Physical Modelling in Geotechnics

Uniform compacted models for centrifuge testing of plastic fine-grained soils

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ABSTRACT: Centrifuge models with fine-grained soils are usually prepared by consolidating soil slurry to obtain better control over the soil stress history. This method is well-established and suitable for soil models with relatively moderate permeability and larger values of coefficient of consolidation. However, to model soils with high plasticity, low permeability, and smaller values of coefficient of consolidation, the time needed to consolidate the slurry models will often be very prohibitively large. In such cases, compacted soil models are most widely used as the models can be prepared in a more practical timescale. However, the consistency of compacted fine-grained soil models is questionable as there is no measure to confirm the uniformity of compaction throughout the model. This paper discusses the consistency of compacted silty clay models with the support of miniature cone penetration (CPT) tests. The soil under discussion is a mixture of silt, kaolin and bentonite which was developed to be representative of spoil (or overburden) material from coal mining sites within UK and EU regions. This paper discusses the spoil geotechnical characteristics, centrifuge model preparation, consolidation characteristics of compacted and consolidated clayey models, and the results obtained from CPT tests at different locations of the models.

Keywords: centrifuge, compaction, cone penetration test, fine-grained soil, spoil.

1 INTRODUCTION

Fine-grained soils are widely found along coastal regions and are generally considered to be problematic due to their significant strength or stiffness variation with moisture content. Geotechnical centrifuge modelling is known for its stress-strain similarity in model and prototype cases and has been found to be advantageous for understanding the seepage and consolidation characteristics of fine-grained soils. For a reasonable comparison between different centrifuge tests, it is essential to use the same type of soil in centrifuge experiments. Thus, while dealing with fine-grained soils, centrifuge modellers around the globe have widely used kaolin in their experiments as it is commercially available and exhibits consistent behaviour across different centrifuge tests. In order to obtain better control over the stress history, centrifuge models are prepared by consolidating kaolin slurry. However, more problematic soils (in terms of swelling and shrinkage characteristics) exist in the field. Sometimes, it may be difficult to replicate such soil behaviour using kaolin alone in centrifuge experiments. For certain field issues, fine-grained soils with high plasticity, low permeability, and smaller values of coefficient of consolidation may need to be modelled in the centrifuge. In such cases, the time needed to prepare a consolidated soil model from slurry stages will generally be prohibitive. The widely known alternative to consolidated models is compacted models, where the soil will be mixed with a particular moisture content and densified using static or dynamic compaction techniques. Nevertheless, the uniformity of compacted models is questionable as it is challenging to induce similar energy at all locations within a soil model using dynamic compaction techniques or the possibility of having deep entrapped air pockets with static compaction techniques. To this end, a novel approach to prepare the compacted models for centrifuge tests is proposed in this paper. The consistency of compacted models is evaluated using a miniature cone penetration device.

2 MATERIAL PROPERTIES

The main objective of the work is to investigate the behaviour of spoil (overburden) material from EU and UK mining sites. By performing extensive soil characterisation tests on samples obtained from spoil samples from the ČSA mine, Czech Republic, it was found that a mixture of 50% silt (A50 silica flour), 30% bentonite, and 20% kaolin provided a good match of particle size distribution, plasticity, and shear strength characteristics with the ČSA open-pit mine spoil (detailed results will be discussed elsewhere). The published literature (e.g. Masoudian et al. 2019) also confirms that the majority of mine pits within the UK and EU regions are composed of silty clay material. The proposed soil mixture will be referred to as the equivalent spoil in the following sections. Figure 1 shows the particle size distribution of the equivalent spoil, which has a specific gravity (G_s) of 2.52, liquid limit (*LL*) of 46%, plasticity index (*PI*) of 25.6%, and critical state friction angle of 22.5°.

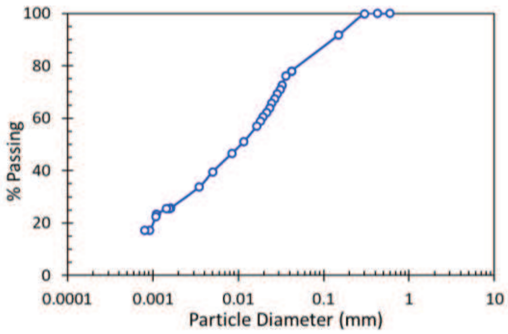

Fig. 1. Particle size distribution of the equivalent spoil.

2.1 Consolidation characteristics of equivalent spoil prepared from slurry

To estimate the consolidation characteristics of equivalent spoil, oedometer tests (ASTMD2435 2011) were performed. The samples for oedometer tests were prepared by mixing oven-dry soil with de-aired water at a water content equivalent to twice the liquid limit of the equivalent spoil (~ 46%). Figure 2 shows the variation of void ratio (*e*) with the effective vertical stress (σ_v'), referred to as the consolidation curve. From Figure 2, compression index (C_c) and recompression index (C_r) can be calculated as 0.545 and 0.07, respectively. The average coefficient of consolidation (c_V) for the tested soil was determined as 5×10^{-9} m^2/s with a permeability (*k*) of 1.30 $\times10^{-11}$ m/s. The c_v and *k* of Speswhite kaolin ($c_v = 2.7\times10^{-7}$ m^2/s, $k = 3\times10^{-8}$ m/s, (Springman 1989)) which is widely used in centrifuge experiments, are much larger than the equivalent spoil considered in this study. As a result, the time needed to consolidate the equivalent spoil will be much longer than kaolin. For example, to 90% consolidate a soil thickness of 330 mm with double drainage, equivalent spoil will take up to 58.5 days, whereas kaolin needs just one day. Therefore, for soils like the equivalent spoil considered here, an alternative method of model preparation is warranted. As mentioned earlier, compaction is a well-known alternative to consolidation for preparing centrifuge models with fine-grained soils.

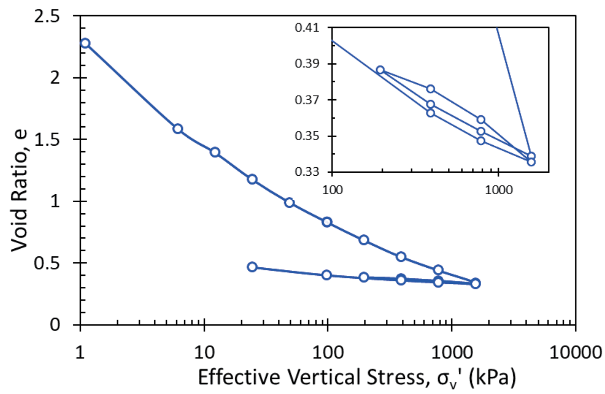

Fig. 2. Consolidation curve of the equivalent spoil.

2.2 Compaction characteristics of equivalent spoil

The compaction characteristics of the equivalent spoil are determined using the standard Proctor test (ASTMD698 2012). Figure 3 shows the variation of dry density with moisture content. As can be seen in Figure 3, the equivalent spoil has a maximum dry density of 1.56 g/cm^3 and optimum moisture content of 20%.

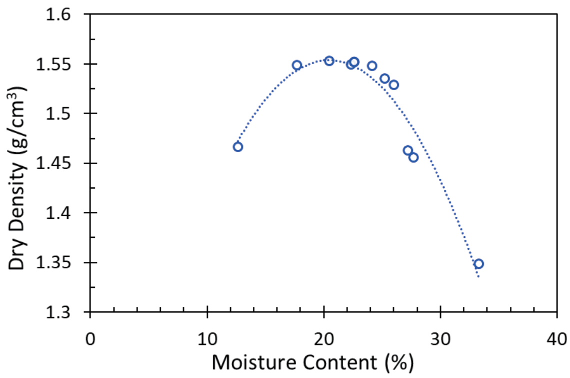

Fig. 3. Compaction curve of the equivalent spoil.

To obtain the required stress profile or over consolidation ratio (OCR) variation with depth at the required *g*-level in centrifuge tests for the prototype considered in this study, models prepared from slurry need to be consolidated under a vertical stress of 180 kPa. The equivalent spoil at the end of 180 kPa consolidation stress will have a moisture content of 29% and a dry density of 1.48 g/cm^3 (computed from Figure 2). It was decided to maintain the same dry density between consolidated samples and the compacted models. For the moisture content of compacted models, the moisture content corresponding to the dry density of 1.48 g/cm^3 on the wet side of the compaction curve (around 27%) was chosen. This high moisture content for compacted models does make the compaction process more difficult, nevertheless, the chosen moisture content results in a degree of saturation of 92%, thereby reducing the time required for full saturation after compaction.

 ISBN 978-89-952197-7-5

2.3 Consolidation characteristics of compacted equivalent spoil

The consolidation characteristics of the compacted equivalent spoil are evaluated using oedometer test results (ASTMD2435 2011). A sample was prepared in a Proctor mould by compacting equivalent spoil prepared at a moisture content of 28% using a standard Proctor rammer. Three specimens were extracted from the compacted sample at different depths, one in the upper-third, the second in the middle, and the last from the lower-third of the sample. All three specimens were fully saturated by submerging in de-aired water under vacuum conditions for two days. Figure 4 shows the consolidation curve of the compacted equivalent spoil. Though there is some minor deviation in the e- σ_v' variation, all the three specimens have pre-consolidation stress (σ_c') of approximately 180 kPa, determined by following the standard Casagrande's method.

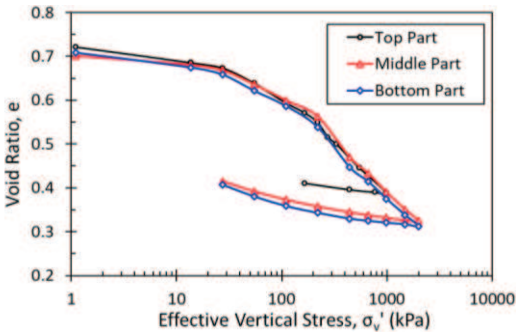

Fig. 4. Consolidation curves of the compacted equivalent spoil.

3 PROPOSED MODEL PREPARATION FOR COMPACTED MODELS

As can be seen in Figure 4, the samples extracted from different depths of the compacted sample have a slight difference in e- σ_v' curves, indicating slight inconsistency within the model. By subjecting the whole soil model to uniform stress, preferably to σ_c', the effects of any inconsistencies arising from the compaction process can be reduced. To verify the proposed method, trial tests were performed on a container with dimensions 160 mm × 160 mm × 277 mm (length × width × height). Oven-dried silt, bentonite and kaolin were dry-mixed to prepare the equivalent spoil material. The calculated amount of de-aired water for a soil mass to obtain 250 mm thickness was then added to the equivalent spoil and mixed thoroughly to prepare a uniform sample. This wet mixture was then placed inside a sealed container for a minimum of 48 hours to equilibrate the moisture content and ensure uniform water distribution. The model was prepared by compacting soil in three layers, with the thickness of each layer increased from bottom to top. This placement method was selected to minimise the over-compaction of bottom layers while compacting the top layers (any difference in stress distribution will be minimised while subjecting the model to a uniform σ_c'). The number of rammer blows required to compact each soil layer was computed by keeping the compaction energy the same as the standard Proctor test. The compacted soil mass of each lift was scarified with a spatula before the placement of the next lift to encourage continuity between the soil layers. Once the model of the required thickness was compacted, the model was saturated with deaired water. During the saturation process, the container was sealed at the top with a lid, and a gauge pressure of -90 kPa was applied at the top. The bottom of the container was connected to a deaired water supply and a slow rate of water ingress into the soil model was provided using a needle valve to avoid the formation of any preferential flow paths. Once the compacted model was saturated, the container was placed under a loading actuator and a static stress of 180 kPa (equivalent of σ_c' determined from Figure 4) was applied. The model was subjected to 180 kPa vertical stress until no significant settlements were observed within the soil. Once the compacted model was consolidated under a vertical stress of 180 kPa (or σ_c'), the vertical stress was reduced to 90 kPa, by allowing the model to swell by letting water into the model. However, while reducing the vertical stress from 90 kPa to zero, no water was allowed into the model, thereby leaving the model under suction or a net effective vertical stress of around 90 kPa.

4 CONSISTENCY OF PROPOSED MODEL PREPARATION BASED ON CPT TESTS

The consistency of the proposed compaction-based model preparation technique for centrifuge models was evaluated through a series of miniature cone penetration tests (CPT). A miniature CPT device developed at the University of Nottingham for in-flight centrifuge testing was used in this study. The miniature CPT is 150 mm long with a cone tip of 60° and a diameter of 8.5 mm (see Figure 5). The CPT body is fabricated from stainless steel tubing with an inner cone rod and outer sleeve. The inner rod (5 mm diameter) is connected to the cone tip at one end and to a load cell at the other end (Load cell 1 in Figure 5), thereby directly measuring the cone-tip resistance. The outer sleeve (8 mm diameter and 1 mm thickness) covers the inner rod and is connected to another load cell (Load cell 2 in Figure 5) which measures the total resistance as the CPT penetrates through the soil. The small gap between the inner rod and outer sleeve at the cone tip is covered with an O-ring to prevent soil or water entry into the gap. An actuator was used to drive the CPT into the soil. Based on the c_v of the equivalent spoil, the rate of cone penetration was determined as 0.2 mm/sec to ensure undrained conditions and avoiding rapid straining.

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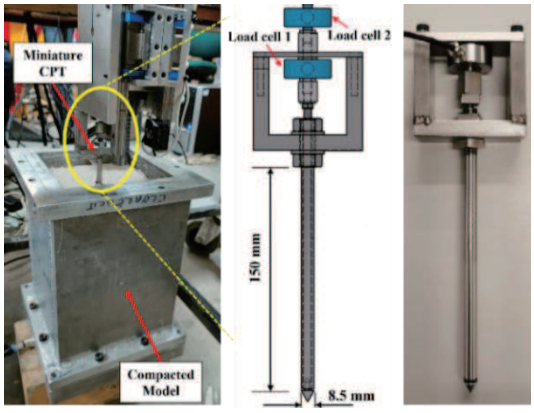

Fig. 5. Miniature CPT used in the study.

Five CPT tests were performed at different locations in the model, one at the centre and the remaining four at the corners of the box at 40-45 mm distance from the container boundaries. Figure 6 shows the results obtained from CPT tests. The total resistance and cone tip resistance at the five locations within the model exhibit acceptable similarity throughout the penetration depth. As expected, the total resistance increases with depth due to the increase in outer sleeve length with penetration. On the other hand, the cone tip resistance increases with depth up to a depth of about 80 mm, after which the cone tip resistance slightly drops till a depth of 110 mm and again increases with depth beyond 110 mm. This variation in tip resistance is likely due to the incomplete consolidation of the soil, as indicated by the relatively higher moisture contents at mid-depth in Figure 6(b) (based on samples taken from the container after the CPTs were completed). Though not used in this test, pore-pressure transducers within the soil model would assist in assessing the degree of consolidation of the soil under applied vertical stresses.

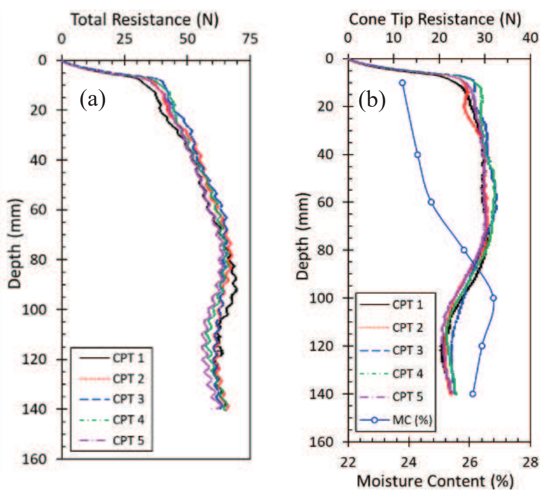

Fig. 6. Variation of (a) total resistance, (b) cone tip resistance and moisture content with depth.

Unsaturated compacted soil models and saturated consolidated models will have different at rest (K_0) conditions. However, the limited literature (e.g. Tarantino 2010) suggests that reconstituted samples from slurry consolidation and compacted soil under saturated conditions tend to exhibit the same shear strength, thereby indicating similar K_0 values for both consolidated and saturated compacted soil models. In this study, the compacted models were saturated and consolidated to certain vertical stresses and hence their K_0 values after consolidation should be similar to those of the slurry consolidation models. Nevertheless, a further investigation is required to evaluate the K_0 conditions in the models prepared by the above suggested methods.

5 CONCLUSIONS

A novel method for the preparation of compacted fine-grained soil models for centrifuge tests has been proposed in this study. The consistency of compacted models was evaluated through miniature CPT tests. The results reveal that following the procedure of compaction, saturation, and consolidation under stresses beyond the pre-consolidation stress of the compacted soil can result in consistent and homogeneous soil models. Further consolidation of models prepared using the suggested method in the centrifuge should further improve the consistency of the soil model. The proposed method considerably reduces the time needed to prepare plastic fine-grained soil models for centrifuge testing.

ACKNOWLEDGEMENTS

This work received funding from the EU's Research Fund for Coal and Steel under the projects "RAFF – Risk Assessment of Final Pits during Flooding" Grant No. 847299 and "SUMAD - Sustainable Use of Mining Waste Dumps" Grant No. 847227.

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