Tests of varied sample preparation methods for centrifuge modelling

Eric Ritchie[1], Leonardo Lalicata[1], Sam Divall[1] and Richard Goodey[1]
[1]*Department of Civil Engineering, City, University of London, London, United Kingdom*

ABSTRACT: Centrifuge modelling is an established technique capable of investigating the ground's response to complex geotechnical events. Centrifuge models are often created from reconstituted soil, with well-defined boundary conditions and known soil parameters. Clay soil models may be prepared by mixing clay powder with distilled water to form a slurry. This slurry is placed within a soil container and subjected to a vertical stress (usually in a consolidation press or consolidated inflight). This creates an isotropic model but there is a fundamental difference between this soil model and naturally occurring soil deposits. The structure and fabric present within a naturally occurring clay is not reproduced by this preparation process. It is well-established that structure and fabric in naturally deposited soils are as significant in their effect on soil behaviour as, for instance, the stress history. Inherent structure and fabric within clay soils creates anisotropy which can vary with depth, this is particularly apparent when considering the permeability. Creating a soil model for centrifuge modelling with representative permeability anisotropy would allow for a better representation of consolidation driven events and the ability to observe long-term behaviour of complex geotechnical events. Currently, there are limited methods of doing so, leading to a considerable gap in knowledge associated with the behaviour of layered ground. This paper describes the development of the equipment and experimental procedure for quantifying the structure developed by different sample preparation techniques for centrifuge modelling.

Keywords: Laboratory testing; centrifuge modelling; soil structure

1 INTRODUCTION

Centrifuge modelling has enabled researchers and engineers to investigate construction and geotechnical events. Most commonly centrifuge modelling has been utilised to determine mechanisms and patterns of movement. Predominantly these patterns are as a result of the deformations experienced due to a construction event i.e. the short-term movements. However, in a clay soil there can be continuing movements that occur years after the construction event has finished as excess pore pressure dissipate. These long-term movements can be significant as reported in Hill and Staerk (2016). Long-term settlement between construction stages and after construction has nearly doubled the settlement induced by tunnelling. Hill & Staerk (2016) also highlight the difference between two observation points at Whitechapel Crossrail station, Vallance Road and Kempton Court buildings where no settlement mitigation could be used. Due to the differing invert levels at the two locations the ground conditions subsequently varied. The rate of consolidation at Vallance Road decayed nearly twice as fast as that at Kempton Court, due to the presence of sand beds near the invert at Vallance Road.

Current centrifuge models are idealised and conducted in homogenous blocks of clay, such that there are well known properties and well-defined boundary conditions. However, there is a fundamental disparity between this and a site such as Whitechapel station. London like many other cities is a sedimentary clay which has been deposited in layers creating inherent anisotropy. A homogenous clay model cannot simulate the different dissipation rates of excess pore pressures as seen at Whitechapel station.

There have been efforts to conduct centrifuge tests in layered ground conditions such as Grant (1998), Hird (2006) and Hossain and Randolph (2010), in which the interaction between different stiffness layers were the primary objective. However, these models are not representative of a sedimentary structure. Laboratory sedimentation is not a new procedure and has been used previously to create laboratory samples. Stallebrass et al. (2007)) split open a sedimented sample and a reconstituted sample and the difference in structure is evident (Figure 1). Structure can be defined as the difference in interpedicular bonding and the different arrangement of particles (fabric).

Divall et al. (2018) created layered models within a geotechnical centrifuge by sedimenting high water content slurries in flight. Further developing this preliminary method could create a model in which permeability anisotropies could be designed. Such that representative dissipation of pore pressures could be observed and the long-term patterns of movements can be investigated through centrifuge modelling.

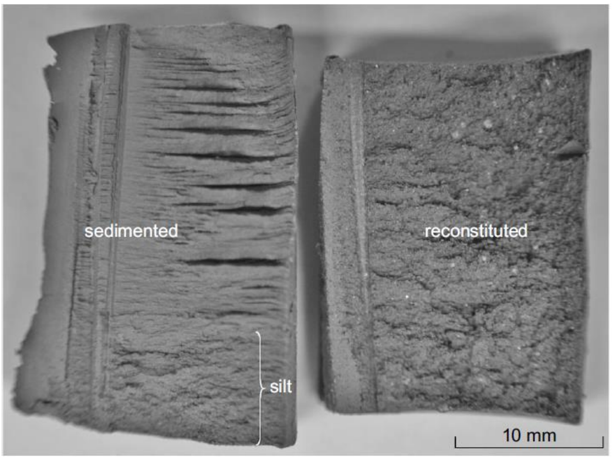

Figure 1. *Photographs of split sedimented and reconstituted London Clay samples Stallebrass et al. (2007).*

The properties of any sedimented samples within a centrifuge need to be quantified, the permeability anisotropy needs to be measured. The compression behaviour needs to be understood such that a desired height of centrifuge model can be achieved. Triaxial tests also need to be completed such that they can be used for numerical analyses. These parameters measured will be compared to the standard techniques of making centrifuge modelling to assess the difference in behaviour. This highlighted a further question, there is no single way that centrifuge models are created, and does the method of sample preparation effect the resulting model properties.

This paper details the preliminary testing of the difference between centrifuge sample preparation techniques. Oedometer tests are presented on a variety of slurries prepared in different ways representing the different sample preparation procedures commonly used in centrifuge modelling.

2 MODEL MAKING PROCEDURES

2.1 Kaolin clay powder and distilled water

Cairncross (1973) was cited in Mair (1979) as the earliest example of a method of creating homogenous clay models consisting of powdered clay and distilled water to twice its liquid limit (120% water content). Once fully mixed the slurry is carefully placed into a strongbox container to avoid entrapping air. The clay is agitated to remove any possible air bubbles created during pouring. The slurry is then consolidated in stages to achieve a desired stress history. This is done through either a hydraulic or pneumatic press, in a series of loading stages arriving at a homogenous sample.

2.2 Recycling previous tests in Kaolin clay

Tests previously performed in kaolin clay models created as described above, can be recycled to make another centrifuge model. By cutting the remainder away any part of the clay that has been in contact with grease or contaminants and cutting the remainder into small pieces. These are then soaked in distilled water and mixed to form a second slurry with a water content of 120%. The slurry is then consolidated as described previously.

Work undertaken by Phillips (2016) found that when natural and reconstituted clay cuttings are agitated in water they do not break down to the particulate size. They will disaggregate into slurries that contain a higher percentage of silt size agglomerates of clay particles also referred to as ‘clay peds’. This effectively changes the particle size distribution of the material.

The fabric of a sample consolidated from a slurry consisting of recycled material may be noticeably different from a sample consolidated from clay powder. As soil behaviour is partly governed by the influence of structure (Leroueil & Vaughan, 1990), the difference in structure may be significant enough to change its engineering properties compared to a sample prepared from powder and distilled water.

2.3 Mixing under a vacuum

Slurries prepared from powder or recycled material can be subjected to vacuum to de-air the mixture. Slurries can be mixed under a vacuum and then pumped directly into a strongbox container reducing air being introduced to the sample. Alternatively, the slurry can be mixed as previously described but before being poured into the strongbox it is subjected to a vacuum (Hossain & Randolph, 2010). The slurry is then carefully placed into the strongbox container and consolidated as described previously.

The use of a vacuum to de-air the sample may change the compressibility of the sample as well as increase the consistency of the sample preparation technique. Reducing the chance of air pockets being trapped in the sample, which if in contact with a structure being modelled, could be significant. This method removes variability from researcher to researcher as it does not require any manual agitation.

2.4 Consolidating models inflight

Alternatively, from consolidating a sample within a press, a slurry can be consolidated under self-weight within a centrifuge. A slurry prepared by any of the methods above is poured into a strongbox and then placed onto a centrifuge swing. Alternatively, the slurry can be pumped into the strongbox inflight. In both cases typically the slurry is placed on top of a geofabric matt or porous plastic sheet to allow for drainage at the base of the sample. The slurry is then accelerated in stages to consolidate under self-weight at varying g-levels. This creates a stress profile that increases with depth. To create a uniform stress distribution or an overconsolidated sample a surcharge can be applied to the surface of the sample.

To avoid generation of high excess pore pressures that creates pipping and preferential drainage paths during consolidation, the model is accelerated slowly to the desired g-level. Subsequently, consolidation of samples can be a lengthy procedure and the total model preparation length is comparable to that of a hydraulic or pneumatic press.

Work completed by Mikasa & Takada (1986) recognised segregation caused when consolidating soft soils within the centrifuge, when using a soil consistency (water content) that did not allow for particle segregation. Using post-test investigation techniques, it was determined that segregation occurred from a marked drop off in the effective stress void-ratio curve. The authors suggested using a water content equal or less than twice the liquid limit of the clay to avoid segregation. Townsend et al. (1986) also recognised the issue of segregation in centrifuge modelling and combined with other researchers have proposed to avoid segregation by using low initial water content samples and staged consolidation procedures.

Sorta et al. (2012) investigated the effect of an increased acceleration field to the segregation characteristics of a variety of clay-sand mixtures. Samples where left to consolidate under their own self-weight at 1g for a month, then the segregation index was calculated as defined in Donahue et al. (2018). The same slurries were then consolidated inflight for the equivalent of a month at relevant g-levels. The segregation index was calculated and the segregating boundaries was plotted on a ternary diagram to categorise different properties.

This concluded that the segregation boundaries are significantly shifted at elevated g-levels (i.e. a sample may not segregate under normal conditions but may during consolidation inflight). The boundary is also dependent on the source of the material. If the resulting structure of the sample consolidated inflight is different from that of sample prepared in a mechanical press then the sample behaviour may also differ. From existing literature, it is inconclusive if consolidating a sample on a centrifuge would yield different material properties.

To investigate the influence of different sample preparation techniques a series of one-dimensional compression tests were completed to compare coefficients of compression and swelling, as well as the reputability of results.

3 EXPERIMENTAL PROCEDURE

3.1 Sample preparation

3.1.1 Preparation of slurry from powder

To create the first slurry speswhite kaolin clay was used, the same as what is used for centrifuge models at City, University of London. The clay powder was mixed to approximately twice the liquid limit or 120% water content, in a 9-litre Hobart paddle mixer, for approximately 2 hours until the clay was a smooth slurry.

3.1.2 Preparation of slurry from recycled material

To create a slurry from recycled material, a 6-inch California bearing ratio mould (CBR mould) of kaolin clay which had been prepared as described in section 3.1.1, was consolidated to a stress of 500 kPa to create a triaxial sample. The remainder of the clay was trimmed removing any parts in contact with the CBR mould. The sections were cut into small cubes approximately 40-50mm^3. The cubes were soaked in distilled water and mixed to a water content of 120% in the same Hobart mixer.

To create a different slurry using recycled material a CBR mould was filled with clay slurry mixed from powder and loaded to a maximum stress of 200 kPa. The sample was then removed from the press and cut into small cubes of 40-50 mm^3 and mixed with distilled water to a target water content of 120%. Both slurries had been mixed for a minimum of 5 hours, it was sometimes necessary to stop the mixer to break the larger lumps by hand.

3.1.3 Preparation of a slurry using a vacuum

The samples subjected to a vacuum were prepared in the same was as that from Speswhite kaolin powder in section 3.1.1. Once the slurry was mixed it was transferred to a vacuum chamber where it was subjected to a vacuum and agitated for 30 minutes. After which the sample was removed from the chamber further agitated by hand and subjected to the vacuum for a second time for a further 30 minutes. The sample was then ready for testing in an oedometer.

3.1.4 Consolidating samples within a centrifuge

To consolidate samples in flight for testing in an oedometer or a standard element test, clay is poured into a sedimentation column designed to be used within the centrifuge as shown in Figures 2 and 3. These sedimentation columns will be used for a future test series to create sedimented samples similar to Stallebrass et al. (2007) but using a centrifuge. In which the resulting samples permeability and mechanical properties will be measured. These sedimented samples will be compared to the aforementioned standard techniques of creating centrifuge models to assess any differences.

The sedimentation columns are manufactured from 3mm thick, 54mm internal diameter PMMA tubing that has a total height of 800mm. The column can be split into two sections the lower section being 180mm tall allowing for the samples to be extracted or converted to a permeameter cell by attaching a top cap. 100mm of clay slurry prepared from a powder was poured into the tube. The column was then accelerated to 10g and allowed to consolidate under self-weight for 24 hours, after every 24 hours the g-level was doubled to a maximum g level of 100g is achieved. The effective radius is set to two thirds of the slurry height within the columns for all tests as per Taylor (1995). After allowing for consolidation at maximum acceleration the centrifuge was decelerated and the columns removed for further testing.

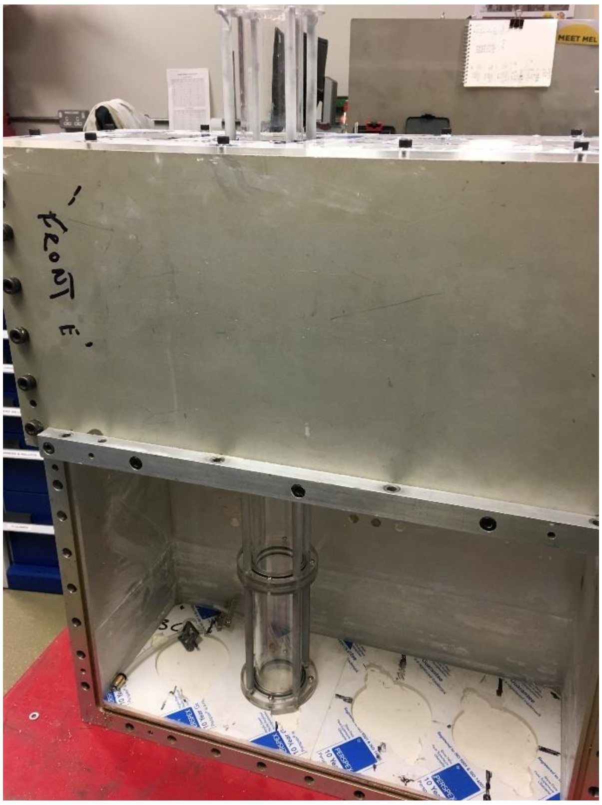

Figure 2. *sedimentation column arrangement*

Figure 3. *sedimentation columns on centrifuge swing during commissioning tests.*

3.2 Summary of tests completed

Table 1 summarises the slurries created, that were tested within the oedometer. All tests were prepared using distilled water.

Test Number	Kaolin powder	Recycled material	Subjected to a vacuum
T1	✓		
T2	✓		
T3	✓		✓
T4	✓		✓
T5		✓	
T6		✓	
T7		✓	

Table 1. *summary of tests undertaken*

3.3 Oedometer testing

Once the samples were created they were then tested within a standard 75mm oedometer. The loading platern and the bottom porous stone were saturated within a vacuum chamber. The slurry was placed carefully in the centre of the oedometer cell then spread to create an even layer. The clay was then agitated manually prior to testing to remove any air introduced when pouring the clay samples.

The samples created using the centrifuge, are extruded into a custom made oedometer with an oedometer ring diameter the same as the internal diameter of the sedimentation columns. This is to minimise disturbance caused by trimming samples. The oedometer ring initially sits inside a recess within a PMMA holder. Once the base has been removed from the sedimentation column it is secured to PMMA holder and the clay sample was extruded into the oedometer ring. The sedimentation column is removed and resealed for future testing. The oedometer ring fits into an adapter such that it can be used in a standard 75mm cell. A custom piston has also been manufactured and applies a stress of 1.5kPa.

The samples where then one-dimensionally compressed and swelled within the oedometer to determine the compression and swelling indexes. Samples were subjected to a maximum vertical effective stress of 400 kPa, unloaded to a range of different stress then reloaded back to a maximum stress of 400 kPa. The displacement was measured continuously with a linear variable displacement transducer (LVDT) resting on the arm of the loading frame with a reading taken at one a second.

4 RESULTS

For this paper the results for samples consolidated inflight have been omitted due to insufficient data. The one-dimensional compression data for the other sample preparation techniques are compared in Figure 4. It can be seen there is a 5% difference in compression indexes between the samples consolidated from a powder versus those that have been subjected to a vacuum prior to testing. The samples subjected to the vacuum are always less compressible, this is thought to be due to the volume of air being expelled from the sample during the consolidation stages. Thus, creating a higher compression index. The samples prepared using a vacuum had a greater consistency with the difference in compression index being less than 1%. The samples prepared from powder and mixing with distilled water are consistent within a 5% bracket, thought to be due to the varying amount of air present within the sample.

The slurries consisting of recycled material as opposed to powder were around 20% less compressible than the other sample preparation techniques. The results of the tests are also more varied than the others and fall within a 10% bracket. The reason for this is thought to be due to the different grading curve achieved after recycling the clay cuttings (after Phillips, 2016). The silt agglomerates within the slurry are not broken-down during mixing and once loaded in the oedometer it creates a less compressible sample.

Phillips (2016) noted that when disaggregating kaolin clay cuttings after 30 minutes of mixing there was an increase in sub 63μm particles. However, after a further 30 minutes of mixing there was a reduction in sub 63μm particles.

Oedometer test 1 and 2 with recycled material were from the same batch of slurry. The slurry was sealed and then remixed prior to testing. The second oedometer test conducted of recycled material is less compressible than the first, this could be variation within the sample or as the second sample is mixed for a longer period of time there was more 'peds' present creating a less compressible sample.

Oedometer test number 3 with recycled material is very similar to test number 1. These were both the first samples to be prepared from the slurry directly after initial mixing. From these preliminary tests it is inconclusive to what effect stress history had on of the cuttings. There could be a more complex interaction between cuttings, mixing duration, mixing speed and waiting and remixing a slurry.

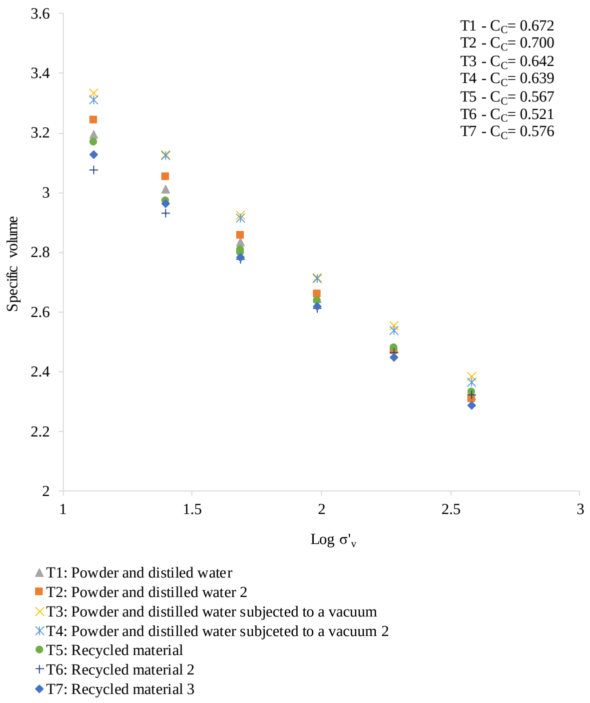

Figure 4. *One dimensional compression curves for different sample preparation techniques*

The average swelling index for each of the sample preparation techniques was 0.11. There is no obvious trend and all results sit within a 10% bracket of the average value. There is the smallest variation in swelling index with the samples prepared from recycled material, the reason for this trend is not clear and requires further testing.

5 CONCLUSIONS

The compression test results show there is a significant difference between the sample preparation procedures that deserves further investigation. From the preliminary tests it can be determined that;

1. Samples consisting of kaolin powder and distilled water become slightly less compressible after being subjected to a vacuum
2. Slurries consisting of recycled clay cuttings are significantly less compressible than samples prepared from powder thought to be due to presence of peds.
3. The swell indexes fall within a similar range for all preparation techniques.

The difference between clay properties are potentially significant for centrifuge modelling if within a series of tests there are some models prepared from powder and some prepared from recycled material. The response of any test may differ producing a variation in results. This also influences numerical modelling, models are often compared to centrifuge test data. If the soil model properties do not reflect the test parameters this could affect the results for such models.

There needs to be further testing on samples consolidated inflight to see where this fits within the other sample preparation techniques. Further testing on samples consisting of recycled material that have also been subjected to a vacuum should be investigated. It is predicted that this will further reduce the compressibility as seen with the samples prepared from powder.

5 ACKNOWLEDGEMENTS

This research was supported by the George Daniels scholarship at City, University of London. Additional thanks should also go to the members of the research centre for Multi-Scale Geotechnical Engineering London for their support during the project.

6 REFERENCES

Cairncross, A.M. (1973). Deformations around tunnels in stiff clay. PhD thesis, University of Cambridge.

Divall, S., Stallebrass, S.E. Goodey, R.J, & Ritchie. E.P. (2018). Development of layered models for geotechnical centrifuge tests. Physical Modelling in Geotechnics – McNamara et al. (Eds) 2018 Taylor & Francis Group, London, ISBN 978-1-138-34419-8.

Grant, R. J. (1998). Movements around a tunnel in two-layer ground. Doctoral thesis, Department of Civil Engineering Geotechnical Engineering Research Centre. The City University, London.

Hill, N., & Staerk, A. (2016). Long-term settlement following SCL-tunnel excavation. Crossrail project: Infrastructure design and construction- Volume 3, pp 227-248.

Hird, C.C., Emmett, K.B.& Davies, G. 2006. Piling in layered ground: risks to groundwater and archaeology. Science Report SC020074/SR. Environment Agency: Bristol.

Hossain, M. S. & Randolph, M. F. (2010). Deep-penetrating spudcan foundations on layered clays centrifuge tests. Géotechnique 60, No. 3, 157-170.

Mair, R. J. (1979), Centrifugal modelling of tunnel construction in soft clay. PhD thesis, University of Cambridge.

Mikasa, M, & Takada, N, (1984). Self-weight consolidation of very soft clay by centrifuge. In Sedimentation Consolidation Models—Predictions and Validation (Yong RN and Townsend FC (eds)). ASCE, New York, NY, USA, pp. 121–140.

Philips, N. S. (2016). Disaggregation of soil during slurry pipe jacking. PhD thesis, City University of London, Geotechnical Engineering Research Group, School of Mathematics, Computer Science and Engineering

Sorta, A. R., Sego, D. C. & Wilson, W. (2012). Effect of Thixotropy and Segregation on centrifuge modelling. International journal of Physical Modelling Geotechnics, 2012, 12(4), 143-161.

Stallebrass, S. E., Atkinson, J. H. & Mašín, D. (2007). Manufacture of samples of overconsolidated clay by laboratory sedimentation. Géotechnique 57, No. 2, 249–253.

Taylor, R. (1995). Geotechnical centrifuge technology. London: Blackie Academic & Professional.

Townsend FC, McVay MC, Bloomquist DG and Mcclimans SA (1986) Reclamation of Phosphatic Clay Waste Ponds by Capping. Volume 1: Centrifugal Model Evaluation of Reclamation Schemes for Phosphatic Waste Clay Ponds. Florida Institute of Phosphate Research, Florida, Bartow, FL, USA, FIPR publication no. 02-030-056.