Centrifuge Modelling of Long-term Tunnelling Ground Movements

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ABSTRACT

The increasing demand for public transport provision in cities has resulted in a requirement for enlarged public transport infrastructure. Where underground railways represent an important component of these systems, tunnel construction will inevitably lead to some degree of ground movement that can cause damage to surface structures and buried structures and services. It is important, therefore, that in the design of tunnels in urban environments these ground movements are predicted reliably. Predicting short-term ground movements resulting from tunnelling is standard when assessing the potential for damage to adjacent infrastructure. However, long-term tunnelling-induced ground movements and how these develop are understood less well and a research programme, based on geotechnical centrifuge modelling, is being conducted to improve our fundamental scientific understanding of this. The first stage of the programme has been to develop an apparatus that simulates the construction of a tunnel with a lining of known stiffness and permeability and allows construction ground loss to be replicated correctly. This paper describes the initial development of the apparatus along with results and analysis that demonstrates the suitability of the technique for the proposed study. The results obtained were observed to represent the short-term settlements that might be expected above a tunnel excavated in clay. The results also prove the modelling technique suitable for application in a full parametric study in which the geometry and boundary conditions of the model will be varied together with the permeability of the tunnel liner.

Keywords: centrifuge modelling, tunnels and tunnelling, ground movements, consolidation.

1 INTRODUCTION

The increasing demand for public transport in cities, caused not only by population growth but also changes in policies related to cultural heritage and the environment, is driving the expansion of underground railway systems, e.g. Crossrail in London. The execution of such projects is becoming increasingly complex due to the congested nature of underground space in cities as well as existing, aged infrastructure which may be sensitive to construction related disturbance.

Tunnel construction inevitably leads to ground movements that potentially can damage surface structure (including their foundations) and subsurface structures (e.g. existing tunnels and services). It is therefore important, when designing tunnels in urban environments, that the resulting ground response is predicted reliably (Mair *et al.*, 1996; Burland, 2001). Short-term ground movements are attributed to the volume loss caused directly by excavation: these can be predicted reliably with confidence (Peck, 1969; O'Reilly & New, 1982). Long-term ground moments occur from consolidation, creep and lining deformations taking place after tunnel construction (Cording, 1991). These movements, additional to those generated in the short-term, are attributed to dissipation of pore-water pressures generated during construction and changes to drainage boundary conditions over an extended period (Figure 1).

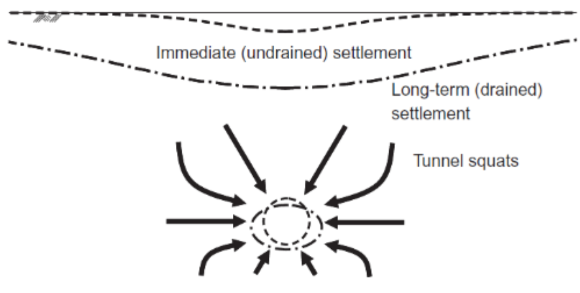

Fig. 1. Tunnelling-induced ground movements (Mair, 2008).

There is a dearth of guidance on predicting the magnitude and extent of long-term tunnelling-induced ground movements. They have implications on projected potential damage to nearby buildings and assets: mitigation measures can be costly. Recent research (Providakis *et al.*, 2020) suggests that even tunnelling-related damage described as "negligible" costs, on average, £48/m^2 of floor area to rectify, increasing to £240/m^2 for the "very slight" damage category (a 500% increase) and rising to £2,400/m^2 in the case of very severe structural damage. Long-term tunnelling-induced ground movements are complex and how they develop is not well understood. Both researchers and practitioners have emphasised the need to address this lack of knowledge (e.g. Mair, 2008; Hill & Stark, 2016).

The work described here details some preliminary testing, utilising geotechnical centrifuge modelling, of an experimental procedure that simulates tunnel construction in an overconsolidated clay and the long-term behaviour of the surrounding ground that subsequently develops.

2 EXPERIMENTAL DESIGN

Geotechnical centrifuge modelling has been widely used to investigate collapse mechanisms and the short-term ground response of tunnelling. The accepted modelling technique in clay is to "wish in place" the tunnel cavity i.e. the tunnel is pre-cut into a consolidated soil sample, provided with a means of support, further consolidated on the centrifuge to obtain equilibrium with a pre-determined water table and finally the volume loss event is simulated. This is often achieved by reducing the pressure in a pressurised rubber bag (e.g. Mair *et al.*, 1993) or by withdrawing a volume of fluid equal to the required volume loss (e.g. Jacobsz *et al.*, 2004). Models examining collapse mechanisms or those looking at soil response only do not generally model the tunnel lining (e.g. Grant & Taylor, 1996; Divall & Goodey, 2015).

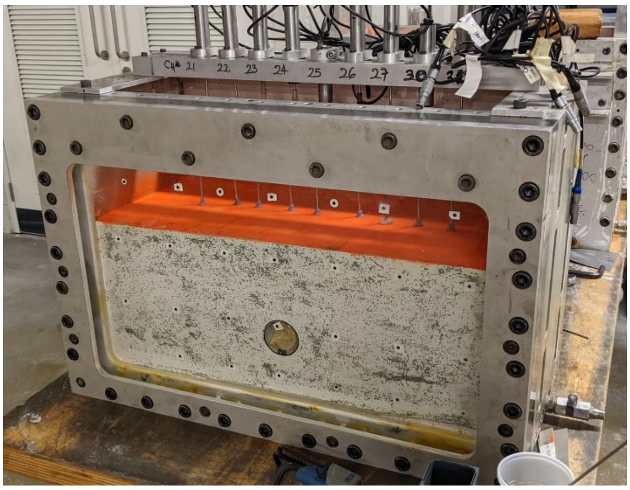

Fig. 2. Completed centrifuge model.

Investigating the long-term behaviour of a tunnel necessitates the use of a lining. This model lining should provide support to the soil during the in-flight consolidation phase of the test, be able to reduce in size to simulate the volume loss event and have an equivalent stiffness representative of the full-scale prototype.

The model is shown in Figure 2. A preconsolidated block of Speswhite kaolin clay was prepared in a centrifuge strongbox. The surface of the clay was trimmed to give the desired cover-to-depth ratio and a tunnel cavity was excavated using a series of precise cutters and guides. The tunnel lining and support apparatus was placed within the cavity and comprised of a 3D printed liner within which was a rubber bag. The liner had a clasp mechanism such that, during in-flight consolidation, the rubber bag can be inflated to support the lining at the position d = 50 mm. Upon deflating the bag, the mechanism would close, and the outside diameter reduced to 49.2 mm. This generated a change in cross-sectional area equal to 3% volume loss. The liner material (ABS) and final thickness (1.2 mm) were chosen such that it had a stiffness equivalent to a prototype concrete tunnel lining of 300 mm thickness. Figure 3 shows the detail of the model lining in its "open" and "closed" stages.

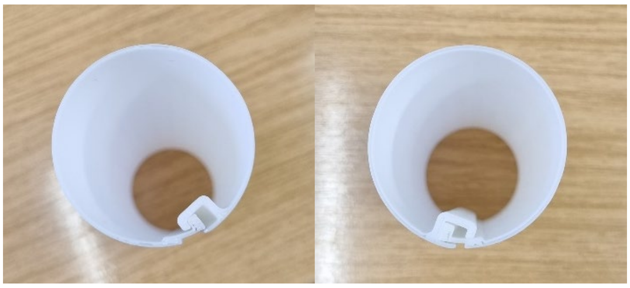

Fig. 3. Model liner in the open (L) and closed (R) position.

3 MODEL TEST

The results from a proof of concept test is presented here. The test represented plane strain tunnelling conditions and was performed in a strongbox of width = 550 mm and depth = 200 mm. The clay sample was one-dimensionally consolidated in a press with σ'_v = 500 kPa followed by a swelling period at σ'_v = 250 kPa. This gave an overconsolidated sample which was then trimmed to a C/D ratio of 2 resulting in a total sample height of 205 mm. The test was performed at 100*g* and therefore the model tunnel (d = 50 mm) scales to a diameter of 5 m – approximately the size of a deep running tunnel in the London Underground network. The surface of the water table was set by means of an external standpipe and was 5 mm below the clay surface.

Instrumentation consisted of pore pressure transducers embedded within the clay and standard LVDTs to measure surface settlements. In addition, via a Perspex window, images were acquired to enable subsurface measurements using digital image correlation but these data are not reported herein.

The model was assembled on the bench, transferred to the centrifuge swing, appropriate connections were made, and the model accelerated to 100g. During spin-up the bag within the liner was pressurised to hold it in the "open" position. This also provided support to the liner and the soil. After in-flight consolidation (approx. 48 hours) the pressure in the bag was reduced (over about 30 seconds) and the mechanism moved to the "closed" position. This action simulated the volume loss observed during construction. The liner was not restrained at either end and thus the closing of the mechanism and the final position of the liner are dictated by the stresses the soil exerts on the liner.

The liner was fully sealed both at the ends and along the clasp mechanism and therefore represents a completely impermeable tunnel lining. This seal was created by placing the liner in the closed position and gluing a latex cap over each end. The joint along the liner was also covered with a latex strip and all joints sealed with liquid latex to ensure a watertight structure. The internal latex bag which maintains the overburden stress was located within the model liner via a hole in one end using a special fitting. This fitting also clamps the entire mechanism against the wall of the strongbox creating a seal and simultaneously providing a passage for the compressed air.

Results from this test should be comparable with the semi-empirical prediction methods for surface settlements (e.g. Peck, 1969; O'Reilly & New, 1982) immediately upon the completion of excavation. Additionally, in the long-term, there should be zero or minimal further movement if the liner was truly impermeable.

4 RESULTS

4.1 Surface settlements

As previously stated, the test was undertaken to verify that the liner mechanism operated correctly and that settlements were generated that were commensurate with previous (short-term) experiment and field observations. It is widely accepted that the transverse surface settlement trough generated above a plane strain tunnel excavation takes the form of a Gaussian curve as in Equation 1 (Peck, 1969).

$$S_v = S_{max} exp\left(-\frac{x^2}{2i^2}\right) \qquad (1)$$

where S_v is the settlement, S_{max} is the maximum settlement above the tunnel crown, x is the distance from tunnel centreline and i is the distance to the point of inflection on the Gaussian curve.

Verification that the experimental apparatus represents a volume loss event of this type can therefore be achieved by fitting a curve of this type to the surface settlements measured immediately upon completion of tunnel excavation simulation. Figure 4 shows the surface settlements obtained from LVDT readings immediately after the tunnel lining mechanism is closed and after a further period of 45 minutes. Consolidation and seepage effects scale with N^2 in the geotechnical centrifuge (Taylor, 1995) and thus, at the level of 100 times gravity used here, this 45 minutes represents almost 1 year at prototype scale. After this point (which may not be viewed to be long-term) the tunnel liner buckled and thus the experiment is halted. Also shown is a curve in the form of Equation 1 generated by a fit to the experimental data using a least squares method.

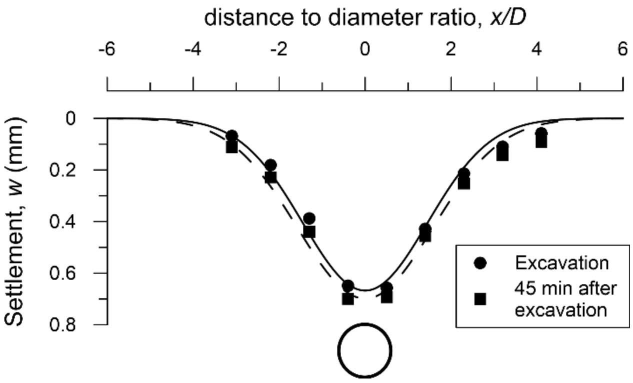

Fig. 4. Surface settlements obtained from centrifuge test.

The value of i determined from this fitting exercise enables comparison with previously published data. Measurements presented by Mair & Taylor (1997) showed that, despite some scatter, the value of i was generally found to lie between $0.4z_0$ and $0.6z_0$ where z_0 is the depth from the original ground surface to the tunnel centreline. Gaussian curves were fitted to the data and the values of i determined. Immediately upon completion of the excavation simulation the value is $0.6z_0$, at the higher end of the range observed by Mair & Taylor (1997).

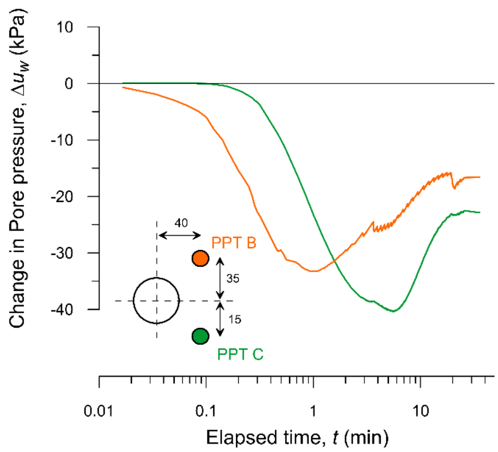

Fig. 5. Pore pressure changes post-excavation in Test 2

4.2 Pore pressure measurements

The test was instrumented with pore pressure transducers in the clay at various radii from the tunnel.

Figure 5 shows the measured change in pore pressures from two transducers near the tunnel after the completion of the excavation simulation. Pore pressures are observed to continue to decrease after the completion of the tunnel excavation. In time, they begin to recover back towards the hydrostatic condition. As noted previously, the tunnel lining buckled after 45 minutes and the change in response seen in Figure 5 at around t = 20mins is almost certainly related to the onset of that buckling.

6 DISCUSSION

The overall movements observed were rather larger than might be expected given the initial design target of 3% volume loss. Given that the liner buckled, the assumptions made when determining the equivalent stiffness may need to be revisited. The liner was intended to represent a concrete thickness of 300mm but a full-scale tunnel lining would have increased stiffness in the form of ribs (segmental lining) or reinforcement (sprayed concrete lining). These would influence the overall stiffness of the liner which may not be accounted for in the current design of the model. This will be addressed as part of the next stage of the experimental programme.

7 CONCLUSIONS AND FURTHER WORK

The test performed shows that the developed apparatus successfully replicates the ground movements associated with tunnel construction in the short-term. The results also demonstrate that, in the absence of any drainage into the model tunnel liner, minimal settlement occurred in a period of up to 1 year (prototype scale) of construction.

In order to investigate long-term behaviour the model liner will need to be modified such that it has a finite permeability. This will be achieved by installing a series of porous plastic discs within the liner. These will be sized appropriately to control the rate of water ingress into the tunnel. A parametric study will be undertaken across a representative range of permeabilities.

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