An apparatus for centrifuge modelling of a shaft construction in clay

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ABSTRACT: Tunnelling systems have been widely used for housing transport links and service lines. The preferred method for accessing tunnels is via narrow vertical excavations (referred to as ‘shafts’) because of the advantages it provides in the congested urban environment. These shafts can exist as staircases, lifts or for ventilation purposes. The settlements and ground movements associated with shafts are influenced by the method of construction, type of soil and geometry of excavation (i.e. diameter size and depth). Literature describing the ground movements arising from shafts is relatively limited when compared with other geotechnical construction events (for example tunnelling). Therefore, apparatus has been designed, fabricated and tested to explore the behaviour of a clay ground model when constructing shafts. The apparatus outlined in this paper is a novel approach for the centrifuge modelling of short-term shaft-sinking induced settlements in clay.

1. INTRODUCTION

The rapid development of modern cities has led to a shortage of surface space and in response engineers have pursued alternatives below ground level. Tunnelling systems have been widely used to great success for housing transport links, water services, sewage services, communication networks and electrical lines. However, there has to be a series of routes constructed to access these tunnels. Vertical axisymmetric excavations (referred to as ‘Shafts’) are commonly used to provide this access to the subsurface and can exist as staircases, lifts or for ventilation purposes. Powderham (2000) stated that the construction sequence of axisymmetric shafts make them a dramatically simple solution. This is perhaps why shafts are preferred in situations of restricted space or unfavourable ground conditions.

Allenby & Kilburn (2015) discuss four, soft ground, shaft-sinking techniques and propose relationships between ground conditions (i.e. undrained shear strength), stability and ground water for each of the techniques. Shafts in urban environments are usually constructed by underpinning or caisson-sinking. Underpinning is described by Allenby & Kilburn (2015) as a construction technique which incrementally excavates, and installs a pre-cast concrete segmental ring complete with watertight gaskets when grouting behind the annulus is completed (see Figure 1a). Essentially, caisson-sinking is described by Allenby *et al.* (2009) as facilitating the shaft structure to be progressively sunk (by self-weight or with the aid of jacks) in a controlled manner from the surface level (see Figure 1b). This technique utilises a ‘cutting edge’ attached to the first caisson ring to assist the driving process.

Irrespective of the method used, any underground construction project will cause ground movements which have the potential to cause damage to existing structures. Modern geotechnical engineering practice aims to reduce these movements to a minimum but the need for accurate assessments is critical to the success of many projects. For example, BS EN 1997-2:2007 (BSI, 2007) specifies that the location and condition of adjacent underground and surface infrastructure should be determined implying that existing structures should always be considered during design and construction.

Shallow excavations such as basements (which are often roughly rectangular) can often be simplified to plane strain conditions for design purposes, however axisymmetric and non-axisymmetric deep excavations are fundamentally different due to the hoop/circumferential forces in the retaining structure. The ground response to these different forms of construction will be different and this should be considered in the design or in settlement predictions (Schwamb, 2014) but often, methods based upon basement excavation are applied to deep shaft construction.

The purpose of this paper is to describe apparatus developed to explore the behaviour of an over-

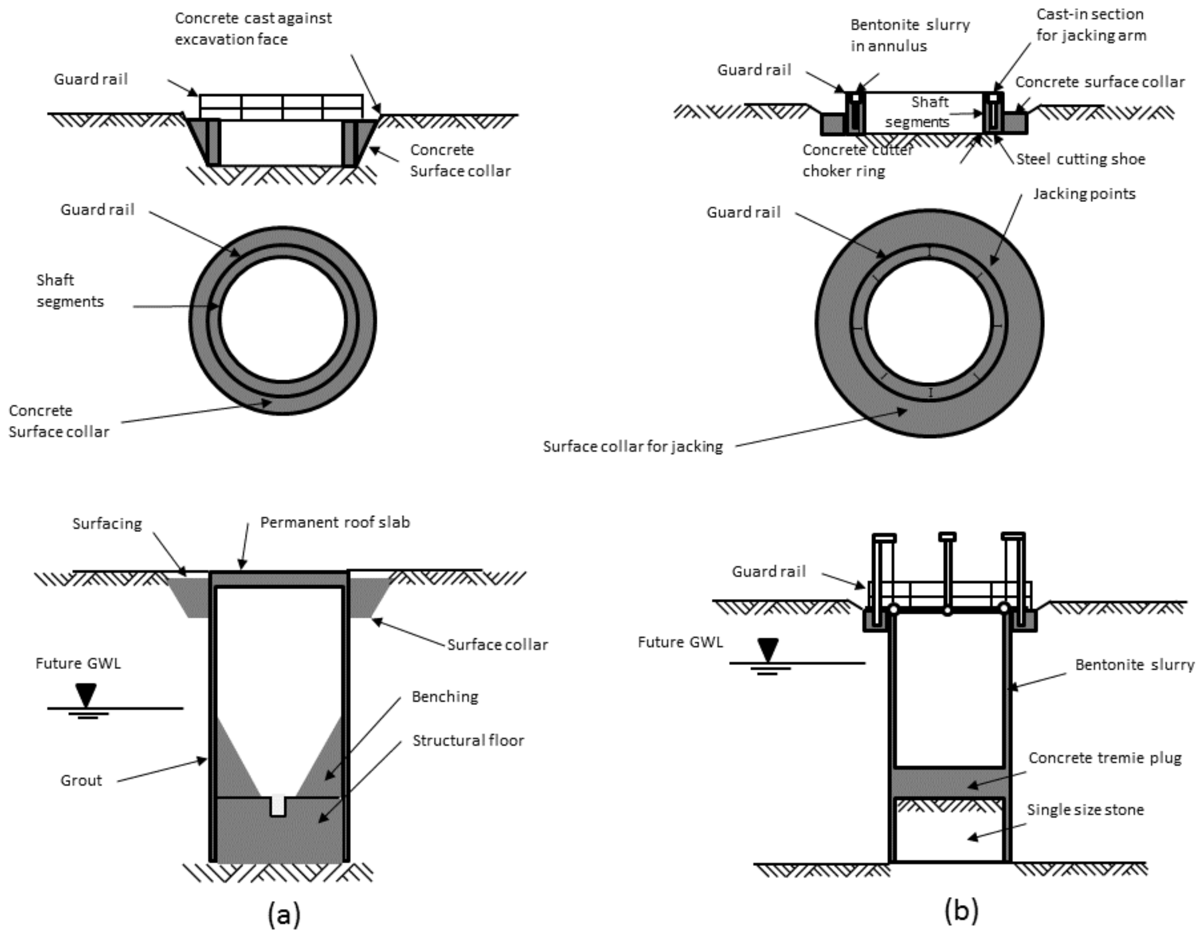

Figure 1. Construction sequence of (a) underpinning and (b) caisson sinking (after Allenby & Kilburn, 2015).

consolidated clay ground model when constructing axisymmetric shafts. A secondary aim of this paper is to show the extent of subsurface ground movements which could affect existing underground infrastructure (for example a tunnel).

2. CURRENT PRACTICE FOR PREDICTING GROUND MOVEMENTS

Literature describing the ground movements arising from axisymmetric shafts is relatively limited when compared with other geotechnical construction events (tunnelling for example). Perhaps this is because, until recently, shafts have been used in areas of low concern. However, the recent increased use in urban areas drives the need for a reliable prediction method.

2.1 Case studies

New & Bowers (1994) recorded the response from the tunnelling works and a shaft-sinking during the Heathrow Express Trial Tunnel to establish maximum settlements and settlement trough shapes. The excavation was 26 m deep (H) and 11 m in diameter (D) in London Clay.

The settlement, S_V, measured at a distance, d, behind the shaft wall is normalised by the shaft excavation depth, H, and plotted versus distance (also normalised with shaft excavation depth). A parabolic curve was fitted to the data to obtain an empirical relationship for surface settlement behind the wall.

$$S_V = \frac{\alpha(H-d)^2}{H} \qquad (1)$$

where α = an empirical constant that depends on ground conditions and construction method (in the original work this had a value of $6\text{x}10^{-4}$). The limitations of this method are that the diameter of excavation is not considered (although this may be unimportant for low values of D/H) and there is a level of uncertainty surrounding the value of α.

Schwamb (2014) commented that it had been shown from case studies the maximum horizontal movements ($S_{h,\,max}$) had been determined to be equal to the maximum vertical settlement ($S_{V,\,max}$).

Additionally, Schwamb (2014) determined that the existing approaches for producing reliable and realistic lateral earth pressure changes during excavation (which govern movements) vary considerably; particularly with depth. Therefore, it is the intention of this study to develop centrifuge apparatus capable of verifying the subsurface displacements resulting from shaft excavations in clay.

3. CENTRIFUGE MODEL TESTS

3.1 Previous centrifuge tests

The concept of simulating ground movements by removing pressurised air from within a latex bag supporting an excavation has been successfully implemented for tunnelling (e.g. Mair, 1979). This technique has been successful because the lining has minimal or no structural rigidity and allows the soil to deform, essentially, unimpeded. Following on from these works; Jacobsz (2002) and Divall & Goodey (2012) have applied these techniques to model more complex geotechnical events such as lining deflection or twin-tunnelling effects by substituting pressurised air for water. Similarly these techniques could be applied to the centrifuge modelling of shafts in clay. Phillips (1986) and Britto & Kusakabe (1982) undertook centrifuge tests on shafts. These tests modelled the 'half excavation' profile (i.e. the plan shape of the excavation was semi-circular). These soil models were performed in large rectangular boxes where the excavation was forced against a poly (methyl methacrylate) (PMMA) window to observe the subsurface ground movements induced by the construction.

An apparatus has been developed, based on the aforementioned studies, for centrifuge modelling short-term shaft-sinking induced settlements in clay. Figure 2 shows a schematic of the typical model being tested. The apparatus developed has been divided into two main systems (i) Excavation support system and (ii) Fluid removal system.

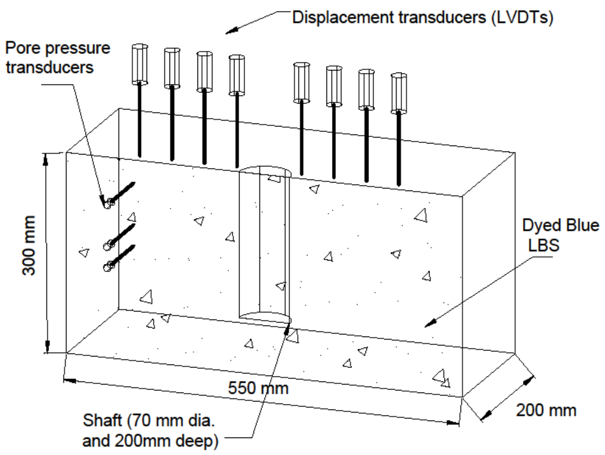

Figure 2. Schematic of typical shaft centrifuge model.

3.2 Common Apparatus and instrumentation

Experiments were performed in City University London's plane strain strong box at 100 g. A similar basic set-up was used in Divall & Goodey (2012). This system has a strong box of internal dimensions 550 mm x 200 mm x 375 mm (high) with drainage grooves machined into the base plate. During the experiments the front-wall of this strong box can be removed and replaced with a PMMA window, enabling observation of the subsurface ground movements during the test.

In addition to image analysis utilised to monitor the subsurface ground movements Linear Variable Differential Transformers (LVDTs) were used to record any settlement at the surface. The arrangements of these LVDTs were such that surface displacements close to the window could be recorded. Druck Pore Pressure Transducers (PPTs) were used to monitor the pore-water pressure within the model and were embedded into the clay before the model making stages began.

3.3 Excavation support system

The 'excavation support system' consists of two parts; a hanger with a hollow section the same cross-section as the excavation and a permanent liner which is suspended from it (Figure 3). This system is essentially hung from the top of the PMMA window into the soil container. A latex bag encloses this system and the annulus is filled with a heavy fluid (commercially known as Sodium Polytungstate or SPT). This fluid provides horizontal support to the soil while the model reaches hydrostatic equilibrium and can then be drained to simulate reduction in horizontal stress arising from excavation.

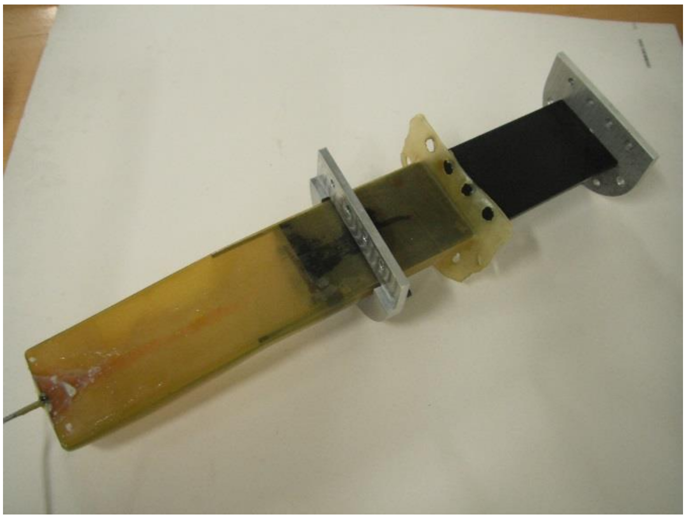

Figure 3. Photograph of hanger, liner and latex bag (exploded view)

Use of a heavy fluid implies a K_0 value of 1 within the soil mass. Given the stress history of the soil this is a reasonable assumption, although at the very surface of the model the horizontal support is low, evidenced by some small movements during the hydrostatic equilibrium stage of the experiment.

The purpose of the permanent lining was to represent the final position of the pre-cast segments in the construction process and fill the void which would otherwise require a large amount of heavy fluid.

3.4 *Fluid removal system*

A union fixed to the bottom of the latex bag allowed fluid to flow through a 3 mm stainless steel tube to a reservoir ('Fluid removal system'). This tube was routed directly below the excavation and then along the base plate to the interface between window-strong box and O-ring. A recess in the O-ring groove of the strong box allowed for the tube to pass underneath the O-ring cord and be sealed when pressure was applied from bolting on the PMMA window. This tube was connected to a quarter-turn plug valve controlled by a servo actuator. The rate at which the excavation was simulated was directly related to the drainage flow rate; controlled by an in-line bleed valve. When opened, this system allowed the drainage of the heavy fluid (under its self-weight) into the reservoir mounted on the swing behind the strong box (Figure 4).

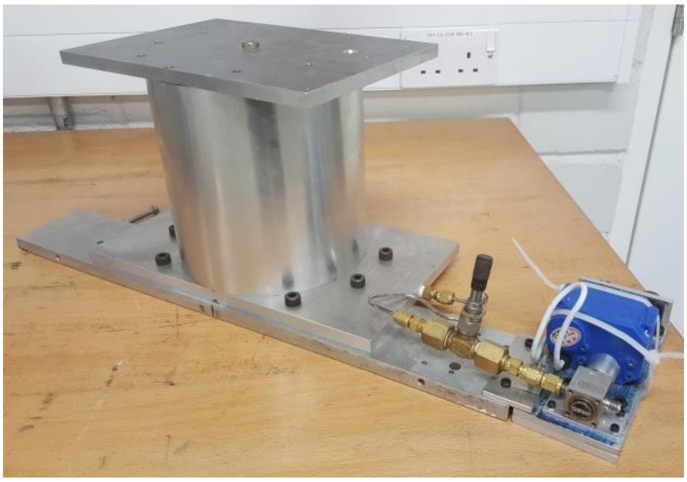

Figure 4. Photograph of reservoir, bleed valve, plug valve and servo actuator.

4. TEST PROCEDURE

4.1 *The centrifuge and facility*

All the testing and apparatus development was undertaken at City University London's geotechnical centrifuge facility. Specifically, an Acutronic 661 geotechnical centrifuge with a 1.8 m radius with the capacity to test models weighing 200 kg at 200 g was used.

4.2 *Soil used and stress history*

The clay used was Speswhite kaolin supplied by Imerys, England. A slurry, to a water content of 120 %, was prepared and placed in a strong-box. Samples are consolidated, in a hydraulic press, under a vertical stress of 350 kPa followed by swelling to 250 kPa before model preparation and further in-flight consolidation. The rationale behind this is to achieve an overconsolidated soil that was stiff enough to enable model making on the bench but would fail in-flight.

4.3 *Model preparation*

After the sample was removed from the consolidation press the front-wall of the strong box was removed to gain access to the clay front surface. A specially fabricated jig was clamped to the front of the strong box and a square aluminium cutter used to trim excess clay from the surface. The final height of the model was then 275 mm. It is imperative that the soil is not allowed to dry out. The top surface of the clay was sealed as quickly as possible with Plasti Dip (see Gorasia, 2013 for full details).

Dyed blue Leighton Buzzard Sand (Fraction E) was sprayed into the front surface of the clay using a modified modelling paint gun. This allowed the Speswhite kaolin to have the texture necessary for geoPIV (Stanier *et al.*, 2015) to be able to monitor the subsurface displacements. An ink roller was then used to embed the dyed blue sand particles and spray-able silicon oil applied to the front surface. This was necessary to stop the fine sand particles being 'washed away' and to limit the amount the sample dried out. A second jig was bolted to the strong-box to carve a semi-circular shaft cavity into the front face of the model using a cutter to carefully remove the soil (Figure 5).

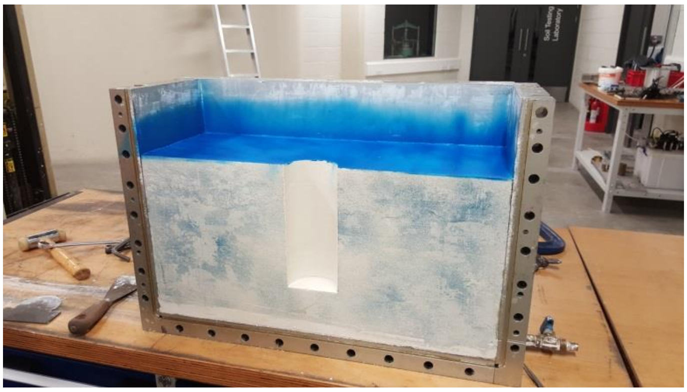

Figure 5. Photograph of shaft cut into front surface of model

The diameter of this cavity was 78 mm leaving a 3 mm void between the liner and the soil which was filled by the heavy fluid. The rationale behind the size of this gap was to model the overcutting that would occur during shaft-sinking. In practice this could be in the order of 100 mm at prototype scale so the void created in the model is a little larger than might be expected in order to generate observable patterns of ground movement.

The excavation support system apparatus was bolted to the top of the PMMA window. This arrangement could then be carefully positioned such that the apparatus was within the newly created cavity. The PMMA window could then be bolted onto the front of the strong box. Prior to being bolted in place, the PMMA window was lubricated with a high viscosity, clear silicone oil to reduce interface friction. The SPT supporting the cavity from within the latex bag was poured from the top hanger into the annulus of the excavation through channels in the permanent lining. The drainage pipe from the bottom of the excavation supporting system was bled at the union to the plug valve which restricts flow to the reservoir.

A rack containing Linear Variable Differential Transformers (LVDTs) was bolted to the top of the strong box to measure vertical surface settlement. The distribution of pore water pressures in the model during the consolidation and testing stages were monitored by the aforementioned PPTs.

4.4 Testing

The test began with the SPT providing the ground support to the cavity during spin-up. When the model reached 100 g it was left, at least overnight, for the pore-water pressures to reach equilibrium. To simulate the construction, the heavy fluid was drained from the annulus between liner and latex bag by opening the drain plug valve. Once all movements had stabilised the model was spun-down and the test was finished.

5. TYPICAL RESULTS

5.1 Observed surface settlements

Figure 6 shows the surface settlement profile from an example test '6LT'. The axes of this settlement, S_d, against distance from retaining wall, d, have been normalised against shaft depth, H. The settlements were taken on either side of the excavation but have been plotted for positive distances away from the shaft wall. Curves generated by two generally accepted prediction methods have been overlain for context. These curves have been adjusted to account for the reduced stiffness of a reconstituted model when compared with a natural soil and, particularly in the case of New and Bowers (1994) which is derived from observations of an actual shaft excavation, show good agreement with the centrifuge data.

5.2 Patterns of subsurface displacements

Figure 7 shows how the subsurface displacements propagate throughout the soil mass. Although, further detailed analysis is required of these displacements it is clear in Figure 7 that the traditional Rankine wedge has not manifest. Instead the pattern of displacements is deeper around the base, possibly owing to the inherent additional stiffness of a circular rather than rectangular structure.

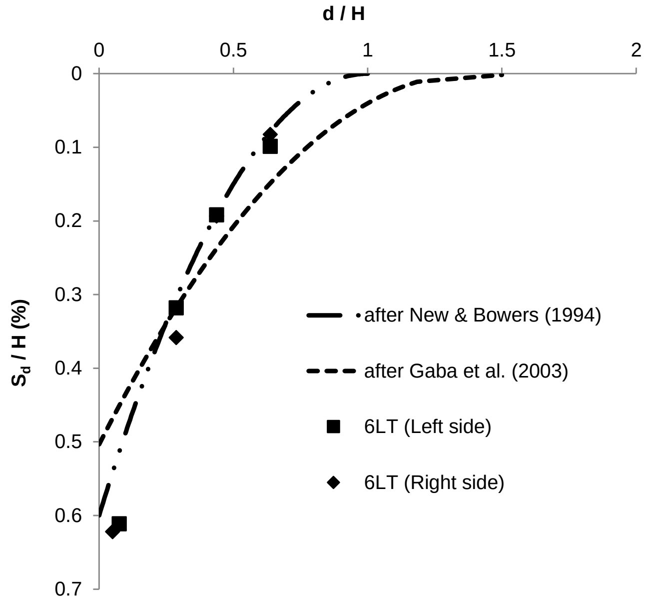

Figure 6. Surface displacement measured during a simulated shaft construction.

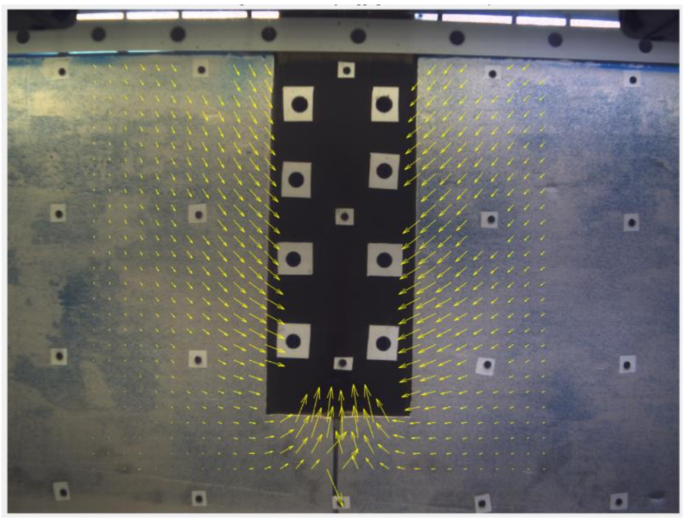

Figure 7. Subsurface displacement measured during a simulated shaft construction.

6. CONCLUSIONS & FUTHER WORK

The centrifuge model tests described have provided the basis of a new investigation into the ground movements resulting from a shaft construction. New apparatus has been designed, fabricated and compared against existing well-established prediction methods. The accepted surface settlement predictions have shown to be well-matched with the centrifuge test data. The propagation of subsurface displacements introduced in this paper could give new insight into how these soil displacements affect existing buried infrastructure.

The future work would be to introduce a tunnel liner in close proximity to the excavation and use geoPIV to monitor the effect. The apparatus has also been specifically designed to provide a provision for non-axisymmetric shafts. Simply by changing the cross-sectional shape of the liner hung from the window it is possible to investigate elliptical shafts. This could potentially lead to better utilisation of the available surface space. It is clear more research is needed in this area of geotechnical engineering.

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