Development of layered models for geotechnical centrifuge tests

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ABSTRACT: Centrifuge modelling is an established technique for investigating the ground response to complex and non-standard geotechnical events. These models are usually made from re-formed soil, allowing for comparisons with naturally occurring soil deposits. Clay models are formed by mixing clay powder and water into a slurry. This slurry is placed within a container and loaded to create a uniform stiff clay model. However, there is a fundamental disparity between this process and the deposition of natural soils, because natural soil is deposited in layers creating a unique structure. This structure is important for modelling true soil behaviour because some essential soil properties (such as permeability, stiffness and strength) are not identical in all directions. Currently, there are limited methods for creating layered soil samples. This paper describes the development of a new procedure for creating layered centrifuge models with structure – leading to potentially more representative models of naturally occurring ground.

1 INTRODUCTION

1.1 *Background*

The technique of geotechnical centrifuge modelling has enabled engineers and researchers to better understand geotechnical events and construction processes. One of main benefits has been the ability to observe mechanisms or patterns of movements in small-scale models that can be related to full-scale events. These small-scale models are often idealised homogeneous soil models which primarily consist of either sand or clay.

Mair (1979) developed a method for creating these homogenous samples for clay models by mixing kaolin powder with distilled water. Usual practice since then has been to prepare a slurry to a water content of 120% and place this slurry within a soil container known as a strongbox or strongtub (Grant 1998; McNamara 2001; Begaj 2009; Divall 2013; Le 2017). The slurry is subjected to a known stress history using hydraulic or pneumatic consolidation presses to arrive at a homogenous sample. Models representing overconsolidated soils often follow a period of swelling before the model preparation stage and further in-flight consolidation. Studies concerned with short-term deformations have successfully replicated the stress-strain response of the prototype soil continuum (Grant 1998) by carefully considering the stress history and g-level.

However, reconstituted samples often cannot provide a realistic representation of natural soil structure, particularly the effect this has on permeability and inherent anisotropy. This is because the strength and stiffness of reconstituted soils are governed solely by their state (i.e. packing) and effective stresses (Atkinson et al. 1990). The inability to physically model soil structure has led to considerable gaps in our knowledge regarding the deformations associated with geotechnical events in layered ground (Hird et al. 2006). Whilst the characteristics of layered soils have been fairly extensively documented (Burland 1990 and others), the effect of these differences on the ground response to geotechnical events is not well understood.

This paper gives details of the initial development of a novel procedure for creating a layered clay and sand soil sample for geotechnical centrifuge modelling, with representative effective stresses. The observations from an initial test including the data from a T-bar penetrometer are shown and a predictive framework for the layers is presented.

2 PREVIOUS PHYSICAL MODELLING OF LAYERED MODELS

Soil response is, in part, governed by the influence of structure (Leroueil & Vaugham 1990). Soil structure can be described as the combination of 'fabric' (or the arrangement of particles) and interparticle 'bonding' (Mitchell 1976).

Burland (1990) stated that the main aim of studies into the behaviour of natural sedimented soils were 'to bring the same unity and coherence that Critical State Soil Mechanics brought to reconstituted soils'. In some respects, this was also achieved by Cotecchia & Chandler (2000) who sought to better model the behaviour of fine-grained soils by introducing the term 'sensitivity'. Sensitivity is the ratio of the undisturbed to remoulded compressive strengths. Their study suggested that if data were normalised with respect to sensitivity there was a unique shape of the state boundary surface for all clays. The state boundary surface is defined in stress: volumetric space as the boundary of all possible states of soil.

Studies have attempted to clarify the shape of the state boundary surface by creating small samples, using sedimentation columns, to be used in element tests (Ward et al. 1959; Been & Sills 1981; Edge & Sills 1989; Mašín 2004). The latter used a specially fabricated sedimentation column laboratory apparatus to create triaxial samples. This sedimentation column was a 2m high, 100mm diameter, Poly(methyl methacrylate) or PMMA cylinder. A buoyant PMMA piston loaded the slurry and allowed for top and bottom drainage to accelerate the consolidation and sedimentation of the London Clay. London Clay was submerged in water and thoroughly mixed for 36 hours to an initial water content of 5800%. The samples were prepared using distilled water mixed with Saxa brand fine sea salt to 3.509% (similar to the conditions in the North Atlantic Ocean) to act as a flocculant. The slurry was left to sediment for approximately 3 days and the cycle was repeated 4 times to produce a 76mm high triaxial sample. The result were samples that consisted of four layers and, like those of Been & Sills (1981), each layer had been separated according to size. Figure 1 (taken from Stallebrass et al. 2007) clearly shows the visual differences between a sedimented soil sample and a reconstituted soil sample.

Studies using layered samples in centrifuge tests have not applied this approach to create their models. Grant (1998) undertook a series of tests investigating movements around a tunnel in two-layered ground. These models consisted of a single Leighton Buzzard Sand layer overlying a Speswhite kaolin clay layer within a strongbox. The overall depth of the model was 225mm with each of the clay layers ranging from 37.5mm to 175mm and the sand layers ranging from 67mm to 187.5mm. The clay layer was prepared in much the same way as Mair (1979) with the sand layer placed on top. Marshall et al. (2014) utilised a similar method for a study into non-displacement piles and pile groups within a strongtub. The bottom layer was Speswhite kaolin clay with Fraction E silica sand placed by air pluviation.

Muñoz & Caicedo (2014) modelled shallow tunnels in heterogeneous soils by omitting layers altogether. The study implemented a random field generator which dictated specific sections within a strongbox which could have various kaolin: bentonite proportions. This attempted to simulate the 2D variability of a clay model with inherent variability represented by soil with different Liquid Limits. Soils were placed with a 'caulking tool' in strips across the full depth of the strongbox. Samples were then consolidated in a consolidation press to a vertical effective stress of 50kPa.

The aim of the new procedure is to establish a method for the creation of a sedimented sample (with 'sensitivity' as defined by Cotecchia & Chandler, 2000) within a strongbox. The soil bed created can be used during centrifuge testing to investigate the behaviour of geotechnical processes (such as piling or tunnelling). The combination of these two procedures would enable the effect of 'sensitivity' on ground response to be investigated and allow soil behaviour which is dominated by permeability, such as long-term tunnelling-induced ground movements, to be modelled experimentally.

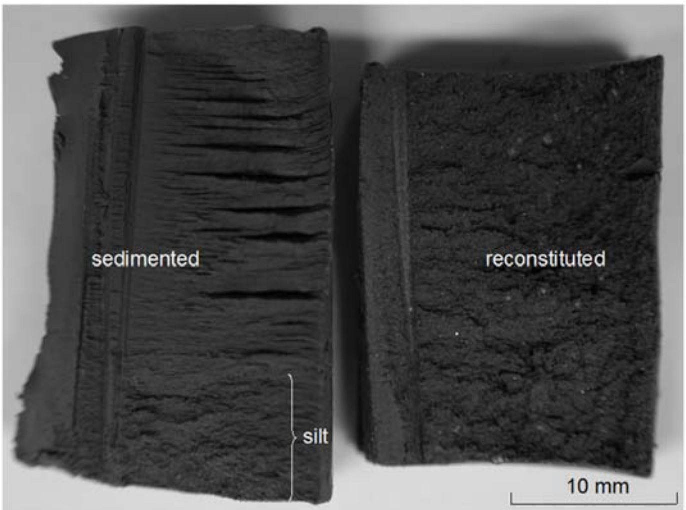

Figure 1: Sedimented vs reconstituted samples (Stallebrass et al. 2007)

3 EXPERIMENTAL WORK

3.1 *Preparatory work*

The clay sedimentation process started when a slurry containing disaggregated clay (see below) and Fraction E Leighton Buzzard sand was introduced into a strongbox containing distilled water. Prior to testing, an investigation was undertaken to determine i) the minimum water content of slurry that could be held in suspension and ii) whether the size of container affected the suspension of the slurry.

Figure 2a shows four sedimentation columns each with 500 ml of distilled water with 125 ml of slurry poured into the top. The 125 ml slurry introduced ranged in water content from 200% to 400%, such that the nominal water contents when the slurry and water are combined range from 1148% to 2153%.

The minimum water content which was held in suspension was 250%. Figure 2 also shows three containers of different diameters and depths. The 250% water content slurry was placed in these demonstrating that regardless of container diameter, 125ml of slurry was held in suspension in 500ml water, which is equivalent to a water-content for the suspension of 1403%.

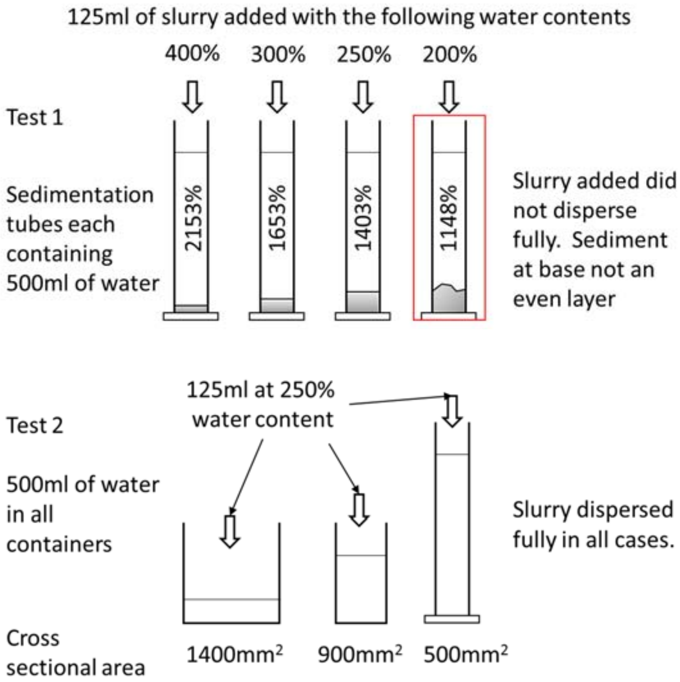

Figure 2: Test 1: Sedimentation columns with varying percentages of water-content slurries. Test 2: Sedimentation containers of various diameters.

3.2 *Mixing stage*

Work undertaken by Phillips *et al.* (2014) established that when both natural and reconstituted clay cuttings are agitated in water they disaggregate into slurries containing a high proportion of silt sized agglomerations of clay particles or 'clay peds' rather than individual clay particles. Since many sedimented soils are deposited from eroded and transported material it is likely that the majority of sedimented clays are formed from these silt sized clay peds and not the clay particles present in powdered clays such as Speswhite kaolin.

Consequently, before the sedimentation stages could be undertaken, an initial slurry of Speswhite kaolin clay powder (supplied by Imerys Minerals Ltd), was mixed with distilled water in a ribbon blade mixer to a water-content of 120%. This initial slurry was placed within a strongtub and subjected to a vertical stress of 350 kPa. The vertical stress was applied by a hydraulic consolidation press over approximately one week. This created a moderately stiff normally consolidated clay sample. The clay was removed from the strongtub and divided into 'cuttings' (of approximately 40-50 mm^3) and placed into the planetary mixer with more distilled water to a water-content of 1285%. This consisted of 500 g of clay, 200 g of sand and 9 litres of distilled water. It was then mixed for about 30 minutes until fully disaggregated.

3.3 *Sedimentation stage*

The silt-sized clay agglomerate and sand based slurry was poured into a second soil container (strongbox). The strongbox had been modified for this application with a PMMA window replacing the front face and with a porous plastic sheet silicone sealed to the bottom drainage plate. The slurry was subjected to acceleration on the centrifuge of 160*g*. This forced the larger soil particles and agglomerates to sediment first with the finer material sedimenting later.

This process created the layered soil structure that can be seen in standard sedimentation columns but across a soil container suitable for larger scale centrifuge model testing. The sedimentation of this first layer took approximately 1½ hours. The process could be observed through on-board USB cameras. The centrifuge was decelerated and pipette samples were taken of the remaining surface water on top to confirm that the sedimentation process was essentially complete. The water-content of the pipette samples was determined and it was found that the average water-content was 99.95%. This showed that the sedimentation process had completed within the time frame.

At this stage of testing a second slurry (identical to that previously described) was poured into the surface water. The centrifuge was then accelerated again until a second layer could be observed. This was repeated a third time to arrive at the final model height.

3.4 *Testing*

Once the third layer was sedimented a T-bar penetrometer (Gorasia, 2013) was bolted to the top of the strongbox at 1*g* (see Figure 3).

The undrained shear strength, S_u, of the model could be determined using the readings from the T-bar and the equation below originally from Stewart & Randolph (1991).

$$S_u = \frac{P}{N_b \cdot d} \tag{1}$$

where P = force per unit length acting of the bar; d = diameter of the bar (in this case 7 mm); and N_b = bar factor. Stewart & Randolph (1991) cited Randolph & Houlsby (1984) for a value of N_b as 10.5 for general use. Stewart & Randolph (1991) also state that the tool should be utilised in soft clay investigations. The T-bar was driven at 60 mm per minute. The aim was to record the resistance in at least two clay layers and their respective interfaces with the sand layers.

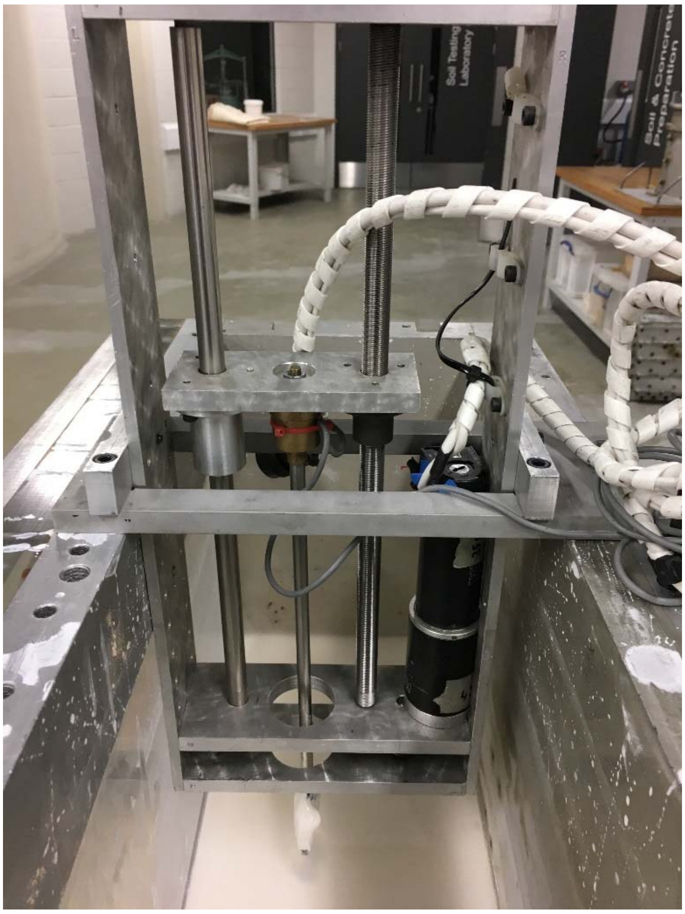

Figure 3: T-bar penetrometer and frame used for determining the undrained shear strength with depth

4 RESULTS

4.1 *Visual inspection*

Figure 4 shows the layers in the soil once the front PMMA window of the strongbox had been removed. The steel rule held against the layers shows the consistency and even distribution of the layers created. Moreover, it is possible to observe that the sand particles appear at the bottom of each layer, as expected, and there appears to be an interface between the largest clay agglomerates and smallest sand fines.

The soil on the top layer was very weak and had very little 'stand-up' time. This was assumed to be owing to the unloading process during deceleration of the centrifuge and the standing water above the soil as part of the sedimentation process. No drainage was allowed from the sample inflight and when the test was stopped, the sample swelled reabsorbing some of this standing water.

4.2 *T-bar penetration data*

The T-bar readings confirm that at 1*g* the clay layers had very low undrained strengths. Figure 5 shows a standard undrained shear strength with depth profile.

There are three points of interest in this data. Firstly, the point at which the T-bar connects with the soil gives reading of 0.25kPa. Secondly, the readings increase dramatically when passing through the sand layer below and then drop to approximately 0.65 kPa. This layer is assumed to be the second clay stratum. This has been stressed by the weight of the layer above and therefore has a slightly higher undrained shear strength compared with the uppermost layer. Thirdly, the readings decrease for the intermediate clay layer before increasing once again for the sand layer.

Figure 4: Three layers created through sedimentation (sand-Speswhite clay per layer)

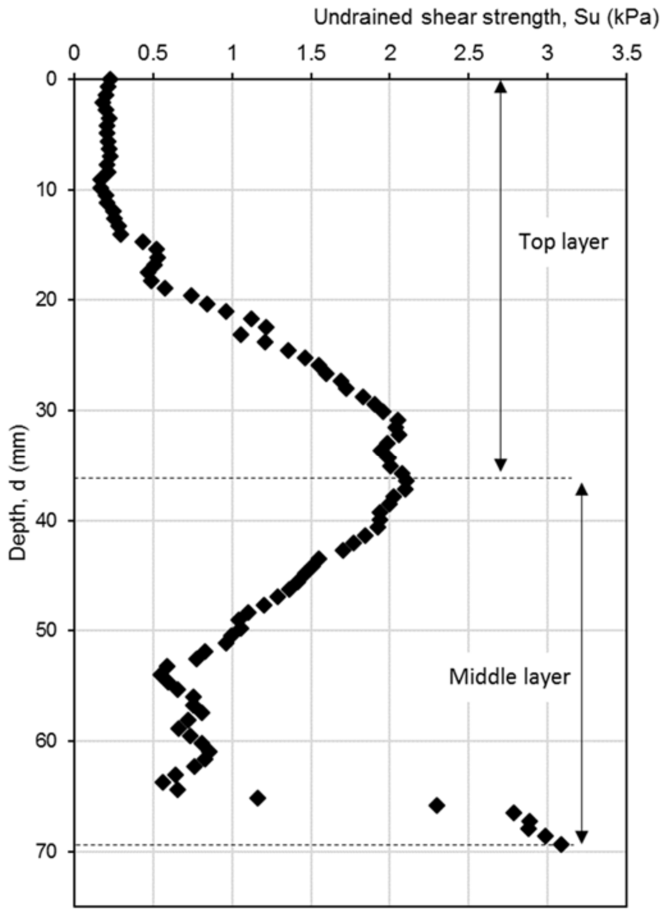

Figure 5: T-bar readings with depth for the layered soil model

This shows it is possible to identify the sand and clay layers and possibly their relative strengths. Although, caution should be applied here as sand derives its strength from angle of friction which cannot be identified on this plot.

4.3 *Prediction of soil layers*

To verify the approach, the depth of the layers was predicted using standard relationships for the compression of clays. These predictions should represent a lower bound to the thickness of the layers as they would not take account of 'sensitivity'.

The depth of each sublayer of sand or clay was calculated assuming the particles settled to a state which could be described by a normal compression line (in specific volume, v, and average stress, ln p', space). The height of the sand layers was determined by calculating the total volume using the weight of sand used and average voids ratio values from Grant (1998). This volume was divided by the internal plan area of the strongbox to arrive at an average height.

The height of the clay sublayer was determined iteratively as the vertical stresses imposed at 160 times the earth's gravity are determined by the unit weight of the clay which changes with voids ratio, e. The voids ratio is in turn determined by the vertical stresses.

The overall height of the top sand and clay layer was computed to be 20.6 mm. It is difficult to make comparisons with Figure 4 because the soil has slumped forwards after the window was removed. However, given the relatively small measurements recorded this was considered a reasonable prediction of the height of the layers. The T bar readings indicate a combined height of sand and clay layer which is 36.4 mm. The second layer was predicted to be 19.2 mm and the T-bar indicates the depth of this sand and clay layer to be 30.1 mm.

5 CONCLUSIONS

It is possible to create a centrifuge model with a sedimented soil structure as defined by Mitchell (1976). This paper details the initial development of a novel procedure for creating a layered soil model within a geotechnical centrifuge. The results of an initial test are shown including a prediction of the height of the layers.

The one major shortcoming is that the method currently creates very weak soil samples. This would be overcome by creating more layers and allowing drainage after the layers have been created, to remove the surface water. This would help prevent the soil swelling and reabsorbing the standing water on top of the final layer. Further tests are required to characterise the layers to quantify the values of permeability in the vertical and horizontal directions.

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REFERENCES

Atkinson, J.H., Richardson, D. & Stallebrass, S.E. 1990. Effects of recent stress history on the stiffness of overconsolidated soil. *Géotechnique*, 40(4): 531-540.

Been, K. & Sills, G.C. 1981. Self-weight consolidation of soft soils: an experiment and theoretical study. *Géotechnique*, 31(4): 519-535.

Begaj, L. 2009. Geotechnical centrifuge model testing for pile foundation re-use. PhD Thesis, City University London, UK.

Burland, J.B. 1990. On the compressibility and shear strength of natural clays. *Géotechnique*, 40(3): 329-378.

Cotecchia, F. & Chandler, J. 2000. A general framework for the mechanical behaviour of clays. *Géotechnique*, 50(4): 431-447.

Divall, S. 2013. Ground movements associated with twin-tunnel construction in clay. PhD Thesis, City University London, London, UK.

Edge, M.J. & Sills, G.C. 1989. The development of layered sediment beds in the laboratory as an illustration of possible field processes. *Quarterly Journal of Engineering Geology*. 22: 271-279.

Gorasia, R.J. 2013. Behaviour of ribbed piles in clay. PhD Thesis, City University London, London, UK.

Grant, R.J. 1998. Movements around a tunnel in two-layered ground. PhD Thesis, City University London, UK.

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.

Le, B.T. 2017. The effect of forepole reinforcement on tunnelling-induced movements in clay. PhD Thesis, City, University of London, London, UK.

Leroueil, S. & Vaugham, P.R. 1990. The importance and congruent effects of structure in natural soils and weak rocks. *Géotechnique*, 40(3): 467-488.

Mair, R.J. 1979. Centrifugal Modelling of Tunnel Construction in Soft Clay. PhD Thesis, Cambridge University, Cambridge, UK.

Marshall, A.M., Cox, C.M., Salgado, R. & Prezzi, M. 2014. Centrifuge modelling of non-displacement piles and pile groups under lateral loading in layered soils. *Proceedings of the Eighth International Conference on Physical Modelling in Geotechnics* (ICPMG 2014), Perth, Australia, 2: 847-852.

Mašín, D. 2004. Laboratory and numerical modelling of natural clays. MPhil dissertation, City University London, London, UK.

McNamara, A.M. 2001. Influence of heave reducing piles on ground movements around excavations. PhD Thesis, City University London, UK.

Mitchell, J.K. 1967. *Fundamentals of soil behaviour*. New York: Wiley.

Muñoz, G. & Caicedo, B. 2014. Centrifugal modelling of shallow tunnels in heterogeneous soils. *Proceedings of the*

Eighth International Conference on Physical Modelling in Geotechnics (ICPMG 2014), Perth, Australia, 2: 937-942.

Phillips, N.S., Stallebrass, S.E., Goodey, R.J. & Jefferis, S.A. 2014. Test development for the investigation of soil disaggregation during slurry tunnelling. *Proceedings of the Eighth International Conference on Physical Modelling in Geotechnics* (ICPMG 2014), Perth, Australia, 2: 979-984.

Stallebrass, S.E., Atkinson, J.H. & Mašín, D. 2007. Manufacture of samples of overconsolidated clay by laboratory sedimentation. *Géotechnique*, 57(2): 249-253.

Stewart, D.P. & Randolph, M.F. 1991. A new site investigation tool for the centrifuge. *Proceedings of the International Conference - Centrifuge 1991*, Colorado, USA, 531-538.

Ward, W.H., Samuels, S.G. & Butler, M.E. 1959. Further studies of the properties of London Clay. *Géotechnique*, 9(2): 33-58.