5th ECPMG
Delft · 2024

Proceedings of the 5th ECPMG 2024
5th European Conference on Physical Modelling in Geotechnics
2-4 October 2024, Delft, the Netherlands

How to deal with glauconite sands in physical models

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ABSTRACT: The current trend of the offshore wind industry is to exploit areas of the world that were not previously considered suitable for windfarm developments. For instance, in the coming years a large development is expected in the East coast of the United States, where the soil conditions are particularly demanding due to the presence of glauconite sand. To understand the mechanical behaviour of challenging geomaterials during pile installation, physical modelling is a cost effective and valuable tool. There are well established methods for preparation of clean sands and cohesionless soils such as silica sands, however these approaches cannot be directly used in case of sand containing fines such as glauconitic sand collected in Antwerp, Belgium. This paper describes a novel approach to prepare repeatable and homogeneous samples under fully water saturated conditions for chamber testing, including practical information and limitations, developed for glauconitic sand containing fines.

1 INTRODUCTION

The urgency and ambition to replace fossil fuels with renewable energy by 2050 have led to a significant growth of the offshore wind industry. As a result, several countries are refocusing on renewables to boost their energy security (GWEC, 2023). In the coming years, it is then expected that windfarm developments will progress towards regions with potential challenging soil conditions. An example is the East Coast area (US) which includes the presence of glauconite deposits.

Of great interest for the mechanical response of the glauconitic soils is the high susceptibility to crushing experienced from the glauconite particles at low stresses (Belotti et al, 1992). As a result of the crushing phenomenon, the coarse sized glauconite particles are transformed into a fine-grained material leading to a different geotechnical behaviour (Westgate et al., 2022). This is relevant for piling operations as highlighted by many authors observing a high number of blow count and driving time during pile installations (De Nijs et al., 2015, Ganne et al., 2020, Perikleous et al., 2023).

In order to investigate the geotechnical behaviour of this challenging geomaterial, more research is needed both in field and laboratory. Physical modelling is a cost effective and valuable tool to gain more insights on the mechanical response of glauconite sands.

Some trial pile and cone penetration tests were performed in calibration chamber (CC) using glauconitic sand collected in Antwerp, Belgium. As the sand contained fines, it was challenging to prepare homogeneous water saturated samples. Therefore, different sample preparation methods were thoroughly investigated prior to testing.

This paper intends to provide an overview of the difficulties encountered during sample preparation and practical information when testing glauconitic soils.

2 LITERATURE REVIEW ON SAMPLE PREPARATION

Sand specimens for calibration chamber (CC) tests have been commonly prepared by pluvial deposition in air or vacuum due to their highly repeatability and good uniformity in the results (Ghionna and Jamiolkowski, 1991). In the pluviation technique (dry or wet), the material is poured dry into the dry container or in water. For dry pluviation, the final density of the specimen is controlled by the fall height

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of the particles, which influences the energy of particle deposition (Zania et al., 2020).

For offshore studies, saturation of the sample is a requirement. Instead of saturating the sample after its preparation, sand can be pluviated directly into (de-aired) water. In order to achieve denser saturated soil models, tamping can be used to compact the sample. The soil surface is continuously tamped while the soil is poured into the sample container (Mulilis et al., 1975). The wet tamping method presented by Ladd (1978) aimed to minimise particle segregation when using well-graded and silty sands and to achieve uniform specimens. This so-called under compaction method was based on increasing the compaction for each new layer of moist soil applied so that each following layer could further densify the previously poured soil.

Another method to achieve denser saturated soil samples was described by Poel and Schenkeveld (1998) and is called the dynamic fluidization-compaction method. Dry sand is directly poured in sufficient de-aired water, leading to a homogeneous low-density sample. After the pluviation stage, the whole sample is compacted by means of tamping. Relative densities varying from 30% to 65% can be achieved. A variation on this method was presented by Rietdijk et al. (2010). Instead of pouring dry sand, a mixture of sand and de-aired water was pumped from a storage cell to a model container and a showerhead was adopted to let the sand drizzle down. At the same time, the excess water flows back to the storage cell containing the sand-water mixture. This technique can be also combined with the layered compaction described by Mulilis et al. (1975) in case a relative density higher than 65% is aimed for. An advantage of this so-called drizzle method is the possibility of using moist soil in the model preparation.

Minimisation of segregation in sample preparation procedures ensuring fully saturated state was also studied by Kuerbis and Vaid (1998) who proposed the slurry deposition method for the reconstitution of homogeneous samples of well-graded and silty sands in a triaxial cell by means of preparing two separate slurries of fines and sand, and pouring them into a mixing tube in order to minimize the particle drop height through water during deposition. This method produced homogeneous well mixed samples that could be repeatable.

3 TEST MATERIAL

The glauconitic sand used for this research was obtained from a natural deposit in the Oosterweel connection project in Antwerp, Belgium, and it belonged to the Kattendijk formation (DOV Portaal, n.d.). Magnetic separation test results indicated 11% of glauconite content.

To ensure an adequate and consistent soil sample preparation and avoid the impact of gravel particles on friction resistance and crushing characteristics during CC experiments, particles larger than 5mm were removed. The material obtained is denoted as "as-received" throughout the paper.

The particle-size distribution of the as-received soil was obtained using a Malvern laser diffraction particle sizing device, compliant with ISO 13320:2020 (ISO, 2020) (see Figure 1 and Table 1 for averaged results of two samples). It was classified as silty sand with 2% clay content (<2μm), 10% silt (2÷63μm) and 88% sand (>63μm).

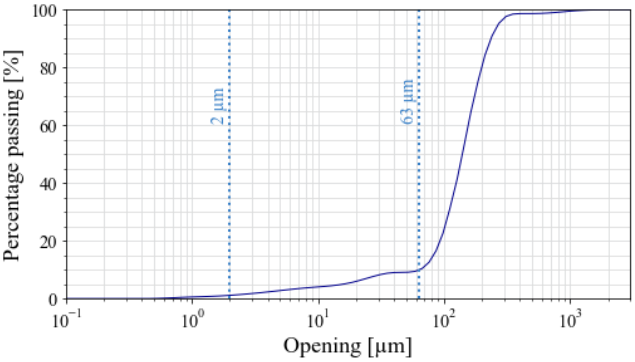

Figure 1. PSD as-received glauconitic sand.

Table 1. Summary of particle sizes for as-received glauconitic sand.

	D_{60} [μm]	D_{50} [μm]	D_{30} [μm]	D_{10} [μm]	C_u [-]	C_c [-]
Malvern	160	137	107	50	3.20	1.43

The specific gravity (G_s) of the as-received soil determined using the Gas Pycnometer type Ultrapyc 5000, compliant with ASTM D5550-23 (ASTM, 2023) was 2.728. The maximum and minimum dry density ($\rho_{d,max}$, $\rho_{d,min}$) were determined using ASTM D4253 (ASTM, 2016) and ASTM D4254 (ASTM, 2016) as 1.33 g/cm^3 and 1.06 g/cm^3, respectively. These relative low values can be explained by aggregated clumps remaining in the sample due to oven drying (Westgate et al., 2023).

4 PROPOSED SAMPLE PREPARATION

4.1 Experience with the as-received material

Before obtaining the dense homogeneous saturated samples for CC tests, a familiarization phase was performed with the as-received material. The objective of this phase was to assess the applicability of the standard preparation methods used for silica sand in relation to glauconite sand specimens previously studied in the literature review.

An initial attempt was made by pluviating with a scoop the moist silty glauconitic sand into a plastic/glass jar filled with a thin layer of water, followed by tamping (Figure 2). The same procedure was also performed using oven-dried soil. Although segregation was not occurring in both cases due to the thin layer of water used, a quicksand effect was observed in response of the tamping process followed by the impossibility to compact the material. Different ratios of soil and water were also used to evaluate the soil response. Increasing the thickness of the water layer induced considerable segregation due to the subsequent longer depositional time for fines. Also, a significant amount of foam was noted on the water surface after pouring the material into water.

Figure 2. Photo frames from a video trying wet tamping in the moist as-received soil.

After the difficulties experienced with the approaches described above, another attempt was made by consolidating the sample through the application of a static uniformly distributed load. After 3 hours hardly any compaction was observed. This seemed to be a result of the relative large percentage of sand particles. The resulting sample was still loose and soft after the consolidation period.

Wet tamping followed by vacuuming the sample or vibrating the walls of the container were also tested to improve the compaction process. This procedure however did not allow to have a homogeneous saturated sample.

After all the trials, it was then decided to test an "idealised material" to obtain a more homogenous sample in fully saturated conditions. This was created by washing out the fines (<63 μm), as will be described in detail in the following section 4.2. Pluviation of moist soil followed by wet tamping was then tried with the new idealised material which resulted in obtaining a dense, well-compacted, homogeneous and fully saturated sample. It should be highlighted that crushing of the material was checked by observing the particles in the microscope before and after tamping, and crushed particles were not observed. This procedure was considered a good compromise to create the glauconite samples in the CC for the purpose of the research.

4.2 Soil preparation: removal of fines

After the initial familiarisation phase, it was decided to adopt an "idealised material" (i.e., clean material) consisting of a particle size distribution ranging between 63μm and 5mm (Figure 3). This, not only allowed to obtain a dense and well compacted sample, but also to better evaluate the crushing phenomenon during the CC experiments.

The procedure had to be cautious in order to avoid the occurrence of crushing of the glauconite granules during sample preparation. The procedure consisted of the following steps (see Figure 3 for reference):

a. Fill approximately half of a cylinder or container with as-received glauconitic sand.
b. Fill the same cylinder/container with water, using a high flow (e.g. high-pressure water hose) to the top in order to properly mix the soil and to remove the foam formed.
c. Allow segregation to occur, waiting approximately 5 minutes. Check with a beaker the fines remaining floating in the water and repeat steps b-d until almost no fines are observed (approx. 5-8 times).
d. Pump the water containing fines out.

In order to avoid fully saturated soil for the sample preparation and be able to quantify its moisture content, the bag containing the soil was lifted up to allow for drainage some days before preparing the sample.

Figure 3. Soil preparation process: removal of fines.

This process aimed to be equivalent to performing wet sieving using a 63 μm opening sieve, since it was proofed by passing the pumped water through this mesh. Magnetic separation test results (Table 2) showed similar glauconite contents between as-received material and clean material highlighting the fact that the bulk of glauconite granules were kept in the sand fraction. Figure 4 shows the comparison between the PSD curves of the as-received soil and the idealised glauconitic sand sample obtained from the abovementioned procedure. The latter was analysed from the undisturbed soil after performing the CC tests. The particle sizes are summarised in Table 3. A visual comparison of the change in texture of the soil is shown in Figure 5.

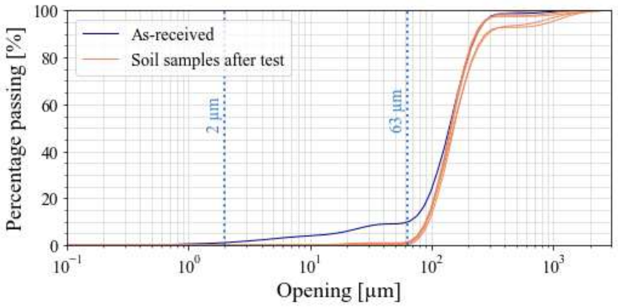

Figure 4. PSD of the soil used to prepare the samples compared to the as-received soil.

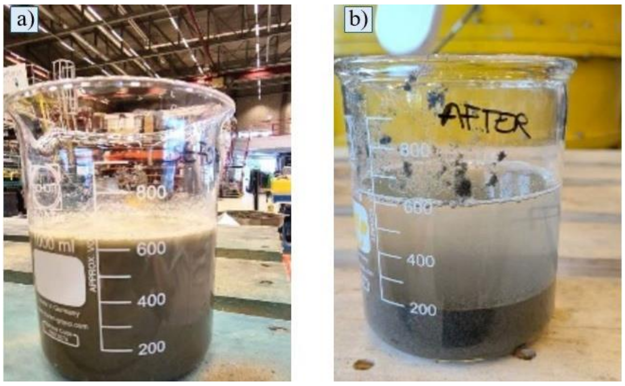

Figure 5. Visual comparison between the soil as-received (a) and the soil after removal of fines (b). These are frames from a video in which the soil is poured and mixed during 30 seconds in water.

Table 2. Results of magnetic separation tests on as-received and clean samples of glauconitic sand.

	As-received	**Clean**
Average glauconite content by weight [%]	11.1	13.2

Table 3. Summary of particle sizes for clean material samples of glauconitic sand.

	D_{60} [µm]	**D_{50} [µm]**	**D_{30} [µm]**	**D_{10} [µm]**	**C_u [-]**	**C_c [-]**
Malvern	160	145	118	90	1,78	0,99

The clean sand fraction of the soil had a specific gravity (G_s) of 2.667 and the maximum and minimum dry densities ($\rho_{d,max}$, $\rho_{d,min}$) were 1.66 g/cm^3 and 1.48 g/cm^3, respectively. The corresponding maximum and minimum void ratios (e_{max} and e_{min}) were 0.8 and 0.61, respectively. These were determined using the wet method of ASTM D4253 (ASTM, 2016) and ASTM D4254 (ASTM, 2016).

4.3 Calibration chamber sample preparation

The soil models were prepared in a 1 m high calibration chamber, with an inner diameter of about 0.85 m, previously designed and constructed by Deltares (Delft, the Netherlands).

The soil model consisted of 460 mm thick layer of Baskarp B15 sand overlain by a 500 mm thick layer of glauconitic sand (Figure 6). As the pile and cone penetration target depths were limited to 400 mm, this was seen as more efficient compared to filling the whole chamber with glauconitic sand due to the laborious and physically demanding process of removal of fines.

The homogeneous sand layers were prepared mixing the techniques from Mulilis et al. (1975) and Rietdijk et al. (2010), in which the moist sand was constantly poured with a scoop into the partially filled chamber with de-aired water, while the material was simultaneously being tamped manually with a flat cylindrical plate so that the air inclusions were reduced and a denser specimen could be achieved.

The bottom layer was created by pluviating dry Baskarp B15 sand in water, while the glauconitic sand layer was prepared by pluviating moist soil (see Table 4). The latter was done by scooping the material, then submerging it under water level and turning the scoop. The water level was approximately 400 mm above the soil surface during sample preparation to maximise the separation of clumps and the degree of saturation.

After the preparation, the sample was anisotropically consolidated (200 kPa effective vertical stress and 100 kPa effective horizontal stress).

Table 4. Summary of sample preparation with glauconitic sand.

		Sample		
		1	**2**	**3**
Average moisture content	[%]	24.2	20.3	24.0

5 RESULTS

To verify the sample preparation procedure after the 3 CC tests, 12 local density measurements at 3 different depths (4 samples per depth) were taken for each model. Moreover, a CPTu test in the first soil sample prepared was performed. The cone used had a diameter of 16 mm. The cone was penetrated with a hydraulic plunger up to 400 mm below top surface at a controlled rate of 10 mm/s.

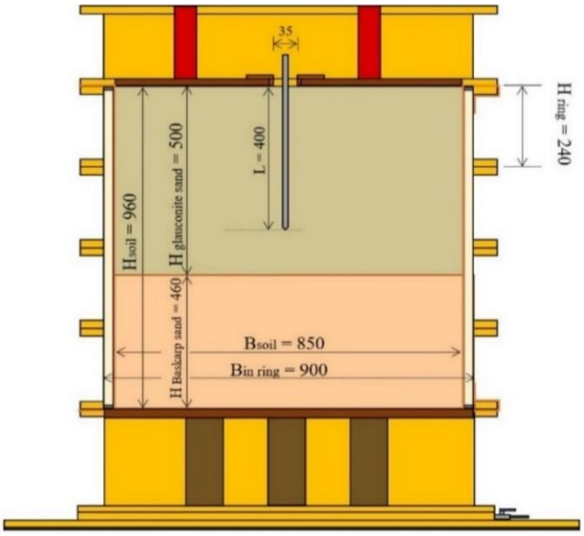

Figure 6. Sketch of the CC indicating the thickness of the soil layers to be prepared and the final pile/cone penetration (measurements in millimetres).

5.1 Density and void ratio measurements

The averaged results of the four local relative density measurements per layer for each soil model with depth are shown in Figure 7. A more or less constant variation of the local density for the soil models and no trends with depth can be observed. The relative density was calculated based on the relative position between the void ratio of the samples taken and the minimum and maximum void ratio obtained from minimum and maximum density tests. Overall, the sample preparation led to a relative density between 65-85%. No trends with depth were observed, however, deviations were noted for each test and per layer, due to the difficulty of the determination of $\rho_{d,min}$ and $\rho_{d,max}$, the small difference there is between them and the accuracy in obtaining the samples.

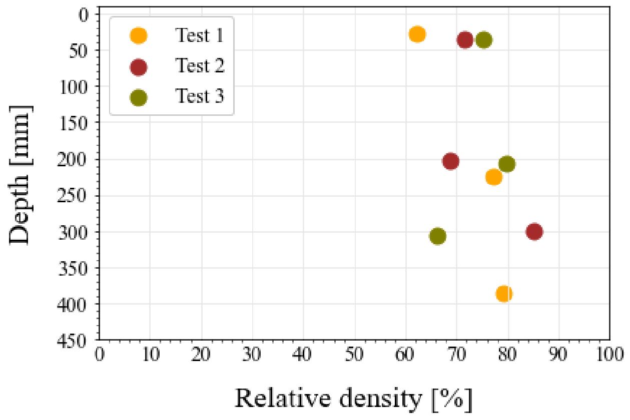

Figure 7. Averaged relative density measurements per layer over the depth below the surface level of the sample.

5.2 CPT recording

The cone resistance (q_c) profile over depth is plotted in Figure 8, together with an average value of the q_c from the field under similar stress conditions. After a first phase of buildup attributed to shallow mechanisms (8 to $10D_{cone}$), the fully mobilized cone resistance was obtained between 30-35 MPa, increasing with depth, suggesting a relatively homogeneous sample.

The higher cone resistance obtained in the calibration chamber compared to the average q_c measured in the field (25MPa) might be attributed to a different relative density and to the different particle size distribution of the tested material. This has to be verified by means of additional tests.

It should be mentioned that, after excavating the soil surrounding the cone, crushing of glauconite granules were observed around it, indicating a soil-type transformation from sand-like to clay-like type.

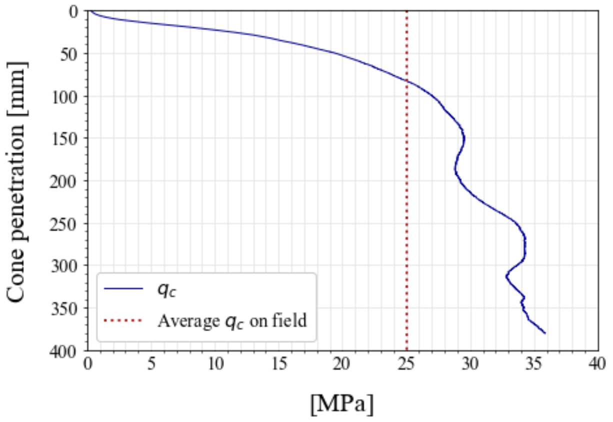

Figure 8. Cone resistance (q_c) profile with depth.

6 DISCUSSION AND CONCLUSIONS

This paper presented an approach on how to deal with glauconitic sands, containing fines for preparing saturated samples for medium scale model tests.

When using the as-received material, standard procedures for silica sand led to different issues during sample preparation, inducing non-homogeneity in the specimens. Therefore, it was decided to remove the fine fraction of the as-received soil by washing out the fines and subsequently pouring under the water the humid glauconitic sand followed by constant tamping in order to compact the soil. This second phase was characterized by a water table level higher than the soil surface, allowing to maximize the separation among glauconitic sand clumps. This procedure ensured keeping a similar glauconite content to the as-received soil. Moreover, both after removing the fines and after tamping, the crushing of glauconite particles was examined and it was concluded that no crushing was occurring.

Local density measurements at different depths and a cone penetration test were performed to determine the homogeneity of the sample prepared for the calibration chamber. The results confirmed the validity in obtaining dense saturated glauconitic soil samples (relative density approximately of 65-85%). This procedure was used to prepare samples for medium-scale model tests aiming at a better understanding of the mechanical behaviour of glauconitic sand during pile installation.

Lastly, the idealised soil created based on washing out the fines showed a q_c profile consistent with the q_c registered in situ, considering the removal of fines and a denser sample prepared. Moreover, crushing of glauconite granules around the cone was observed. However, it is also recommended to investigate the behaviour of the material containing fines in future research.

ACKNOWLEDGEMENTS

This paper is part of broader research program funded by IQIP aimed at better understanding the mechanical response of glauconitic sand under pile installation. The first author is also grateful to the company IQIP who offered her the opportunity to carry out her first research as a MSc student at TUDelft, and Deltares, whose researchers and technicians provided all the knowledge and assistance possible for performing the experiments.

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