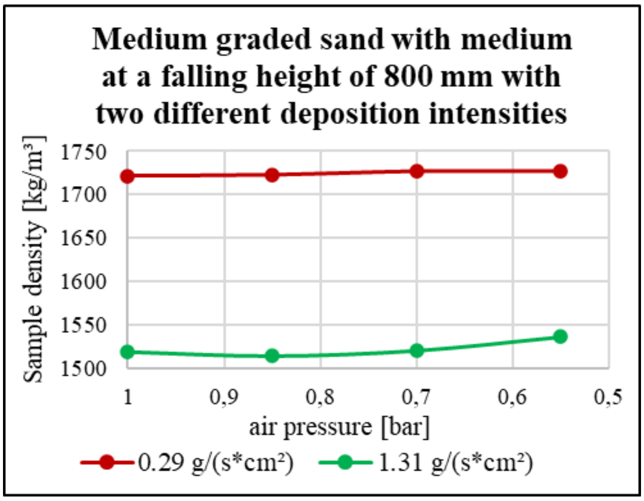

Figure 7: Preliminary test results regarding the effects of partial vacuum on the sand-pluviation of a medium graded sand at a falling height of 800 mm

6 CONCLUSIONS

The described newly developed sand-pluviation test stand has generally led to a versatile testing equipment. The adjustability concerning falling height, deposition intensity, air pressure and general set-up has already proved to be helpful investigating the influence of different influencing factors separately. With this, the effects on sample density, homogeneity and grain size separation can be investigated, leading to a more comprehensive understanding of sand-pluviation under a variety of conditions.

Additionally, the linear actuator and scraper for levelling of the sample have not created any issues and are both powerful and resilient enough. This also applies to the electrical vacuum feedthrough.

However, certain aspects of the sand-pluviation test stand still require improvement. First, the entire set-up needs to be more easily cleanable. This will require another redesign, to allow for pressurised air to reach all components of the apparatus more easily. Furthermore, the slide damper should be redesigned for future pluviation stands, to require less maintenance. The same applies to the material choice. While the use of acryl glass can provide important insights on the processes which occur during the pluviation, the material is not suitable for long term use without replacement. Finaly, the corrosion tolerance of the materials, specifically the metals used also needs to be considered, to improve the longevity of the testing equipment.

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