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Short-term structural response of a model shaft linear as a baseline to inform a simulated shaft breakout in clay

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ABSTRACT: The growth of underground infrastructure that is being driven in major cities by the increase in population and lack of surface space, requires access between the ground surface and the underground space. In urban environments this can be for a range of applications from transportation to service systems (such as water management). In tunnelling, new sections of permanent works access are achieved via the construction of a connection between a new shaft and the tunnel known as "shaft breakout". This construction process involves the formation of an opening in the side wall of the shaft near its base, which will disturb the loading and supporting equilibrium of the shaft. Currently, there is limited published knowledge about the behaviour of the shaft lining and the ground adjacent to the opening during the breakout. This results in conservative design approaches and substantial temporary works. To assist with this, baseline results are presented from geotechnical centrifuge modelling and finite-element modelling designed to simulate a shaft breakout. The shaft breakout comprises an opening situated in the wall of the cylinder fitted with a plug that can be removed. The model shaft consists of a preformed instrumented cylindrical liner of diameter of 101.6 mm and depth of 254.0 mm located in a sample of overconsolidated Speswhite kaolin clay. At the test acceleration of 118 times Earth's gravity, this represents a 12 m diameter shaft sunk to a depth of 30 m. The structural response of a freestanding continuous shaft and the same shaft embedded in clay and tested at 118g is presented. The stress distribution in the shaft prior to the breakout is compared to the redistributed stresses following the construction of shaft breakout providing confidence in the instrumentation used and its interpretation.

KEYWORDS: Centrifuge, shaft, tunnel

1 INTRODUCTION

1.1 *Background*

In many cities, the construction of major underground infrastructure involves both tunnelling and shaft sinking operations. Shafts in clay were typically constructed using cast iron rings, however, recently a range of methods are used including precast concrete segments, sprayed concrete and caissons (Faustin et al., 2018). Once constructed, these shafts are used for level access, ventilation and material transportation from the surface to subsurface space. Adits, short horizontal tunnels, then serve as an entrance or access point between the shaft and other elements of the underground system.

The start of the construction process for creating an adit requires the formation of a lateral opening (sometimes referred to as a "shaft breakout") in the shaft. The size of the lateral opening can vary depending on the purpose of the shaft or tunnel. A conservative lateral opening size of one-third of the shaft diameter would normally be considered standard, though there is currently no published guidance providing an agreed standard for the design or relative opening size (O'Dwyer, 2023). The lack of detailed guidance was confirmed by Challinor (2022) reviewing guidance published by the British Tunnelling Society Tunnel Design (The British Tunnel Society, 2004).

Although, New & Bowers (1994) reported the monitoring of ground movements during shaft sinking operations for the Heathrow Express trial tunnel, the data were subsequently used only to inform the development of simplified prescriptive design methods for shafts. Furthermore, Chudleigh et al. (1999) note that consultants, working on behalf of contractors, must specify overly conservative designs to form the lateral openings because of the lack of detailed understanding of the interaction between new and existing buried infrastructure.

1.2 *Previous work*

Various investigations have been conducted into the overall behaviour and stability of shafts (e.g. Britto & Kusakabe, 1982; Morrison et al., 2004) including Faustin et al. (2018) who reported 27 case studies of circular shaft construction in London, UK. Whilst none of these studies made specific reference to the effect of constructing a shaft near existing buried infrastructure, work by Divall & Goodey (2016) and Le et al. (2019) have begun to address this issue by providing analytical solutions. The study estimated the vertical and horizontal movement with depth. Le et al. (2019) made use of geotechnical centrifuge modelling techniques to provide this new insight. The effect of openings for cross passages on tunnels has been investigated by Lu et al. (2022). A model tunnel with three openings was modelled using geotechnical centrifuge modelling techniques. The study investigated the mechanical characteristics of shield tunnels with a range of opening shapes and sizes. It concluded that the size of the opening influenced the behaviour of the tunnel, specifically the larger the opening, the larger the concentration of the stresses close to the opening.

2 METHODOLOGY

Centrifuge modelling allows for full-scale prototypes to be modelled at a reduced scaled with the benefits of repeatability and close control over materials and boundary conditions associated with laboratory testing. Parametric studies, such as this, also benefit from the ability to model geotechnical events with variations too impractical to investigate otherwise.

City St George's, University of London has access to the Acutronic 661 geotechnical centrifuge situated in the Civil Engineering Laboratory. This is a 40 *g*-tonne machine capable of accelerating 200 kg to 200 times Earth's gravity using a 1.8 m radius arm. The most recent capabilities and details of this facility are described in Ritchie (2025).

To aid in the interpretation of the measurements made in the centrifuge model test, finite-element modelling has been undertaken using the Abaqus finite element program. Simple linear-elastic analyses with an attempt to replicate representative *in situ* stresses were undertaken and are also described below.

2.1 *Centrifuge testing - shaft lining*

The model lining, Figure 1, is formed from an aluminium tube with a Young's modulus of 69 GPa. The model lining has a 101.6 mm outer diameter with a thickness of 1.6 mm and a depth of 254 mm. The base of the lining is a brass plate with an

O-ring to ensure a watertight seal. The base plate has a cross section as shown in Figure 2 and a total depth of 35 mm to counterbalance the potential upthrust caused by the removal of the soil during the shaft construction and the water pressures acting at the shaft base due to the water table 10 mm below the soil surface.

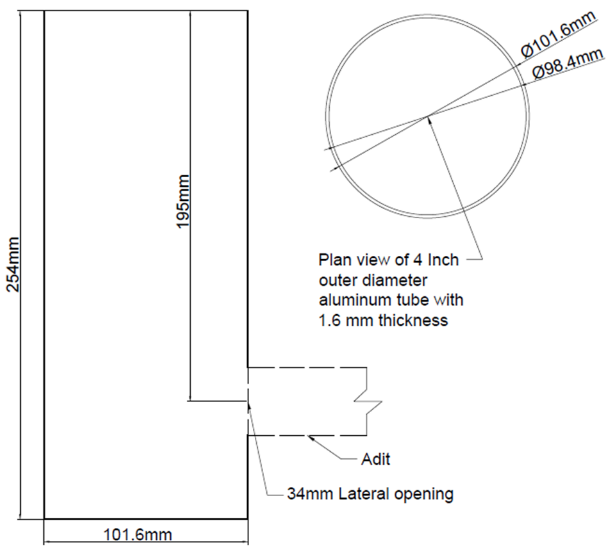

Figure 1. Aluminium shaft lining with an lateral opening and adit.

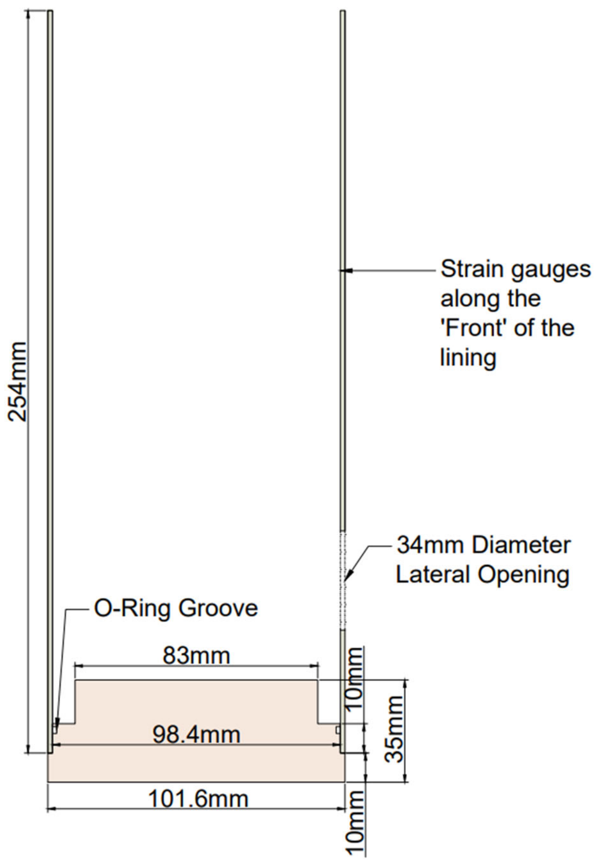

Figure 2. Cross-section of aluminium shaft lining with brass base plate

The model test was conducted at 118 times Earth's gravity (n = 118). Using the scaling for bending stiffness (EI) where in Le (2017):

$$\frac{E_m I_m}{E_p I_p} = 1/n^4 \tag{1}$$

The model corresponds to a prototype shaft having a 300 mm thick continuous concrete lining with a Young's modulus of 30 GPa. The prototype shaft has a 12 m outer diameter, and a depth of 30 m. Ucur et al. (2024) gives more details on the model liner.

This paper focuses on analysing the stress distribution for the aluminium model liner prior to the installation of the lateral opening. For both finite-element model and the centrifuge tests the shaft was analysed under two conditions as seen in Table 1. The initial test has a continuous shaft liner without an opening under its self-weight. The second condition consist of the same shaft liner but now imbedded in Speswhite kaolin. These tests would serve as the baseline readings for around the planned lateral opening.

	Shaft liner with no soil	Shaft Liner with soil
Centrifuge	Test 1	Test 2
FEA	Model (a)	Model (b)

Table 1 Centrifuge and FEM test.

2.2 *Centrifuge testing - instrumentation*

Previous research shows that strain gauges can be an effective means of measuring the distribution of stresses around lateral openings in tunnel linings (Lu et al., 2022). Consequently, strain gauges have also been used to instrument the model shaft lining shown in Figure 1. A total of 18 strain gauges were installed on outer surface of the model shaft lining around the area where the tunnel opening is due to be constructed and along the depth of the model lining as shown in Figure 3. Owing to the chloroprene rubber-based coating applied onto each strain gauge, it is not anticipated that the corresponding readings would be adversely affected by normal or shear stress exerted by the soil on the model shaft liner. In addition, the strain gauges are designed to record the immediate response by the shaft once the plug has been removed.

The strain gauges were installed in vertical and horizontal arrangements as well as two at 45° around the opening to measure the soil-structure interaction and full stress distribution around the opening before and after it has been cut in the shaft. After the tests reported here, this opening will be cut into the continuous aluminium lining and a further test will be undertaken where a plug that supports the opening during model making, centrifuge acceleration and subsequent soil consolidation will be extracted in flight so that clay can extrude into the shaft. Changes to the strain distribution caused by the opening can then be recorded.

The strain gauges were connected to a junction box on the centrifuge arm which transferred the electrical signal output to the data logger with an amplification gain of 1000 with a range of 5 mV. These voltages can, post-test, be converted into strain and stress.

Instrumentation has also been used for monitoring the pore-water pressure levels during in-flight consolidation when clay was present. Two miniature pore pressure transducers (PPTs) were installed at varying depths within the soil model as shown in Figure 4.

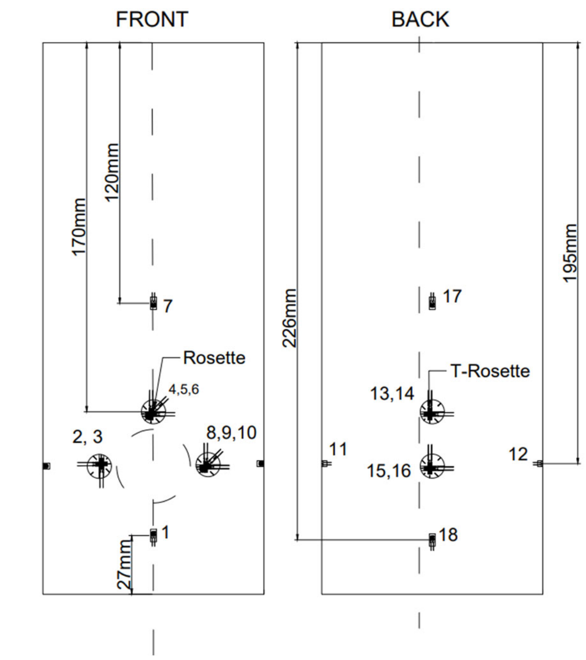

Figure 3. Arrangement of the 18 strain gauges.

2.3 *Centrifuge testing - model*

Figure 4 shows a sketch of the model used in the centrifuge test where clay was present. In the initial test without clay the shaft was placed on the base of the same centrifuge container in the centre of the container. For the second test, the model shaft was embedded into the soil sample (unit weight 17.5 kPa). To create the soil sample a slurry of Speswhite kaolin clay powder and distilled water was mixed to a water content of 120%. The slurry was placed within a circular container or tub, 300 mm internal depth and 420 mm internal diameter. An extension with the same internal plan area is bolted to the tub allowing for a deep model after consolidation. A filter paper and porous plastic sheet are placed at the top and bottom of the slurry allowing for two-way drainage. The soil sample was subjected to a vertical stress of 275 kPa using a hydraulic consolidation press and then swelled back to 175 kPa, resulting in a suitable undrained shear strength for model making.

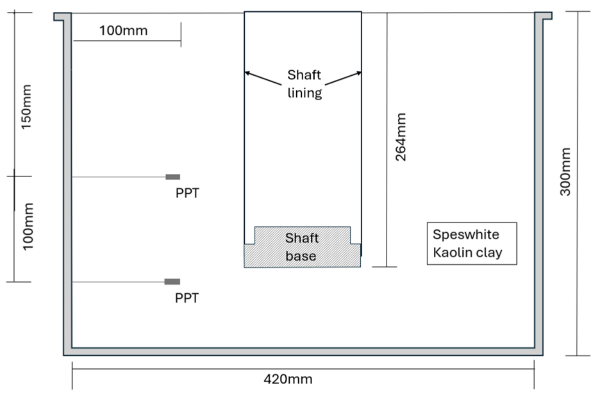

Figure 4. Sketch of centrifuge model

The undrained shear strength that results from compressing to these stresses ensures that the soil would fail by extruding into the opening during the construction phase of shaft breakout but is also sufficiently stiff to allow adequate model making procedures to take place on the laboratory floor as shown in Ucur et al. (2024).

2.4 *Centrifuge testing - model preparation and testing*

For the second test, with clay, after the tub was removed from the hydraulic consolidation press, the extension was removed exposing the clay. The clay was trimmed to the top level of the tub, and a liquid rubber Plasti-dip was sprayed over the exposed clay to provide a seal ensuring minimal evaporation. A bespoke cutter guide was then mounted onto the tub and with the use of a circular cutter and auger a cavity was formed with the same outer dimension as the shaft.

The model liner was carefully placed into the cavity ensuring the strain gauges on the outer surface remained intact. An endoscope was lowered down the centre of the shaft to monitor any potential water ingress.

Prior to accelerating the geotechnical centrifuge, all checks were conducted to ensure instrumentation was correctly connected and a standpipe was connected to the model to provide a water table, 10 mm below the clay surface. Following these checks, the centrifuge was accelerated to 118*g* and left in-flight for approximately 48 hours to allow for the sample to re-establish hydrostatic equilibrium. At this point measurements were taken of the strains in the shaft.

2.5 *Numerical Model*

The finite-element analysis software Abaqus was utilised to analyse the distribution of strain along the shaft when it was (a) subjected to an increase in gravitational force equivalent to 118g with no clay present and (b) when it was subjected to the same increase in gravitational force when surrounded by Speswhite kaolin.

The finite-element model simulated both the aluminium shaft lining on its own and with Speswhite kaolin as axisymmetric. Consequently, meshes in both cases just represent half of the shaft and centrifuge model as shown in Figures 5. Model (a) shows the shaft lining with brass base plate with no soil so that the effect of adding self-weight due to increasing gravity to 118g can be investigated.

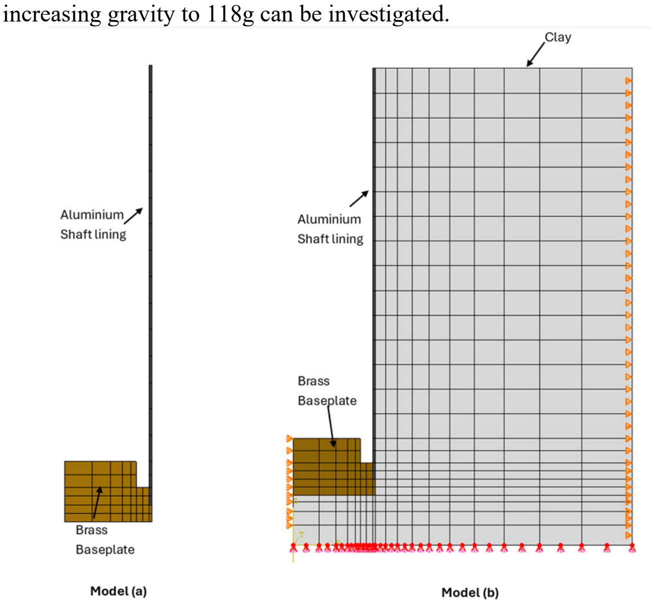

Figure 5. Mesh for Model (a) Aluminium lining and brass plate and Model (b) combination of soil model and structural elements

The soil was given a buoyant mass density of 750 kg/m^{3,} a Young's modulus of 180 MPa and a Poisson's ratio of 0.3 modelling Speswhite Kaolin under drained conditions. The aluminium and brass mass densities are 2700 kg/m^3 and 8470 kg/m^3 and the Young's moduli were 69 GPa and 100 GPa respectively. Buoyant mass densities used for Model (b) were 1000 kg/m^3 less in each case. There are two "steps" to the analysis for Model (a), the initial step allows for the application of gravity (9.81m/s), while in step two the gravitational force is increased to 118g

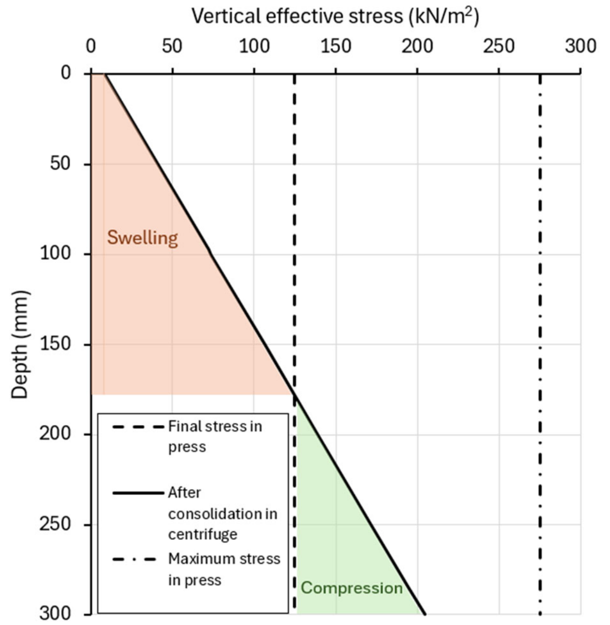

Figure 6. Variation of vertical effective stress with depth

The Model (b) analysis is more complex as it is important to ensure that the change in stress during consolidation in the centrifuge is modelled correctly. Figure 6 shows the vertical effective stress in the consolidation press prior to model making and after consolidation on the centrifuge. It also shows the maximum vertical effective stress imposed on the sample in the consolidation press which was 275 kPa. From Figure 6 it can be seem the vertical effective stress never exceeds 275 kPa and consequently, it is reasonable to model the soil as elastic. Above a depth of 180 mm the clay is swelling whereas below 180 mm the clay is recompressing. To reproduce this behaviour, the simulation was broken into three steps, the initial step consists of the application of a 175 kPa surcharge to the soil, which is assigned an *in situ* stress profile that is in equilibrium with this surcharge. In the second step a cavity is created and the shaft installed by replacing soil elements with shaft and base duplicate elements. In the final step the surcharge is removed, and the gravitational force is increased to 118g. To ensure that stress changes are modelled correctly effective stresses are used with zero pore pressure and buoyant unit weights or mass densities.

The mesh in Figure 5 Model (b) was fixed in the x direction at the lateral boundaries and in the x and y directions at the base. In Model (a), the mesh is only fixed in x and y directions along the base of the shaft. In Model (b) there are no interface elements between the shaft lining and the soil. This means that there is no relative movement at the interface and strain in the soil will be transferred to the shaft. This was assumed because there was no information on the interface strength available.

3 RESULTS

The stress acting on the shaft lining can be calculated in respect to the strain, change in length over the original length.

$$\sigma = E \cdot \varepsilon \quad (2)$$

Where E is the Young's modulus for the model shaft lining and ε is the strain. The relationship between strain and change in voltage output for a quarter bridge strain gauge is such that:

$$\frac{\Delta V}{V} = \frac{GF \cdot \varepsilon}{4} \quad (3)$$

Where ΔV is the change in voltage, V is the original voltage and GF is the gauge factor. This equation can be rearranged to determine strain, ε.

$$\varepsilon = 4 \cdot \frac{\Delta V}{V} \cdot \frac{1}{GF} \quad (4)$$

A quarter bridge configuration was used for all 18 strain gauges with the tests undertaken in temperature regulated room, therefore no variation of the gauge factor due to temperature was expected.

The vertical stress due to self-weight can be calculated with depth from the top of the model shaft lining.

$$\sigma_S = \rho . g . z \quad (5)$$

Where ρ is the density of shaft, g is the Earth's gravity and z is the depth from the top of the shaft lining.

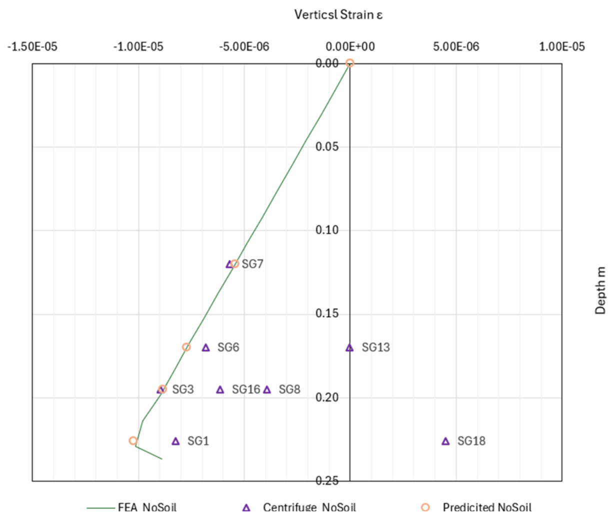

Figure 7. Vertical strain with depth profile with no soil at 118g

Figure 7 presents the vertical strain obtained from the centrifuge test when no soil is present, Test (a). Also shown on the graph are values for strain back calculated from equations 1 and 4 and the strain calculated from the finite element analysis. All but two measurements are negative correctly indicating compression of the shaft. It is interesting to note that although strains at locations 7, 6, 3 and 1 fit well to the back calculated values and finite element predictions, the measured strains at 8, 13 and 18 are quite different from those expected, in particular the strains at 13 and 18 which were measured on the opposite side of the shaft to 7, 6, 3 and 1.

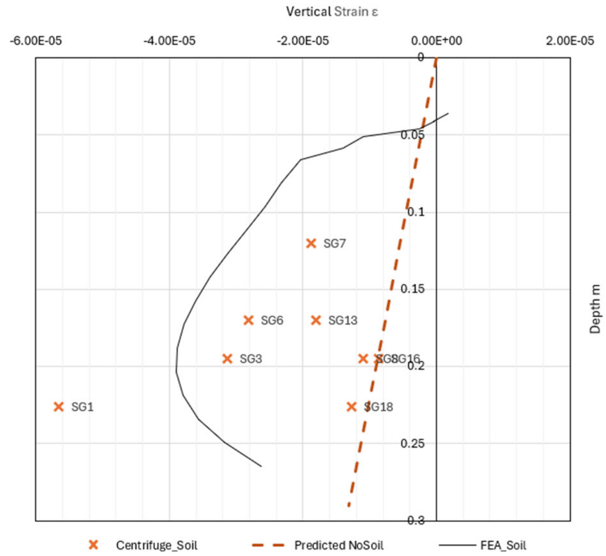

Figure 8. Vertical strain with depth profile in Speswhite kaolin at 118g

Figure 8 presents the vertical strains measured after consolidation for 48 hours at 118g in the geotechnical centrifuge. These are compared to predictions from Model (b), solid line, and the strain distribution when no soil is present from Figure 7, dashed line. All measured strains are greater or equal to the strain distribution expected when no soil was present. The presence of the Speswhite Kaolin has therefore increased the compressive strains in the shaft at all strain gauged locations. The variation in vertical strain with depth predicted by the Model (b) finite element analysis is generally an upper bound to the strains measured in the shaft. At shallow depths, the predicted strains go into tension due to the soil swelling around the shaft near the surface. Also, as the depth increases, the swelling of the clay reduces until at 180mm below ground surface the soil is compressing, this is particularly the case below the shaft due to the weight of the shaft acting on the underlying soil and this adds to the increase in tensile strains calculated.

4 DISCUSSION

Two tests have been undertaken to evaluate strain measurements in a model shaft tested in a geotechnical centrifuge. The strains reviewed are vertical strain measured at nine points around the shaft using quarter bridge strain gauges fastened to the outside of the shaft.

In the first test, model (a), the shaft was accelerated to 118g in the geotechnical centrifuge and strains were measured which should correspond to an increase in stress with depth generated by the self-weight of the aluminium tube. Three of the strain gauges at location 3, 6 and 7 registered strains corresponding very closely to those predicted by calculation and a simple linear elastic finite element analysis. Two strains, at locations 1 and 16 were relatively close to the predictions and strains measured at locations 8, 13 and 18 were sufficiently different to indicate that the gauges in these locations either malfunctioning or possibly reflect strain caused by the shaft bulging under its own self-weight. The latter would not have been predicted by the linear elastic finite element analysis. The effect of placing the shaft off centre in the tub or on a surface that was not flat were considered but would not have led to the differences observed as the base plate is stiff and heavy.

In the second test, model (b), the shaft was embedded in Speswhite Kaolin clay that had been compressed in a consolidation press to 275 kPa and then swelled to 175 kPa. The model was then allowed to consolidate at 118g on the centrifuge for 48 hours. The strains presented were from the end of this consolidation period. The three strain gauges at locations 3, 6 and 7 identified above registered a variation in compressive strain that increased with depth at a rate that was consistent with the variation with depth predicted by finite element analysis, although the results from the finite element analysis were approximately 0.8×10^{-5} more compressive than those measured. The strain gauge at location 1 showed a very high compressive strain. This may be because it is located very close to the base of the shaft where there is a connection to the brass base plate. The aluminium shaft in this region may then deform when the base plate was inserted as it has a very tight fit. The measured response of the remaining strain gauges remained unclear but perhaps indicating the response of the model liner was caused by the shaft bulging under its own self-weight or insufficient contact of a small number of the gauges.

Considering the three strain gauges at locations 3, 6 and 7, it was encouraging that a relatively simple linear elastic finite element analysis was able to predict the increase in vertical compressive strain observed in the centrifuge model test and in particular how this varied with depth. This endorses the simulation of the stress changes taking place using effective stresses and buoyant unit weights to allow for the effect of the pore pressures acting in the soil and the changes in the profile of stress with depth once the model is accelerated to 118g. Nevertheless, the following inaccuracies in the modelling will affect the predicted vertical strains:

- There are no interface elements in the finite element analysis. Thus, any swelling or compression of the soil will have an exaggerated effect on the vertical strains in the shaft.
- The changes in stress calculated by the finite element analysis are greater than those achieved in the centrifuge test.
- Even at overconsolidated states, soil is non-linear, and the stiffness of the soil will be dependent both on the stress state and the change in stress. The soil stiffness used is appropriate to small changes in stress and higher confining pressures.

5 CONCLUSIONS & FUTHER WORK

The two preliminary centrifuge model tests undertaken have provided measurements of vertical strains which are consistent with predictions from finite element analyses.

The first test allowed an assessment of the reliability of the measurements being made indicating that five strain gauges were providing believable results in relatively close agreement with computed and predicted strains. It was then possible to be confident in assessing the results of the second test.

The three most reliable strain gauges from the first test showed a consistent increase in vertical strain at the end of consolidation on the geotechnical centrifuge. These data were also consistent with the simple finite element analysis carried out for comparison. It was not possible to assess whether the predicted decrease in compressive strain at the top of the shaft would be seen in practice as no strain gauges were present. Lower down the shaft a predicted decrease in vertical strain was also not observed but this may be because the strain gauge at the base of the shaft was affected by its proximity to the base plate.

Overall, the strain gauges were seen to perform satisfactorily. However, there is an indication that some strain gauges may be faulty or did not have good contact with the aluminium lining. It appears that accelerating the shaft to 118g without any soil is a good measure of the performance of the strain gauges as measurements from reliable strain gauges compare well with predicted strains.

Future work will consist of the replacement of those strain gauges which were not successful prior to simulation of a shaft breakout with the installation of an opening of one-third of the shaft diameter, consistent with normal construction practice, at a depth of 195mm. These future tests will be compared with the baseline test to quantify the redistribution of strains around the opening during a shaft breakout simulation. In addition, further finite element analyses will be undertaken of the second baseline test to compare predictions of hoop strains with the measurements made.

6 ACKNOWLEDGEMENTS

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