# A method for creating larger clay samples with permeability anisotropy for geotechnical centrifuge modelling.

## Une méthode pour créer de plus grands échantillons d'argile avec une anisotropie de perméabilité pour la modélisation en centrifugeuse géotechnique.

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ABSTRACT: Long-term ground movements associated with geotechnical constructions are predominantly caused by the dissipation of excess pore-water pressures and are governed by the permeabilities of both the soil and the geotechnical structure. Natural soil has inherent anisotropy due to the layering and structure as a result of the natural deposition process. A significant factor that influences the rate of consolidation and seepage in natural soils is that the horizontal permeability can be orders of magnitude larger than the vertical permeability. This is often considered in numerical modelling during geotechnical design however, due to the lack of reliable field measurements available, validating these numerical models can be difficult. Geotechnical centrifuge techniques have successfully been used to investigate responses to complex construction events but are, generally, models created from reconstituted soil. This results in models with well-defined but homogeneous properties. There is a fundamental difference between centrifuge models and natural soil deposits. As a result, centrifuge models are better suited to simulating the short-term response of the soil to a construction event. The work presented outlines a procedure for creating large clay models suitable for geotechnical centrifuge testing with a sedimented structure. These models have anisotropy of the horizontal and vertical permeability allowing for more representative soil behaviour (in terms of dissipation of pore-water pressures) which can be used to investigate the long-term movements resulting from geotechnical construction events.

RÉSUMÉ : Les mouvements de terrain à long terme associés aux constructions géotechniques sont principalement causés par la dissipation des pressions interstitielles excessives et sont régis par les perméabilités du sol et de la structure géotechnique. Le sol naturel a une anisotropie inhérente en raison de la stratification et de la structure provenant du processus de dépôt naturel. Un facteur important qui influence le taux de consolidation et d'infiltration dans les sols naturels est que la perméabilité horizontale peut être de plusieurs ordres de grandeur plus grande que la perméabilité verticale. Ceci est souvent pris en compte dans la modélisation numérique lors de la conception géotechnique, cependant, en raison d'une faible disponibilité de mesures fiables sur le terrain, valider ces modèles numériques peut être difficile. Les techniques de centrifugation géotechnique ont été utilisées avec succès pour étudier les réponses à des événements de construction complexes, mais en général ces modèles sont créés à partir de sols reconstitués. Par conséquent, ces modèles ont des propriétés bien définies mais homogènes. Il existe une différence fondamentale entre les modèles de centrifugeuses et les dépôts naturels de sol. En conséquence, les modèles de centrifugeuses sont mieux adaptés pour simuler la réponse à court terme du sol à un événement de construction. Le travail présenté décrit une procédure pour créer de grands modèles d'argile adaptés aux essais de centrifugation géotechniques avec une structure sédimentée. Ces modèles ont une anisotropie de perméabilité horizontale et verticale permettant un comportement du sol plus représentatif (en termes de dissipation des pressions interstitielles) qui peut être utilisé pour étudier les mouvements à long terme résultant d'événements géotechniques de construction.

KEYWORDS: Centrifuge testing; clays; anisotropy; permeability; long-term movements.

## 1 INTRODUCTION.

All civil engineering projects require ground works, this could be foundations, deep excavations for basements, tunnel boring or the building of embankments. Irrespective of the geotechnical structure, the associated construction event changes the stress conditions of the soil which results in movements. These movements can be in the short-term (movements experienced during and immediately after construction) and in the long-term. Long-term movements are generally caused by the equalisation of pore-water pressures following construction resulting in further ground movement.

In a fine-grained soil the long-term movments can account for a significant proportion of the total settlement experienced after a construction event. Hill & Stärk (2016) monitored and reported ground movements following the excavation for the Crossrail tunnels near Whitechapel station and found the long-term movements accounted for almost 50% of the total deformations experienced. Hill & Stärk (2016) also noted the significance of the relative ground conditions. Two different sites were monitored where no mitigation techniques could be implemented, Vallance Road and Kempton Court. The rates of consolidation at Vallance Road decayed nearly twice as fast as the displacements at Kempton Court owing to the presence of sand bands. These sand bands increased the horizontal permeability and reduced the consolidation time. The London Clay at this location had a horizontal permeability significantly larger than the vertical, which is not uncommon and has been reported in various ground investigation reports and laboratory tests on natural samples (e.g., Little *et al.*, 1992).

In numerical analysis the importance of soil layers and anisotropic permeabilities have also been reported. Wongsaroj *et al.* (2007) modelled the long-term response following the excavations for the Jubilee Line tunnels at St. James Park and noted how modelling the correct permeability anisotropy was essential in obtaining similar patterns of behaviour as those found in the field studies (similar conclusions were also reported by Avgerinos *et al.*, 2016 and Laver *et al.*, 2016). Wongsaroj *et al.* (2013) conducted a parametric study where the permeability anisotropy was varied, and the resultant displacements

simulated. They found that permeability anisotropy affects the magnitude of long-term tunnelling-induced movements and the shape of the resultant settlement trough. Wongsaroj *et al.* (2007, 2013), Avgerinos *et al.* (2016) and Laver *et al.* (2016) all report the need for more long-term movement data to be able to validate and improve numerical models and better predict long-term ground movements in fine grained soils.

Centrifuge modelling has successfully been used to determine short-term patterns of movements and has the potential to provide an insight into the resulting long-term movements following a construction event. However, current centrifuge models are idealised to homogenous soils models and there is a fundamental disparity between this and natural soils, due to omission of structure (after Mitchell, 1976) and permeability anisotropy. The work described here proposes a method to create large clay geotechnical centrifuge soil models with a sedimented structure with predetermined values of permeability anisotropy such that short and long-term movements can be investigated in different ground conditions.

## 2 LABORATORY TESTING USING LAYERED SOIL MODELS

### 2.1 *Creating anisotropic soil beds for experimentation*

There have been construction events investigated using a geotechnical centrifuge using layered soil models which could be viewed as having anisotropy of soil properties. Both Grant (1998) and Marshall et al. (2014) undertook tests using soil samples comprised of different layers. These were generally clay and sand layers produced by consolidating clay slurry or pluviating fine sand. In both studies the primary purpose was to investigate the change in patterns of movements when a second soil layer of a different stiffness was introduced over or underlying a construction event in a clay layer. Both layers in this model making procedure are considered homogenous and will not show the same drainage characteristics as a natural clay sample with a sedimented structure and anisotropic permeability.

Hossain & Randolph (2010) investigated off-shore foundations in two layered clay beds. A centrifuge test series was undertaken in two different soil models termed uniform stiff-over-soft and uniform stiff-over-non-uniform. To create the uniform stiff-over-soft models a Speswhite kaolin clay slurry was one-dimensionally consolidated inside a cylindrical container. The slurry forming the bottom layer was consolidated to a final pressure of 100 kPa and the upper layers were consolidated to either 170 kPa or 500 kPa. The clay samples were then extracted, trimmed, and placed within a centrifuge container to create a layered model. A non-uniform layer is defined in this work as one that is normally consolidated i.e., with an increasing strength profile with depth. To create this layer a kaolin clay slurry was prepared and then pumped into a centrifuge strongbox in-flight and consolidated under self-weight at 200g. After consolidation the top uniform layer was created as described previously and placed on top of the non-uniform layer. Both model making procedures used in Hossain & Randolph (2010) created a layered sample with different stiffnesses similar to the models used in Grant (1998) and Marshall *et al.* (2014) but using only clay.

Pau *et al.* (2018) created anisotropic models using a random field generator to represent three-dimensional soil spatial variability. Pau *et al.* (2018) note how soil is formed in horizontal layers over long periods of time and there is greater homogeneity in the horizontal plane as opposed to the vertical plane and this needs to be incorporated into the random field generator. Different slurries consisting of varying proportions of kaolin clay and bentonite were assigned to elements within the randomly generated fields. To physically create this model different slurries are connected to a 3D printer which allowed a 300mm

cube model to be constructed. Pau *et al.* (2018) concluded that further work was required to improve the method proposed but in principle this procedure can be used to create an anisotropic model. This model making procedure creates random regions of different compressibility by varying its composition, however natural soil is not random. Natural soil has typically well-defined layers leading to changes in compressibility and, of particular importance in relation to long-term movements, different permeabilities.

These methods of creating anisotropic models focus on modelling different layers or regions with differing stiffness and compressibility. These models have not included permeability anisotropy limiting their application for long-term displacement studies.

### 2.2 *Sedimentation*

One method of creating a soil model with the desired structure is through laboratory sedimentation. Figure 1 shows the difference in structure between a sedimented and reconstituted soil sample (Stallebrass *et al.,* 2007). The sedimented sample has a clear silt band at the bottom compared with the reconstituted sample which has an even distribution of silt particles within the clay matrix. It was expected that the presence of this silt band would increase the horizontal permeability.
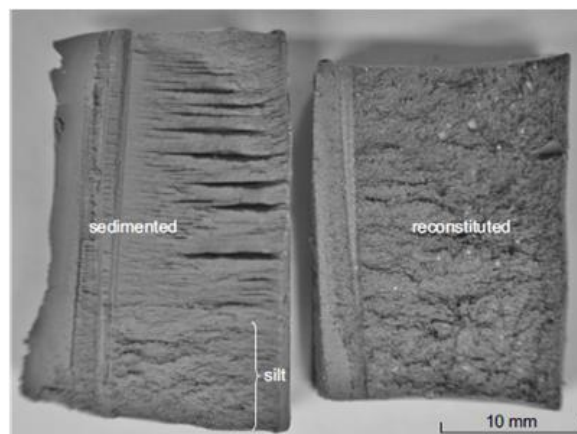


Figure 1. photographs of split sedimented and reconstituted London Clay samples Stallebrass *et al.* (2007).

Stallebrass *et al.* (2007) created these samples by mixing London Clay in salt water (acting as a flocculant) to a water content of around 1250%. Once mixed the slurry was transferred into a sedimentation column (containing further salt water) and left for three days to sediment, after which another identical slurry was added. This process was repeated to create a multi-layered sample. After several layers were sedimented the sample was subjected to one-dimensional compression via a floating piston such that small increments of stress were applied. Samples were subsequently taken from the laboratory sedimented soil and were subjected to triaxial testing. The results from these showed that a laboratory sedimented sample fits the proposed framework for natural, structured soils (after Cotecchia & Chandler, 2000).

Sedimentation column tests are not a new concept and various researchers have investigated the influence of different parameters on the resulting sedimentation characteristics (e.g., Imai, 1980; Edge & Sills, 1989). These tests largely agree that a relatively large water content is required such that particle separation occurs and a sedimented structure is created. However, there is a large variability depending on the material in the suspension fluid. Therefore, the exact water content required to create a sedimented sample with say kaolin clay is not clear from the existing literature. Sorta *et al.* (2012) investigated the effects of an increased acceleration field on the sedimentation characteristics of different slurries. Different slurries were left to

sediment for one month at 1g, and an identical slurry was then subjected to an increased acceleration field using a centrifuge and the slurry allowed to sediment. The segregation index defined in Donahue *et al.* (2008) was calculated and the effect of an increased acceleration field was determined. This study concluded that an increased acceleration field increases the slurry's ability to segregate, i.e., a slurry that does not segregate at 1g may segregate at an elevated g-level. Therefore, guidance from tests conducted at 1g are not directly applicable to sedimentation on the centrifuge.

### 2.3  Sedimenting a centrifuge model

Divall *et al.* (2018) successfully sedimented a large sample using a geotechnical centrifuge (an Acutronic 661). To do so, a slurry consisting of disaggregated Speswhite kaolin clay blocks, Leighton Buzzard fraction E sand and distilled water was mixed to form a slurry of approximately 1250% water content. This slurry was then poured into the strongbox and accelerated to 160g for 1-1.5 hours. After this time the dispersion fluid above the soil was sampled and found to be 99.95% water, verifying that sedimentation had finished in a relatively short period of time. This process was repeated several times to create the multi-layered model seen in Figure 2.

Divall *et al.* (2018) showed that it was possible to sediment a large sample suitable for geotechnical centrifuge modelling, however there were a few issues. The layers within this sample were very thin, each clay band was approximately 20mm deep, and deeper layers would generally be required in which to simulate a construction event. In this study, there were no element tests conducted to determine whether the method created a model with significantly different soil properties compared with a homogeneous sample created by consolidation from slurry.

In order to create a soil bed suitable for use in centrifuge modelling, an initial investigation was required to determine which slurry preparation procedure creates clay models with a sedimented structure and produces permeability anisotropy. The aim was to have a framework and supporting evidence to be able to design centrifuge models to include different layers with predetermined permeability anisotropies and layer thickness. These models could subsequently be used to determine the influence of layered ground and varying permeabilities on long-term ground movements generated by construction events.

## 3  EQUIPMENT AND TESTING PROCEDURE

### 3.1  Sedimentation columns

To investigate sedimentation techniques on the geotechnical centrifuge without the requirement to create large samples, a number of sedimentation columns were produced. These would allow multiple tests to be carried out simultaneously. The height of the sedimentation columns is 800mm (limited by clearance on the centrifuge swing) and were manufactured from 60mm outer diameter PMMA tubes with a 3mm wall thickness. The sedimentation columns were designed to experience a deformation smaller than 0.5% of the diameter when containing a slurry twice the density of water at 100g. The sedimentation column was designed to split into two sections, a lower section where the soil would be located after sedimentation and an upper extension. The two sections of the sedimentation column are sealed using annular flanges and O-rings

As determining permeability is essential for this research the lower section of the sedimentation columns can be adapted into a falling head permeameter. This is done by installing a top cap that connects to a burette to apply a head of water and removing plugs at the base of the sedimentation columns which allows for base drainage during consolidation and as an outlet during

vertical permeability tests. This eliminates potential issues of preferential drainage paths and overestimations of permeability associated with extracting falling head permeability samples. The sedimentation columns filled with slurry for sedimentation are shown in Figure 3. Four sedimentation columns can be used at the same time whilst ensuring they sit on the centreline of rotation.



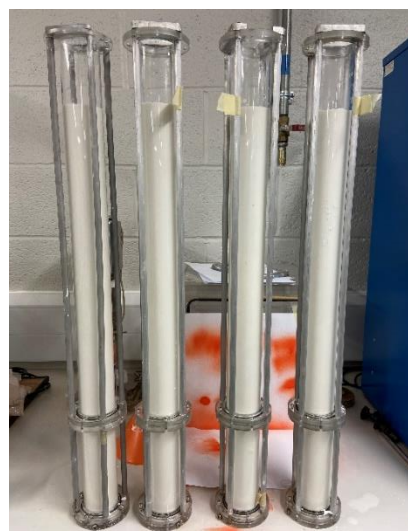Figure 2. Photograph taken inflight during the sedimentation procedure (Divall *et al,.* 2018)



Figure 3. Photograph of sedimentation columns used inflight

### 3.2  Horizontal permeameter

A horizontal permeameter was developed to determine the horizontal permeability of the samples. This operates on the principle of an applied head at the outer circumference of a soil element and pore fluid travelling radially inwards to a permeable core. During the experiment the time and applied head is recorded as in a standard vertical falling head test. The permeability of the soil element can be determined using Equation 1.

$$k = ln\frac{h_0}{h}\,ln\frac{R}{r_0}\,\frac{A}{2\pi LT}$$  Eq. (1)

Where $k$ = permeability; $h_0$ = initial excess head of water; $h$ = excess head of water after time, T; $R$ = external radius of clay sample; $r_0$ = radius of internal filter; $A$ = cross sectional area of burette; $L$ = height of sample and $T$ = time.

It was not possible to adapt the sedimentation columns themselves (as for the vertical permeameter), so a separate piece of equipment was developed using the same PMMA tubing and flanges. The horizontal permeameter was designed to test a 48mm diameter soil element with a height of 30mm.

A series of tests were conducted in the sedimentation column/vertical permeameter to validate the horizontal permeameter. The vertical permeability of a Speswhite kaolin clay sample prepared from a slurry at twice the liquid limit and consolidated to 250 kPa was determined. A second (larger) identical sample was created, and vertical cuts were taken from this using a 48mm internal diameter thin-walled cutter. These cuttings were then placed into the horizontal permeameter (i.e., measuring the vertical permeability in the horizontal permeameter). A total of 20 tests were conducted (10 in the vertical permeameter and 10 in the horizontal permeameter). There was a very strong agreement of results with the average permeabilities deduced from the two measurement techniques varying less than 5%. This proved that the horizontal permeameter is a suitable method of determining permeability and hence assessing permeability anisotropy of the sedimented samples.

### 3.3 *Test procedure*

The sedimentation columns were assembled a day prior to sedimentation in-flight. The porous stones to be placed in the base of the sedimentation columns were saturated individually under a vacuum. Once saturated the sedimentation columns were assembled, covering the stone with porous filter paper and filling the columns with distilled, de-aired water to avoid drying of the porous stones. Monitoring the fluid level in the sedimentation columns overnight also ensured that there were no leaks within the sedimentation columns.

On the morning of the sedimentation experiments the slurry mixing procedure is started. A variety of different slurries and slurry preparation techniques were tested to investigate the effect on permeability anisotropy. All slurries were mixed until a smooth consistency which typically took between 2 and 5 hours. When using recycled clay cuttings, the mixing time was longer than using only clay powder.

Once the slurry was mixed it was passed through a hydro splitter (Figure 5, after Phillips, 2014). The hydro splitter divides the input slurry into identical sub batches, thus ensuring there was the same particle size distribution in each of the columns containing the same slurry. This was essential in obtaining consistent results as a differing particle size distribution would likely change the observed anisotropy. The distilled, de-aired water placed in the sedimentation columns to stop the porous stones from drying was poured away and the slurry poured in to a predetermined level. Within each centrifuge sedimentation test conducted the mass of soil within each of the sedimentation columns were kept consistent.



Figure 5. Hydro splitter used to sub-batch slurry and the vertical permeability set up.

The filled sedimentation columns were then secured into a centrifuge strongbox which was fitted with a guide at the top and bottom such that it keeps the sedimentation columns vertical (horizontal in-flight).

The package was then weighed and placed onto the centrifuge swing, the counterweight was adjusted, and the centrifuge was accelerated to 100g. The slurries were then left to sediment and consolidate for approximately 24 hours. After which the centrifuge was decelerated, and the sedimentation columns were carefully removed. The height of the different samples was recorded, the samples were then consolidated to a vertical effective stress of 250 kPa. The vertical permeabilities were then determined over a period no shorter than 48 hours taking recordings regularly through the working day.

After the vertical permeability of the samples had been determined at 250 kPa, the base of the sedimentation columns was removed, and samples were cored from the bottom up using a 48mm internal diameter cutter sprayed with silicone grease to reduce friction. These samples were then extracted, wrapped in filter paper, and placed into the horizontal permeameter. The top and bottom surfaces of the soil element to be placed into the horizontal permeameter were sealed with a sprayable latex. This ensured that any pore fluid expelled from the sample during the horizontal permeability test was as a result of radial flow and not due to preferential flow around the soil element. The change in applied head was recorded for a period no shorter than 48 hours and the permeability determined using Equation 1. Further details of the horizontal permeameter equipment and testing procedure are detailed in Ritchie (2020).

The prepared samples and the set up used to determine the horizontal permeability are shown in Figure 6.



Figure 6. Prepared samples for horizontal permeability testing (top) and the horizontal permeameter setup (bottom).

## 4 SLURRY PREPARATION TECHNIQUES

Four different slurry preparation techniques were investigated over a range of water contents with the aim of determining the resulting permeability anisotropy of each different technique.

### 4.1 *Speswhite kaolin clay powder and distilled water*

Slurries consisting of Speswhite kaolin clay (supplied by Imerys Ltd) were mixed with distilled water in a paddle mixer to water contents ranging from 120%-1400%. These slurries were passed through the hydro splitter, placed into the sedimentation columns and then sedimented in-flight. This was to investigate if sedimentation of Speswhite powder only created a different

structure compared with a reconstructed homogenous sample and ultimately created different permeabilities and permeability anisotropy.

### 4.2 *Speswhite kaolin clay cuttings and distilled water*

Speswhite kaolin clay cuttings taken from one-dimensionally consolidated homogeneous samples were mixed with distilled water in a paddle mixer to form a slurry with different initial water contents ranging from 120%-1400%. Similar to Divall *et al.* (2018) this was to increase the variation in particle sizes present within the slurry. Work undertaken by Phillips (2014) found when disaggregating kaolin clay cuttings that the cuttings do not break down to their constituent particle sizes. Moreover, after continual mixing there was a reduction in finer particles present as finer particles cluster together to form peds. Therefore, a slurry created by disaggregating cuttings is going to have a more varied particle size distribution than a slurry created by the method described in Section 4.1. Sedimentation of such a slurry created from disaggregated clay may create a more anisotropic sample than that possible using only powder.

### 4.3 *Speswhite kaolin and Polwhite E mixes*

Another method of creating a more varied particle size distribution is by mixing different materials. Polwhite E (supplied by Imerys Ltd) was selected as a suitable coarser material to add into the slurry. Speswhite kaolin is the finest grade of kaolin Imerys produce. Polwhite E is a well refined kaolin clay product with the same mineralogy as Speswhite but, importantly for this research, Polwhite E contains a larger proportion of coarse sized particles, a significant factor for sedimentation characteristics (Imai, 1980). Chan (2020) reported that reconstituted Polwhite E has a permeability approximately 10 times larger than reconstituted Speswhite and this was confirmed by falling head vertical and horizontal permeability tests conducted for this research. After consolidating to 250 kPa the vertical permeabilities were $2\times10^{-9}$ ms$^{-1}$ and $2\times10^{-8}$ ms$^{-1}$ for Speswhite and Polwhite, respectively.

Varying proportions of Speswhite kaolin and Polwhite E powder over a range of water contents were mixed in a paddle mixer. These slurries were subsequently sedimented in-flight and the permeability anisotropy investigated.

### 4.4 *Speswhite kaolin and Leighton Buzzard Fraction E sand*

In tests very similar to those conducted by Divall *et al.* (2018), a slurry consisting of Speswhite kaolin clay and distilled water was mixed to an initial water content ranging from 400-1000%. This slurry was placed into the sedimentation columns. Once the sedimentation columns were secured in the centrifuge strongbox varying proportions of Leighton Buzzard Fraction E sand (LBS E) were poured into the columns. After the sand was added, the centrifuge procedure was then started.

## 5 RESULTS

After every sedimentation test the solid content of the pore fluid above the sedimented soil was taken, the average solid content of the pore fluid after sedimentation was approximately 0.005% (similar to Divall *et al.,* 2018) satisfying that, after 24 hours on the centrifuge, the samples had fully sedimented and there was no clay left in suspension.

### 5.1 *Sedimentation of Speswhite kaolin clay powder/cuttings*

After determining the vertical and horizontal permeabilities of samples prepared using the methods described in sections 4.1 and 4.2 it was clear that using Speswhite alone would not create significant permeability anisotropy irrespective of the initial water content of the slurry. The samples prepared using method

4.1 had a permeability anisotropy of 1.3 (defined as $k_h/k_v$) and those prepared in method 4.2 had an anisotropy of 1.5. This was attributed to the uniform distribution of pore sizes with some particle orientation resulting in a small degree of anisotropy. Another finding was that samples sedimented in-flight and consolidated where typically less permeable than those reconstituted and consolidated at 1g using a "standard" sample preparation technique.

From previous sedimentation column experiments (such as Imai, 1980) increasing the initial water content of the slurry may have changed the resultant properties of the soil as it has been reported that kaolin and kaolinitic soils require very high water contents (2000%+) to allow for sedimentation to occur. This was considered and deemed impractical when trying to create a centrifuge model. Increasing the water content reduces the potential thickness of soil layers that can be created and increases the time required to create a soil model. Therefore, slurry preparation techniques 4.1 and 4.2 were not investigated any further. The results from these tests were consistent in that all the 16 samples created fell within 10% of each other.

### 5.2 *Sedimentation of Speswhite and Polwhite powder*

Within these tests there are two variables; the initial water content of the slurry and the relative proportions of the different materials. Firstly, looking at the initial water content of the slurry shows that as the initial water content of the slurry increases so does the resultant permeability anisotropy. Table 1 shows this variation with a changing initial water content where the subscripts *h* and *v* denote horizontal and vertical respectively.

| Speswhite % | Polwhite % | Initial WC % | $k_h/k_v$ |
|---|---|---|---|
| 70 | 30 | <400% | 1.5 |
| 70 | 30 | 800% | 2.5 |
| 70 | 30 | 1200% | 4.5 |

Table 1. Permeability anisotropy variation with initial water content

Using an initial water content of 1200% the measured permeability of a slice taken from the top of the resulting sample is similar to 100% Speswhite and from the bottom of the sample is similar to 100% Polwhite indicating that during sedimentation, separation of particles sizes has occurred. Any further increases in water content is unlikely to change the resulting permeability anisotropy. When the water content is lowered to 800% the bottom of the sample is still more permeable than the top and there is an increased permeability anisotropy compared with that of samples prepared by methods 4.1 and 4.2. This is due to the initial water content being low enough to prevent the full separation of particle sizes. Finally, when the initial water content is less than 400% it is low enough to prevent separation of particle sizes and therefore the development of anisotropic permeabilities. This shows that to achieve the maximum permeability anisotropy a minimum initial water content of 1200% is required. This pattern of results was seen for all the different proportions of Speswhite tested and again the results of these tests showed good repeatability.

Secondly, the effect of varying the percentage of Polwhite at an initial water content of 1200% was investigated. In all cases, as above, the top of the sample behaves like pure Speswhite having a permeability in the order of $10^{-9}$ ms$^{-1}$ and the bottom behaves like pure Polwhite having a permeability in the order of $10^{-8}$ ms$^{-1}$. From the tests conducted, a Polwhite percentage of around 30% provides the greatest degree of permeability anisotropy where the vertical permeability is governed by the Speswhite and the horizontal permeability by the Polwhite.

### 5.3 *Sedimentation of Speswhite and Leighton Buzzard Sand*

These samples showed the greatest degree of anisotropy with the horizontal permeability being five orders of magnitude larger than the vertical. However, this sample preparation procedure does not create even sand layers as seen in Figure 7. The sand layer slumps towards the back of the column relative to the direction of rotation. The sedimentation time of LBS E is approximately 20 seconds and the sand has sedimented before the centrifuge has accelerated.

Using combinations of Speswhite and LBS E were not investigated any further primarily due to the fact this method creates two layers, a uniform sand layer overlaid by a uniform clay layer. A centrifuge model with these features can be created without the centrifuge as described in Grant (1998). This test did highlight the importance of sedimentation time and the resulting uneven layers.



Figure 7. Sand slumping within the sedimentation columns and after extrusion

## 6 CONCLUSIONS

A total of 40 sedimentation column samples were created testing 4 sample preparation techniques over a range of water contents that allowed the following conclusions to be made.

- Anisotropic clay models can be created through sedimentation on a geotechnical centrifuge however this is not possible using only one material i.e. only using Speswhite kaolin;
- The higher the initial water content, the higher the resulting anisotropy until a limiting water content where the permeability at the top of the sample is governed by the finest material in the slurry and the bottom of the sample is governed by the coarsest material in the slurry;
- Using a 1200% initial water content slurry, with a 70:30 distribution of Speswhite and Polwhite provides the greatest degree of permeability anisotropy.

Transferring this method of creating anisotropic models from a sedimentation column to a centrifuge strongbox has some implications. At City, University of London, the centrifuge strong boxes have internal dimensions of 550mm (L) x 200mm (W) x 375mm (H). Using a 1200% initial water content slurry a maximum layer thickness of approximately 35mm is achievable by completely filling the strongbox and a 300mm tall extension above. Using this setup, combined with sedimentation of each layer for 24 hours, it would take a minimum of 5 days to create a model deep enough to conduct a construction event experiment within. Further tests are being conducted to see if the sedimentation time can be reduced such that numerous layers can be sedimented within a working day to reduce the centrifuge time required to sediment a centrifuge model. Sedimentation column tests are ongoing with the aim of continuing to build a framework such that a centrifuge model can be designed to contain specific layers with predetermined permeability anisotropies.

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