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Centrifuge modelling of shaft excavations in clay

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ABSTRACT: Circular shafts are an integral component of tunnelling projects and can be located very close to buildings and services in urban environments. They enable access of equipment, personnel and material to the tunnel horizon and also provide ventilation and/or emergency access to the completed tunnel. The current state of knowledge concerning the behaviour of circular shafts and the ground movement associated with their construction is limited. Consequently, any conservative assumptions made in the design of the shaft lining or to estimate ground movement due to their construction can have considerable cost implications for tunnelling projects. This paper describes a small-scale model test performed in a geotechnical centrifuge to simulate shaft excavation in clay. The centrifuge model and procedure developed to excavate the shaft in-flight are described. Measurements are presented for instruments used to monitor the response of the shaft lining as well as the adjacent ground.

1 INTRODUCTION

1.1 *Background*

There is an increasing need to use underground space to meet the growing demand for infrastructure development in urban areas. This demand is driven primarily by the lack of over ground space and the fact that underground tunnelling schemes can provide considerable economic and environmental benefits. Large vertical shafts are a major component of such tunnelling schemes. They enable access of equipment, personnel and material to the tunnel horizon and also provide ventilation and/or emergency access to the completed tunnel. The plan geometry of shafts can be any shape but circular shapes are attractive as they are inherently more stable than other plan geometries.

Two key design considerations are how strong to make the shaft lining and how to mitigate the potential effect of ground movement on nearby infrastructure. At present, there is limited guidance available for the design of circular shafts and few well-documented case histories published on shaft excavation. Consequently, circular shafts are often designed using analytical methods applicable to non-circular shapes (Schwamb et al. (2015)). These methods often do not make allowances for the three dimensional hoop stresses that develop in the shaft lining and therefore overestimate structural deformation of the shaft lining.

This paper describes the development of small-scale centrifuge model tests, conducted at Cambridge University, to investigate the behaviour of circular shaft linings and the adjacent ground during excavation. A major feature of the centrifuge tests is the new technique developed to simulate excavation of the model shaft in-flight.

Further details are given in Faustin (2017).

2 PREVIOUS CENTRIFUGE STUDIES

The core principles of centrifuge model testing have been widely reported but only a limited number of publications exist for modelling shafts in the centrifuge. A review of existing literature revealed two common methods for simulating shaft excavation in centrifuge tests.

In the first method, soil at the centre of the shaft is replaced with a fluid having a similar density to the soil that it replaces. The excavation process is simulated by draining the fluid in-flight. This technique assumes that the vertical and horizontal stresses in the ground are equal. This condition may not actually be the case in the field. Lade et al. (1981), Kusakabe (1982) and Britto and Kusakabe (1984) conducted centrifuge tests of shaft excavations using this technique. Divall and Goodey (2016) used this technique to investigate the ground movement around a shaft that was semi-circular in plan. They attempted to capture the ground movement that potentially occurs when the soil is unloaded, before the shaft lining is placed. This was modelled by placing a latex membrane around a solid semi-circular shaft lining. The annulus between the shaft and the membrane was filled with a heavy fluid which was drained in-flight. Use of a solid shaft reduced the amount of heavy fluid required for the centrifuge test.

The second method to simulate excavation of a shaft in-flight is to force a displacement of the shaft lining that may occur when the shaft is excavated. This approach was adopted for centrifuge tests carried out by Fujii et al. (1994) and Kim (2014) to investigate the pressure distribution on a shaft in dry sand.

In addition, Ueno et al. (1996) developed a vacuum excavation system to actually remove sand at the centre of the shaft during the centrifuge test. Their in-flight excavation device comprised a perforated tube located at the centre of the shaft. To simulate an excavation, a negative pneumatic pressure was applied to the bottom of the perforated tube to draw sand from the centre of the shaft to a collection point.

3 CENTRIFUGE MODELLING OF SHAFT EXCAVATION IN CLAY

3.1 *Overview*

The 1:75 scale centrifuge model tests reported in this paper were carried out in overconsolidated clay using the 10 m diameter geotechnical centrifuge at Cambridge University. A detailed description of this centrifuge is given by Schofield (1980). The main purpose of the centrifuge tests was to monitor the development of hoop and bending strains in the shaft lining and to measure deformation of the adjacent clay during excavation of the shaft.

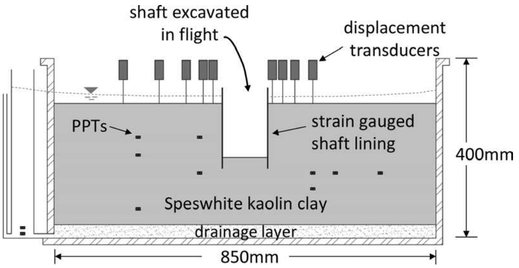

Figure 1. Typical cross section through centrifuge model.

Figure 1 is a typical cross section through the centrifuge model. It shows the Speswhite kaolin clay, the instrumented model shaft and monitoring instruments on the clay surface.

3.2 *Clay stress history*

The clay was consolidated at 1 g to a maximum vertical effective stress of 400 kPa. During the centrifuge test it experienced a linearly increasing vertical stress of up to 140 kPa. The undrained shear strength of the clay, derived using a relationship proposed by Vardanega et al. (2012), increased with depth to a maximum of about 52 at the base of the clay model. Figure 2 shows the undrained shear strength (s_u) profile for the clay at 75 g. It also shows the K_o profile, based on the well-known empirical relationship reported by Schmidt (1983) and the over-consolidation ratio of the clay at 75 g.

3.3 *Main apparatus*

The centrifuge tests were carried out in a steel container 850 mm in diameter and 400 mm high. The 1 mm thick model shaft was machined from aluminium alloy 6082 having a Young's Modulus of 70 Gpa.

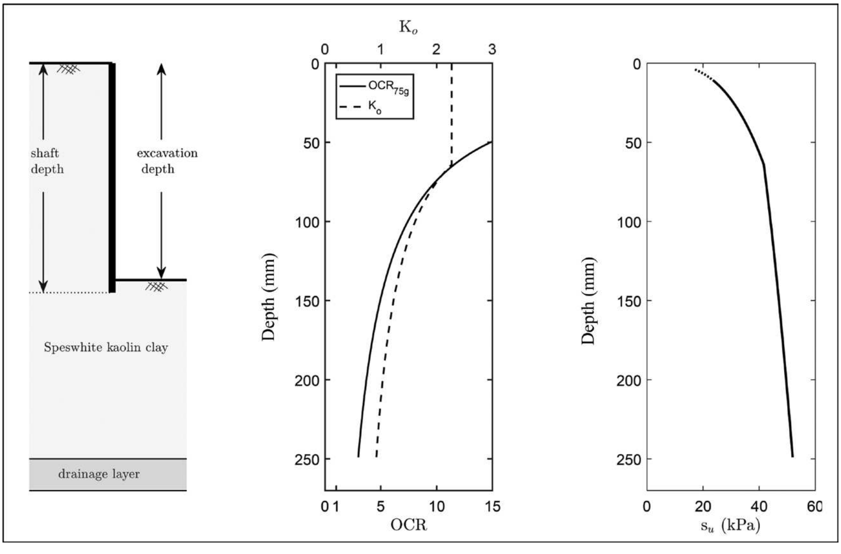

Figure 2. Material properties of Speswhite kaolin clay at 75 g.

The model shaft had an internal diameter of 100 mm and a length of 180 mm. It was instrumented with strain gauges and embedded into the clay at 1 g.

During the centrifuge test, the shaft was excavated using a miniature version of the auger excavators typically used on construction sites. This is analogous to a shaft made up of diaphragm wall panels installed in a circular arrangement that is excavated after all the diaphragm wall panels have been installed. An excavation depth of 140 mm achieved was equivalent to a prototype shaft 7.5 m in diameter and 10.5 m deep.

3.3.1 *Auger excavator*

The miniature auger excavator, developed specifically to excavate the model shaft in-flight, comprised three main features: a single flight auger, a two axis servo-actuator (2D actuator) and a mechanical device to remove the excavated clay from the auger after each excavation step.

The single flight auger was used to core clay from the centre of the shaft. It had an outer diameter of 88 mm which was specially designed to allow a 6 mm clearance between auger and the inner wall of the shaft lining. The stem of the auger was connected to the output shaft of a McLennan IP57-M03 250:1 gearbox as shown in Figure 3. The auger system was mounted onto the moving plate of the 2D actuator and a connection to a M586TE servomotor allowed the auger to rotate.

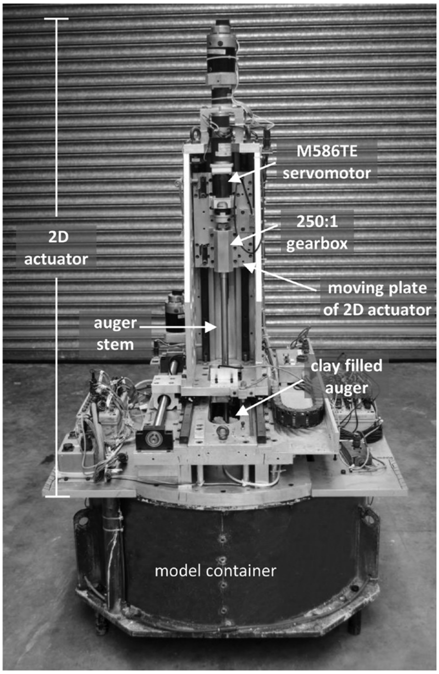

Figure 3. Centrifuge model package used for shaft excavation in clay.

The 2D actuator was placed on top of the model container and enabled movement of the auger in the horizontal and vertical direction. The device is described in detail by Haigh et al. (2010) and its performance specification is summarised in Table 1.

Table 1. 2D actuator performance specification.

Setting	Stroke (mm)	Maximum velocity (mm/s)	Load capacity (kN)	Accuracy (mm/s)
Horizontal direction	450	5	10	0.005
Vertical direction	300	5	10	0.005

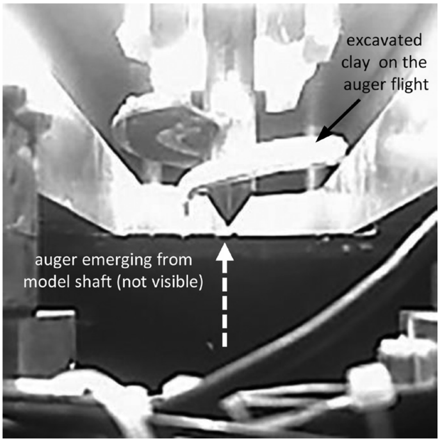

Figure 4. Image of auger filled with clay as it emerges from the shaft during the centrifuge test.

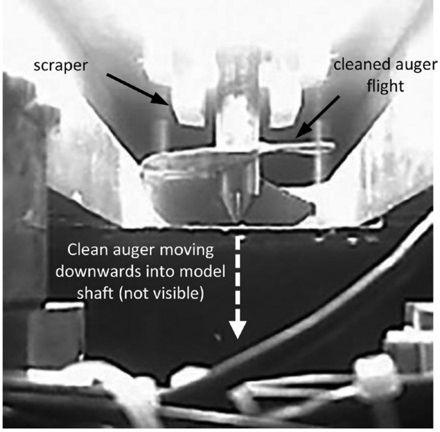

Figure 5. Image of auger as it travels back into the shaft after the clay has been cleaned off the auger blade.

The third component of the auger excavator system was a mechanical system that was mounted above the auger to remove clay from the auger after each excavation step. It consists of a 35 mm square, aluminium block (scraper) which was allowed to travel vertically via an electromechanical linear actuator. In the at-rest position, the scraper was located above the auger. During the centrifuge test the linear actuator was programmed to move downwards so that the scraper made contact with the rotating auger and cleaned the clay off it.

Figure 3 shows the model container, the 2D actuator and the stem of the auger with some clay on its flight. Figures 4 and 5 are snapshots from a camera, mounted on the underside of the 2D actuator, which was focused on the auger during the centrifuge tests. Figure 4 shows the auger filled with clay as it emerges from the shaft after an excavation stage. Figure 5 shows the clean auger travelling back into the shaft, after the clay has been removed from the auger.

3.4 *Monitoring instruments*

Monitoring instruments were placed on the shaft lining and on the clay surface to monitor the behaviour of the shaft and the surrounding ground during the centrifuge tests. A series of strain gauges configured in Wheatstone full bridge and half bridge circuits were secured to the shaft to monitor bending and hoop strains in the shaft lining respectively.

Miniature displacement transducers were placed on the clay surface at varying distances from the shaft lining to monitor displacement of the clay surface during excavation of the shaft (see Figure 1).

A laser with a measuring range of 50 mm to 350 mm monitored the horizontal position of the auger during the centrifuge test.

Two cameras and an endoscope provided a visual inspection throughout the centrifuge test.

3.5 *Centrifuge test procedure*

The centrifuge model was swung up to 75 g in approximately one hour. The clay was then allowed to reach equilibrium. This took approximately 6 hours. Excavation of the shaft was then carried out by augering clay from the centre of the shaft in 4 mm increments. After each excavation step the 2D actuator travelled up to the surface and 150 mm horizontally across the tub to a holding container. The clay removal system was then activated so that the scraper moved downwards and cleaned off the auger. The cleaning mechanism was then retracted and the 2D actuator travelled back to its reference position above the model shaft. The next excavation step was then carried out.

On average, it took approximately 13 seconds for the clay to be cleaned off the auger and forty excavation increments were carried out.

4 TYPICAL RESULTS

4.1 *Ground movement*

Figure 6 shows the excavation progress and the corresponding variation in ground surface settlement measured by the miniature displacement transducers. Negative surface displacements

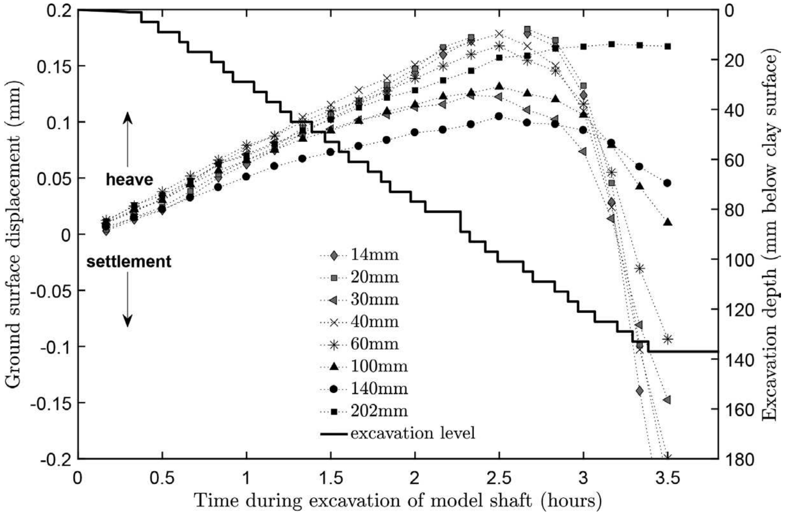

Figure 6. Observed excavation level and measured ground surface settlement during excavation of the model shaft. The displacement transducers were located at eight different distances from the shaft lining.

indicate settlement and positive surface displacements indicate heave. The clay around the model shaft is observed to swell upon unloading of the clay during excavation. Settlement of the clay becomes dominant as the shaft excavation depth increases.

4.2 *Structural behaviour of the shaft lining*

Figure 7 shows the development of circumferential or hoop stresses in the model shaft lining as the excavation progresses. Positive stresses indicate tensile hoop stresses and negative values compressive hoop stresses. In general, the hoop stresses increase as the excavation progresses.

The strain gauge measurements can be verified by considering two excavation depths of 85 mm and 125 mm. The compressive hoop stresses in the shaft lining, derived from strain measurements at these excavation depths are 4 MPa and 8.4 MPa respectively.

The derived hoop stress measurements can be compared to predictions of hoop stress calculated using Equation 1.

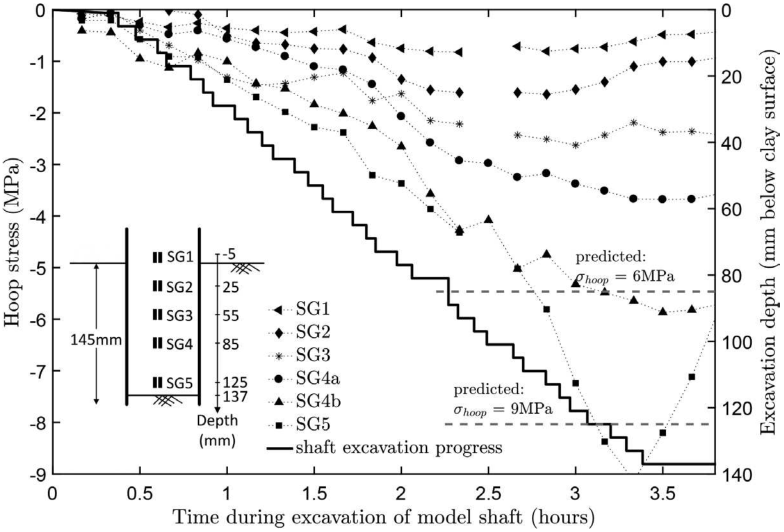

Figure 7. Hoop stresses derived from measurements of hoop strain in the model shaft lining during excavation.

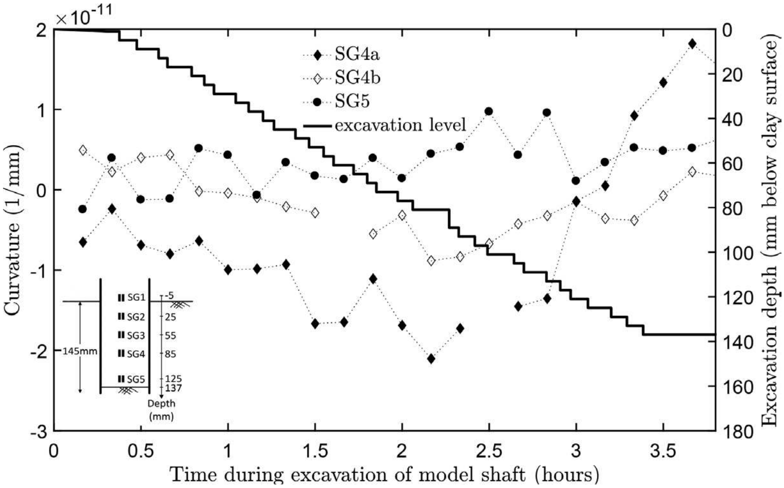

Figure 8. Curvature derived from measurements of bending strain in the model shaft lining during excavation.

$$\sigma_{hoop} = \sigma_h \, D/2\,t \qquad (1)$$

where σ_{hoop} is the hoop stress in the shaft lining, σ_h is the total in-situ horizontal stress acting on the model shaft lining, D is the diameter of the model shaft and t is the thickness of the shaft lining. This approach assumes that the soil imparts a uniform horizontal stress on the model shaft lining and that there is negligible inward movement of the shaft lining during excavation. Assuming an average K_o of 1.5 (see Figure 2) the total in-situ horizontal stress acting on the shaft is expected to generate hoop stresses of 6 MPa and 9 MPa when the excavation depth is 85 mm and 125 mm respectively.

The measured hoop stresses are slightly lower than predicted. This is reasonable given that the shaft lining can be expected to undergo a reduction in diameter due to excavation of the shaft. This would cause the total in-situ horizontal stress acting on the shaft to be lower than estimated from the K_o 'at rest' condition.

Figure 8 shows the curvatures that developed in the shaft lining during excavation of the shaft. These are derived from bending strain measurements recorded at two different depths along the shaft lining, 80 mm and 120 mm. In general, the measured bending strains are considerably smaller than the hoop strains and the change in curvature with increasing excavation depth is small.

5 CONCLUSIONS

Little is known about the performance of circular shaft linings and the behaviour of adjacent ground during excavation of a shaft. Few case histories exist and previous centrifuge tests simplified the excavation process and/or focused on lateral earth pressure distribution around the shaft. Centrifuge testing can be used to investigate the behaviour of shafts and the adjacent ground. To do so, it is important to accurately replicate the in-situ horizontal stress changes on the shaft lining during excavation.

Current approaches for modelling excavations in centrifuge testing generally use the removal of heavy fluid based on the assumption that the horizontal stresses are equal to the vertical stresses. The centrifuge apparatus and testing procedure reported in this paper demonstrate that more realistic stress changes on the shaft lining can be modelled by actually removing soil from the centre of the shaft at high centrifugal accelerations.

As expected, the measurements showed that the majority of horizontal soil stresses acting on circular shafts are translated into hoop stresses with minimal bending stresses in the shaft lining. Hoop strains increased gradually as the excavation progressed

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