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Creating seafloor conditions in geotechnical centrifuges

La création des conditions de sol marin en centrifuge géotechnique

J. Laue & S.M. Springman
Institute for Geotechnical Engineering, Swiss Federal Institute of Technology, Zürich

P. Nater
Mengis & Lorenz AG, Luzern

E. Graemiger & A. Ducksch
Basler & Hoffmann AG, Esslingen

ABSTRACT
Soil models can be built in geotechnical centrifuges under specified procedures with good reproducibility between 40 and 100 % relative density. Nevertheless, many problems require model making with loose samples, especially when seafloor conditions are to be represented. Samples for arm centrifuges are disturbed during transport of a model container from the laboratory to the centrifuge and they require complex procedures to create a model in-flight. Nevertheless, loose granular soil samples can be produced in flight in a geotechnical drum centrifuge, which even offers a large area for potential offshore tests. The procedure adopted to create the sample, as well as first site investigation tests using a piezocone, and shallow foundation tests will be presented, together with a critical discussion on the quality of the sample.

RESUME
Des modèles de sol d'une densité relative comprise entre 40 et 100 % peuvent être construits dans les centrifugeuses géotechniques avec une bonne reproductibilité. Néanmoins, beaucoup de problèmes exigent la fabrication de modèles avec des échantillons lâches, particulièrement quand des fonds marins doivent être représentés. Les échantillons pour les centrifugeuses à bras sont perturbés pendant le transport du récipient contenant le modèle du laboratoire à la centrifugeuse et ils exigent des procédures complexes pour créer un modèle en vol. Néanmoins, des échantillons granulaires lâches de sol peuvent être produits en vol dans une centrifugeuse géotechnique à tambour, qui offre même un grand espace pour des essais potentiels en off-shore. Le procédé adopté pour créer l'échantillon, ainsi que les premiers essais d'exploration de site utilisant un piézocone et les essais de fondations superficielles seront présentés ainsi qu'une discussion critique sur la qualité de l'échantillon.

1 INTRODUCTION

The quality of a soil model has to be one of the major concerns in judging the results of geotechnical model tests. Granular soil models can be built in geotechnical centrifuges under specified procedures with good reproducibility between 40 and 100 % relative density (compare for example Bolton et al., 1999). Nevertheless, modelling of some prototype questions requires model making using very loose samples e.g.. to be able to represent seafloor conditions.

Sample preparation techniques developed for standard laboratory experiments are adopted in centrifuge modelling when building a sample for a geotechnical centrifuge test outside the centrifuge at 1 g in the laboratory. Methods of preparation of loose samples include pluviation, tamping and fluidization. To be able to represent the prototype behaviour with high reproducibility, homogeneity and to represent the strength and stiffness conditions of the sample due to insitu stresses and interlocking of the particles is extremely important.

Creating loose samples by air pluviation requires very low falling heights and relative densities as low as D=10% can be reached (e.g. Stuit, 1995). Air pluviation allows reproducible soil models to be built and many centrifuge centres use automatic sand pluviation apparatuses (e.g. Chen et al., 1998), even though Garnier et al. (1992) already showed that the use of an automatic pluviation system lead to homogeneous soil samples only in a very limited area of a model container, so that relatively big containers are required to eliminate the influence of the boundaries.

Creating samples by tamping leads to lack of homogeneity, representing the conditions of a fill placed in different layers (Lee et al. 1999). Other possibilities to create loose samples at 1g in the laboratory include fluidisation or dynamic fluidization (van der Poel & Schenkeveld, 1998) allowing very homogeneous samples to be created, even though dynamic fluidisation is restricted to densities not lower than 30%.

Even though methods exist to create loose samples under laboratory conditions, the quality of the sample will suffer under the transport conditions from the laboratory to the centrifuge and the subsequent installation procedures. Transferring the sample preparation to a centrifuge basket might restrict sample disturbance due to transport, but the quality and especially the density of the sample will be influenced by the starting and swinging up procedures of the specific centrifuges.

The influence of the layering of grains and their degree of interlocking affects the mechanical behaviour of the soil, which is not only influenced by the density but also by the genesis. Vaid et al. (1995), (Fig. 1) compared the stress strain behaviour of samples of the same material and almost similar void ratio as a function of their preparation. It is clearly visible, that samples prepared by moist tamping and even (less pronounced) dry pluviation showed dilatancy, while samples prepared by pluviation under water show strain hardening.

Based on the previous discussion, it is logical to prepare a soil sample to represent seafloor conditions using water pluviation. If the sample preparation is conducted in flight, it may be possible to annul the influence of transport procedures and of vibrations during the start of a centrifuge, as well as densification processes due to settlements of an existing soil sample while increasing the g-field. Pluviation under g is possible in arm centrifuges, (e.g. Almeida, 1984) but no hopper is available at any big centrifuge centre (arm and drum centrifuges) with the capacity to create a full soil sample to the authors' knowledge.

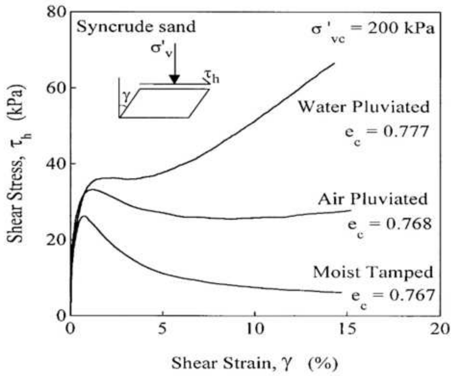

Figure 1: Results of simple shear tests on sand for different sample preparation techniques (Vaid et al., 1995)

2 PREPARING GRANULAR SOIL SAMPLES IN DRUM CENTRIFUGES

Two different methods are used to build a sand sample in a drum centrifuge. One method of placing a sand sample inside a drum centrifuge is described by Dean et al. (1990), (Fig. 2).

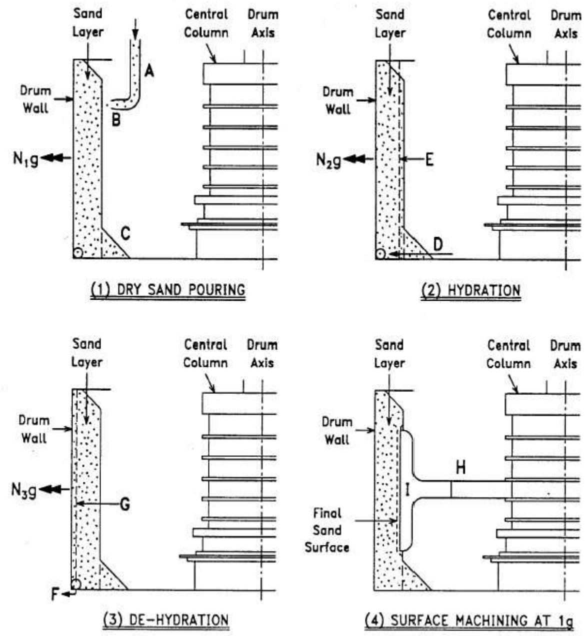

Figure 2. Sand placement in a drum centrifuge (Dean et al., 1990).

Dry sand is blown by air pressure into the drum (Fig. 2.1). The nozzle (B) can be moved up and down to create a specific surface geometry, as the drum rotates around it. A base wedge (C) is required to stabilise the soil deposit when the centrifuge has stopped and the resultant gravity field has returned to the vertical 1 g condition. The density achieved is a function of the flow rate of the sand, air pressure aiding the flow and the centrifuge acceleration. The sand is saturated after infill (Fig. 2.2) and then desaturated (Fig. 2.3) to cause suction in the soil sample. This stabilises the sample while the centrifuge is stopped to conduct further sample preparation events such as installation of transducers or surface preparation by using e.g. a scraping tool (I) at 1g (Fig. 2.4). Saturation and desaturation can be carried out at different g-levels to further influence the density.

Another method, adapted in the drum centrifuge of ETH Zurich (Springman et al. 2001), which is discussed in more detail in Laue et al. (2001), is caused by concerns related to the safety aspects of having a stationary nozzle next to the rotating sample. The nozzle as given in Figure 2 was replaced with a spinning disk. The upward and downward movement of the safety shield provides the change in vertical height. The sand is poured with a controlled flow rate from a sand hopper through the tube and onto the spinning disk, which then accelerates the grains radially (Fig. 3).

Both methods might be used to place sand in the drum, not only under dry conditions, but also on top of a water surface in the spinning drum, to allow particles to sediment out in order to simulate the genesis of most seafloor conditions.

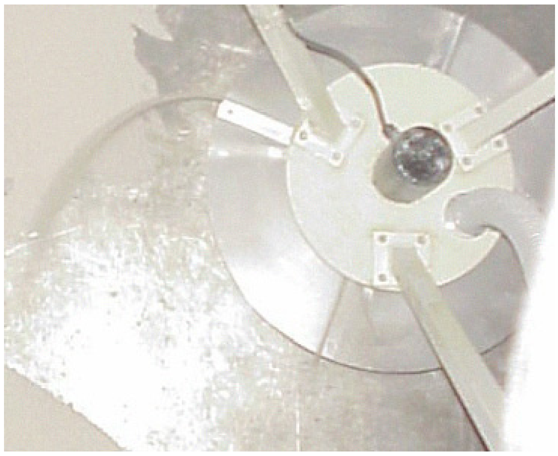

Figure 3. Spinning disk spreading sand in the ETHZ drum centrifuge (Laue et al., 2001).

3 PLUVIATION IN FLIGHT OF GRANULAR SOILS THROUGH A WATER SURFACE

In the framework of two Diploma theses (Grämiger, 2001, Ducksch, 2001), a model was built into the ETH drum channel of the ETH Zurich drum centrifuge to conduct penetration as well as foundation tests. The granular soil was a fine grained sand with 10% silica flour. The gradation curve can be seen in Figure 4. Material parameters according to density (γ_s – density of the solids, γ_{min} and γ_{max} – minimal and maximal density according to ASTM D854, 4254 and 4253 respectivly and C_U – uniformity coefficient d_{60}/d_{10}) are given as follows:

γ_s = 2.65 g/cm^3	C_u = 3.8
γ_{max} = 1.87 g/cm^3	n_{min} = 1 - γ_{max} / γ_s = 0.294
γ_{min} = 1.54 g/cm^3	n_{max} = 1 - γ_{min} / γ_s = 0.419

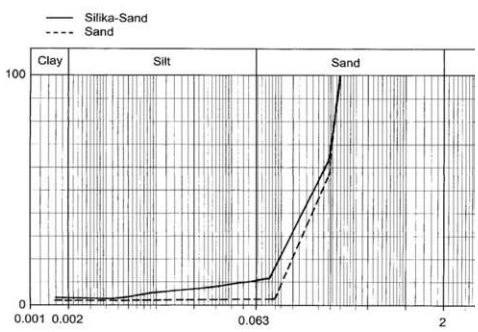

Figure 4: Gradation curves of the used material

The soil has been placed in the spinning drum while it was filled with approximately 10 cm of free water. The velocity of the drum was set to 150 r.p.m. representing a nominal g-level of 25g at a radius of 1m. The sand was pluviated with a flow rate of 280g/s by a hopper onto the spinning disk rotating with 770 r.p.m., which distributes the soil into the drum. The additional fines of the silica flour where mostly segregated (the preparation method and the segregation has been discussed in Laue et al., 2001) so that the resulting sample was effectively a sand sample. Figure 5 shows a section through the sample inside the drum after preparation of the soil model and after scraping the surface. Due to the effect of the vertical component of gravity, the sample is thicker at the bottom of the drum. A natural slope angle of the soil model has been developed at the top. The visible step at a height of about 150 mm was created by pluviating more material in the lower part of the channel.

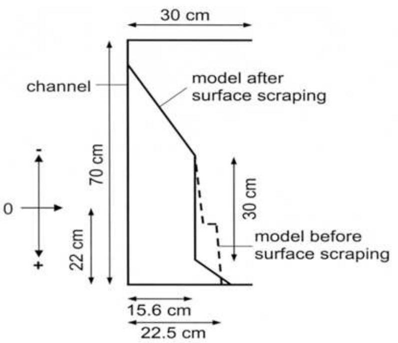

Figure 5: Shape of the soil sample in the channel of the drum after model making before (dotted line) and after (full line) surface treatment by scraping (after Ducksch, 2001 and Grämiger, 2001).

After preparing the soil sample in flight, the sample was dewatered and the centrifuge was stopped in order to create a horizontal surface by scraping the sample at 1g. The sample was held stable by suction due to the remaining amount of fines. Previous attempts of preparing soil samples under water using purely fine grained sand (Fig. 4) failed while stopping the centrifuge as suction forces where too low to keep the sample stable under 1g conditions. The surface of the sample was smoothed by scraping to create an area with a width of 30 cm with a flat surface. The remaining depth of the sample was 156 mm. The scraping procedure of can be seen in Figure 6.

After preparation of the sample surface, the centrifuge has been spun up and the sample has been saturated again. In total 21 cone penetration tests (CPT) and 11 foundation tests have been carried out on one drum sample to study model making as well as the bearing capacity of axisymmetric foundations. The tests have been conducted at four different levels of increased gravity; 25g, 50g, 75g and 100g. Distribution of density along the height of the sample was measured after the test with tube samples. Results of the CPT tests along a radial and a vertical cut are given in Figures 7 and 8.

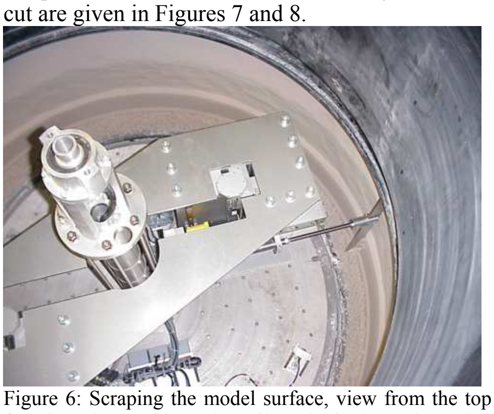

Figure 6: Scraping the model surface, view from the top of the centrifuge into the machine. The soil model is drum channel while the scraping tool is mounted into an actuator placed on the rotating toolplate.

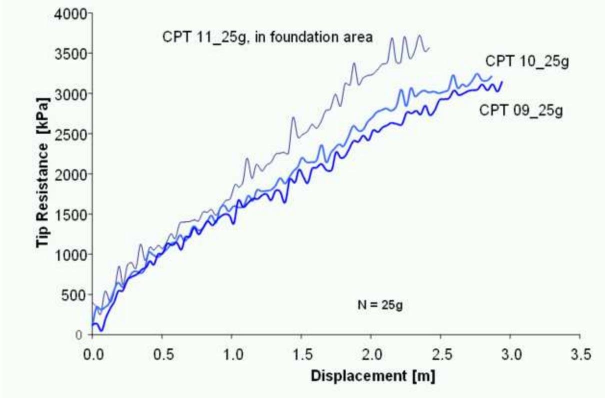

Figure 7: Tip resistance versus displacement at 25g (prototype scale) at three locations around the radius of the drum at a constant height of 220 mm relative to the bottom of the drum as shown in Figure 5 (Grämiger, 2001).

The results of the CPT around the radius of the channel (Fig.7) show good reproducibility of the results. The test CPT 11 shows higher values because it has been conducted in an area of a previous foundation test indicating the influence of densification. Variation of the CPT data over the height of the sample is more noticeable.

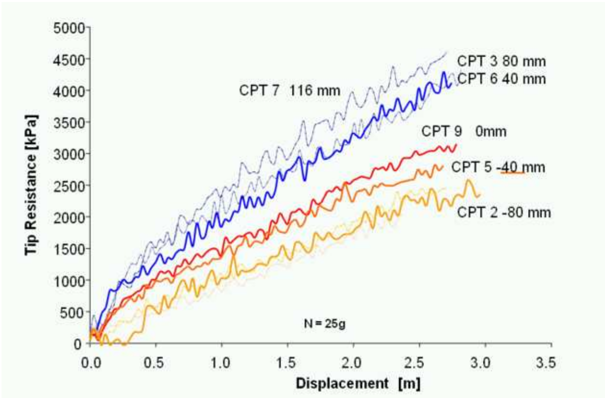

Figure 8: Tip resistance versus displacement at 25 g (prototype scale) over the height of the sample, locations are given according to Figure 5 (after Grämiger, 2001)

Tests conducted at larger height (indicate by negative values in the description having 0 at a real height of 220 mm relative to the bottom of the sample as shown in Figure 5) show lower values (tests further up than CPT2 at -80 mm are not shown but show the same tendency) than those located more towards the bottom of the sample (Fig. 8). This is due to the effect of the slope in the proximity to the slope in the upper part of the sample and due to the step (Fig. 5) causing already a pre-loading of the soil model before scraping. The influence of pre-loading or in this case real overconsolidation can further be seen in Figure 9. Here 2 CPT tests conducted at 25g at the same height are compared, one conducted during the first acceleration towards 25g and the second after finishing all tests and the sample had been accelerated towards 100g and then decelerated back to 25g. An OCR of 4 almost doubled the tip resistance.

The effect of densification must be considered when comparing results of model verification tests on shallow foundation (Fig.10). Two foundation tests conducted at 25g with a model diameter of a foundation of 56mm are presented together with 2 tests conducted at 50g with a foundation of a diameter of 28mm. The stiffness of the soil model is increasing with increasing g-level, which is confirmed by the load settlement curves as well as the CPT tests given in Figure 9. For samples where an increase in settlement due to self weight has no influence, those load settlement curves should be laying on top of each other (Ovesen, 1979). It is also notable, that variations inside the tests conducted under the same g-level have relatively minor effects on the result. A foundation with a flat interface has a slightly lower load-settlement response than a foundation with an interface matched to the surface shape of the sample. The velocity of loading is been varied for the tests conducted at 50g, A faster loading velocity causes a slightly stiffer response.

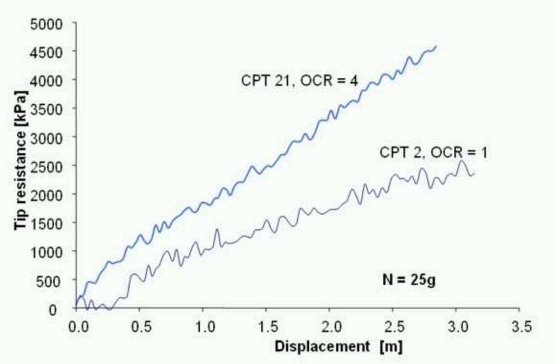

Figure 9: Tip resistance versus displacement at 25 g (prototype scale) for two tests with OCR = 1 and OCR = 4 (after Grämiger, 2001)

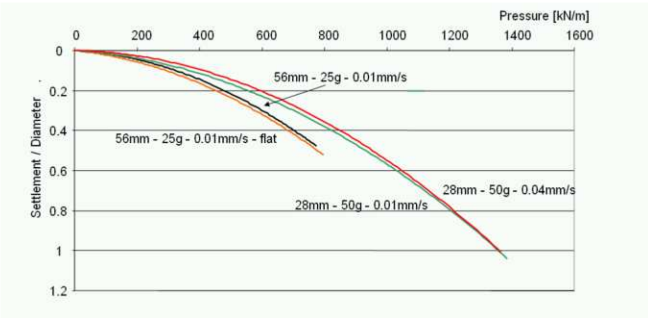

Figure 10: Load settlement curves of circular foundations representing the same prototype (after Ducksch, 2001)

Density has been measured at several locations after all tests have been conducted and the centrifuge has been stopped. The distribution of density is shown together with the results for two tests being prepared with dry pluviation under different boundary conditions (DPA 1.2 and DPA 1.3) in Figure 11. The density for the test prepared by pluviation into water (DPA 1.1) is as low as 1.46 – 1.48 g/cm^3 (equivalent to a relative density of around -20%, while the minimum density derived in the laboratory for the material is 1.54 g/cm^3 according to ASTM, 1111) even though the sample had already experienced a stress history of being brought to 100g. The distribution of density corresponds well with the CPT results.

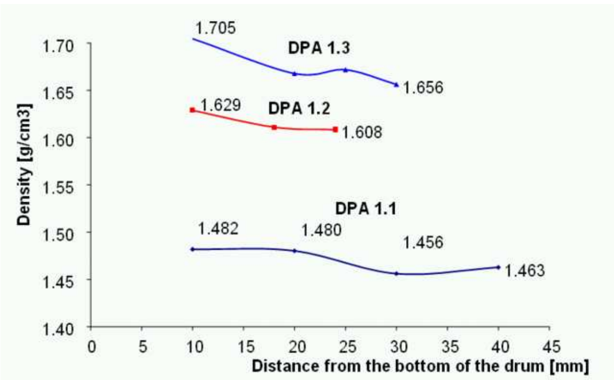

Figure 11. Distribution of density along the height of the sample (after Grämiger, 2001)

4 SUMMARY AND CONCLUSION

Seafloor conditions can be created in a centrifuge by reproducing similar procedures to nature. Sedimentation of sand spread on a free water surface have been shown to be a reasonable method to create samples for centrifuge model tests with relative densities even lower than 0% (relative to ASTM, 1111), while for samples prepared by dry pluviation using the same apparatus a minimum relative density of around 25% could be reached. Consideration of homogeneosity of the sample and the stress history both of which have a major influence on the performance of the sample. Inevitably the test procedures shown here might be refined for exact targeting a specific density.

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