Soil displacement due to tunnelling using small scale centrifuge technology

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ABSTRACT: Soil surface greenfield settlement induced by tunnelling is examined using a small scale centrifuge facility. Ground disturbance is simulated using classical model tunnel volume loss techniques. The development of the miniature tunnel and associated control systems is described. The experimental data is compared to predictions using the Gaussian settlement curve method of Peck (1969) and other existing literature. Good agreement is observed confirming the suitability of the small scale centrifuge environment to model tunnel boundary value problems as (i) preliminary scoping trials to inform larger scale tests, and (ii) integrate tunnel design within the undergraduate curriculum based on experimental test results.

1 INTRODUCTION

1.1 Background

Increased urbanisation and greater population density have made it necessary to utilise underground space in cities to sustain continued congestion growth and mobility of its citizens. The provision and integration of effective transportation infrastructure systems poses one of the greatest engineering challenges in large, densely populated areas. Previous over-ground road and rail transportation corridors are now being relocated beneath cities in an effort to increase the quality of above ground living space and reduce city congestion. In this respect, the creation of large underground open spaces and interconnected tunnels is now commonplace in urban engineering landscapes.

All civil engineering works generate disturbance of the ground and great care should be exercised especially when developments are in a densely populated urban environment. For example, it is well documented (Burland et al., 2001) that new tunnel constructions can effect existing nearby structures such as pile foundations (Jacobsz,2003), utility pipes (Marshall, 2009) and retaining walls (Choy, 2004) located in close proximity to the engineering works. As large cities continue to expand, interference of adjacent structures is unavoidable and hence the impact of tunnel-structure interactions must be fully considered and understood.

The work reported herein pertains to the aspect of tunnel engineering and evaluates ground disturbances that arise in granular soils owing to new tunnel construction. Observations from a suite of preliminary model tests conducted on the University of Sheffield educational centrifuge are reported. The rationale for using the small educational facility is: (i) to generate initial complementary data and insight of key factors as a precursor to inform a more complex series of larger model tests to be implemented on the 4m diameter research beam facility, (ii) student training and development of technological systems, and (iii) to highlight the potential for model tunnel studies to be demonstrated within the undergraduate curriculum in the more manageable and efficient small scale centrifuge environment.

Development of the experimental systems are described and results of the small scale experimental simulations are compared to classic tunnel ground settlement design predictive methods.

1.2 Summary of tunnel research

An extensive literature research base exists in the field of tunnel engineering which can be broadly classified into sub categories associated with (i) predicting soil displacement due to tunnelling, (ii) tunnel face stability and (iii) ground-tunnel interaction. The following section focuses on the first aspect and briefly describes some of the key developments in this respect.

1.2.1 Predicting soil displacement due to tunnelling

Understanding ground movement has been a fundamental area of considerable research focus for tunnel engineers over recent decades. The prediction of surface settlement in `greenfield' conditions was first reported by Peck (1969), who presented as Gaussian settlement equation, (Equation 1) and has been shown to provide good correlation with field meas-

urement data provided by Martos (1958). This approach forms the underlying principle of current design and key aspects are summarised in Figure 1 which indicates the maximum settlement (S_{max}), point of inflection (i) and the extent of the volume loss settlement trough.
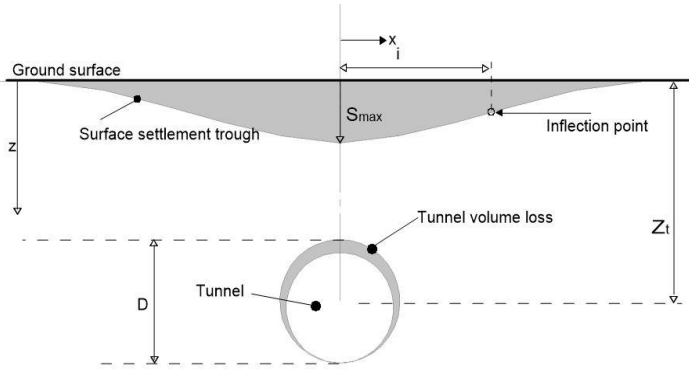

Figure 1. Tunnel volume loss.

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

Since the work of Peck (1969) several authors have presented modified point inflection calculation equation to correlate with a range of different soil conditions; for example, Clough and Schmidt (1981) in clay, O'Reilly and New (1982), Jacobsz (2003) and Vorster (2006) for sand material. Nevertheless, the original form of the Peck (1969) surface settlement equation has remained relatively unchanged with only revised factors proposed to accommodate a broader range of soil types.

Recent works have focused on the aspect of subsurface settlement determination which reflects the increased need for greater understanding of soil-structure interaction behavior of embedded structures in close proximity to tunnels. This need is likely to grow as demand for underground space increases and becomes more congested. Sub-surface settlement curves based on a modified Gaussian equation are presented by Mair et al. (1993) to predict levels of likely sub-surface settlement. Centrifuge test results from Grant and Taylor (2000) Jacobsz (2003) and Vorster (2006), with additional field measurement by Moh et al. (1996) have shown strong correlation to the theoretical prediction of Mair et al. (1993).

2 EXPERIMENTAL SYSTEMS

2.1 Centrifuge facility

The University of Sheffield small scale teaching centrifuge, herein referred to as UoS2gT, was utilised in this research. The centrifuge (Fig.2) has a nominal radius of 0.5 m and is capable of accelerating a payload of 20 kg, measuring 160 mm wide x 125 mm high x 80 mm depth, at 100 times gravity (100g).

The payload incorporates a viewing window which provides plane strain visualisation of the test package (Fig.3). The centrifuge is equipped with an 8 channel onboard wireless data acquisition system, 12 MP camera and LED illumination for image capture, 2 port hydraulic rotary union for in-flight control of a 2 kN dual acting pneumatic vertical actuator and 4-way power slip-ring. Full specification of this centrifuge is described by Black et al. (2014) and is summarised in Table 1.
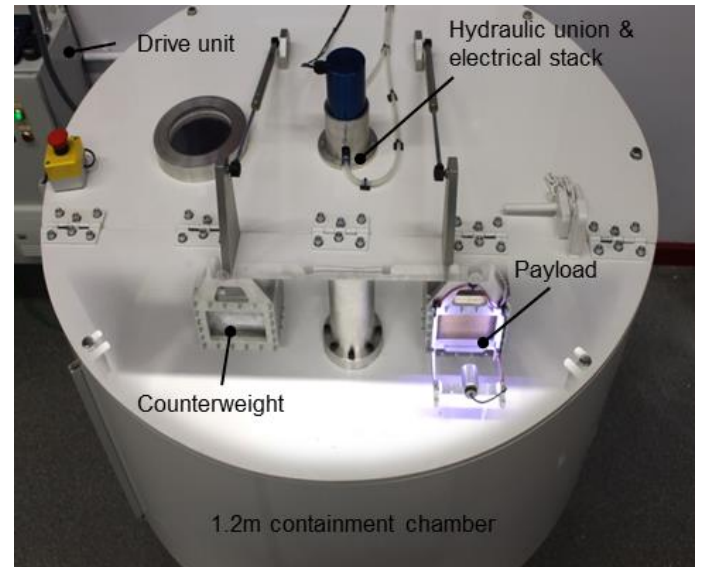

Figure 2. UoS2gT Teaching Centrifuge.

2.2 Model test considerations

It is vital that experimental models conform to appropriate scaling relationships to provide similitude with the full scale prototype. Prototype stress conditions were achieved by applying an acceleration of 100g on the small scale model tunnel tests. For convenience prototype dimensions of the model test configuration subsequently described (equivalent at 100g) are also shown in the adjoining sections in square brackets.

Table 1. UoS2gT centrifuge specification

Specification	Description
Radius (effective)	0.5 m (0.44 m)
Maximum payload	20 kg at 100g (2gT)
Maximum acceleration	100g at 20kg (≈425 RPM)
Size of payload	W = 160 mm H = 125 mm D = 80 mm
User interfaces	2 port 10bar hydraulic union, 4-way electrical 24A slip ring
Data acquisition	8 Ch AI, 12 MP image capture, wireless communication

In small scale modelling it is not always possible to recreate the exact full scale process faithfully, i.e. excavation, borings etc. Centrifuge modellers have become highly adept at developing model processes that albeit are not precisely similar; yet do capture the basic essence and fundamental behavior in model tests. Invention has been applied to tunnel engineering whereby the complete process of prototype tunnel construction is simplified to a volume loss simulation that replicates the effects of tunnelling disturbance. Pioneered by Mair (1978), tunnel volume loss is typically modelled by reducing the internal pressure of a thin latex membrane encasing a brass mandrel that is buried in the soil with decreases in volume implemented to simulate ground based disturbances. This method is a tried and tested approach that is widely accepted and its use is reported by Loganathan et al. (2000), Jacobsz (2003), Marshall (2009), Ng and Lu (2013) and Vorster (2006).

A similar methodology was implemented in the current test programme, albeit at a considerably smaller scale than previously reported tests conducted in larger scale facilities.

2.3 *Payload strongbox*

The payload strongbox and incorporated a front viewing window exposing the soil depth profile in plane strain configuration. The tunnel was integrated and secured into the package using recesses in the front and back faces of the strongbox (Fig.3). This fixed its location at a distance of 20 mm from the base boundary of the strongbox; i.e. at an effective radius of 0.48 m from the center axis of rotation. Various tunnel burial depths to the tunnel centre line (herein referred to as depth of cover - C) were achieved by simply altering the level of soil placed within the strongbox.
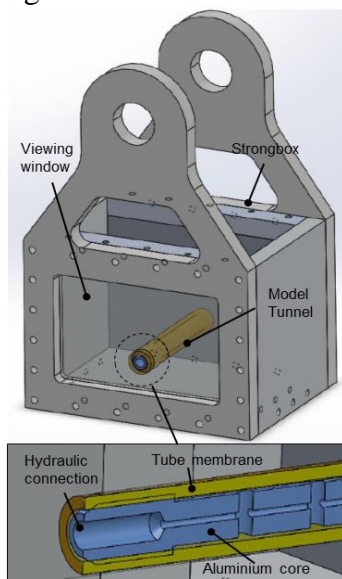

Figure 3. UoS2gT payload and miniature tunnel.

2.4 *Model tunnel*

The model tunnel consisted of two component parts (i) an inner aluminum core to provide rigidity to the tunnel which incorporated internal cavities for fluid flow, and (ii) an outer flexible membrane to seal the tunnel and allow volume change simulation.

The internal aluminium core had a stepped profile, 15mm diameter at each end reducing to 11 mm across the middle 80 mm centre section. A threaded hole was located at either end of the tunnel core to attach hydraulic pressure fittings to allow pressure to be applied within the tunnel and onto the surrounding flexible membrane that encased the model core.

The membrane tube has an outer diameter of 19.05 mm, and was pressure rated to 1000 kN/m^2. The wall thickness was slightly thicker than a convention triaxial membrane in order to prevent any ruptures during placement into the locating holes in the payload front and back plates. The model tunnel was representative of a ≈1.9m diameter prototype. Although this tunnel is smaller than many larger prototype tunnels currently being introduced, this size was selected in consideration of other factors such as (i) boundary effects and (ii) achievable tunnel diameter to cover diameter ratios (C/D). Three tests are presented as part of this study having tunnel depths of 28, 40 and 50 mm [2.8, 4.0 and 5 m respectively] were conducted to observe greenfield settlement response. This configuration is equivalent to C/D ratios of 1.0, 1.6 and 2.1.

Control of the tunnel volume loss was achieved via a pressure/volume controller that ported air onto the beam via the hydraulic rotatory union along 4mm diameter nylon tubing to the tunnel. Due to the air is compressible, the volume loss was derived from the best fit surface settlement, and there is no direct measurement to tunnel volume loss.

3 EXPERIMENTAL PROCEDURES

3.1 *Soil properties and placement*

Model tests were conducted using dry sand of specific gravity 2.65. The maximum and minimum densities were evaluated to be 1.75 Mg/m^3 and 1.45 Mg/m^3 respectively. The sand had a D_{50} of 0.16 mm and was classified as Fraction E.

The sand was placed into the strongbox using a controlled dry pluviation technique. Note the tunnel was fixed into position within the strongbox prior to sand placement. The sand pluviation apparatus consisted of a hopper and nozzle system suspended from a height adjustable arm. This enabled the drop height to be altered throughout the placement process to en-

sure more uniform density conditions throughout the sample. The system also incorporates interchangeable exit nozzles/mesh of various sizes to permit alternative placement conditions. The system was calibrated for the current tests and a repeatable density of 1.65 Mg/m^3, 73% relative density, was achieved for a drop height of 600 mm. The limitation of this pluviation technique is causing a non-uniform sample around the tunnel.

3.2 *Measurement of surface and sub-surface soil settlement*

Soil displacement measurement was achieved using Digital Image correlation (DIC) methods (White et al. 2003). All necessary steps were taken to calibrate the image-object reference frame correcting for co-planarity of the charge-coupled device (CCD) and objective planes, radial and tangential lens distortion and refraction of the viewing window. High contrast black-on-white control markers located on the viewing window that were visible in test images permitted soil displacement measurements.

A 12 Mega-pixel (MP) GoPro Hero 3+ Black Edition camera was mounted on a cantilever support frame that enabled a full viewing field of the exposed soil surface. Two LED strips on the top and bottom of the window were used to illuminate the model surface in-flight. The camera pixel count was suitably high to provide high resolution digital images throughout the test sequence. The camera was viewed and controlled remotely using inbuilt WIFI features via the GoPro camera application on a tablet interface.

3.3 *Centrifuge spin-up procedure*

The tunnel was placed into the strong box and a constant tunnel volume was maintained during sand placement to preserve the outer membrane position and tunnel diameter. Once the sand pluviation procedure was completed, the payload box was placed into the centrifuge and all necessary electronic and hydraulic lines connected. During ramp-up of the centrifuge the pressure within the tunnel was balanced against the increased ground stress using the pressure volume controller system previously described. The gravity level was increased from 1g to 100g in four stages of 25g, 50g 75g and 100g, during which the internal tunnel pressure was increased to respectively depending on the cover to depth ratio. Observations confirmed that this pressure was suitable to preserve the tunnel geometry and neutralise minor changes in volume that would produce dis-

turbance. Once 100g was achieved, the tunnel volume was reduced in controlled stages to simulate ground based settlement, during which digital images were recorded to enable evaluation of the induced ground displacements.

4 RESULTS

Three C/D ratios of 1.0, 1.6 and 2.0 were considered in this investigation. Captured images were processed using digital image correlation methods via GeoPIV (white et al. 2003) to evaluate the surface and subsurface soil settlement. Where appropriate the observed greenfield displacements are correlated with analytical equations presented in the literature to evaluate the performance of the small scale model tunnel tests. Tunnel volume loss (V_l) is presented as a percentage of initial tunnel volume.
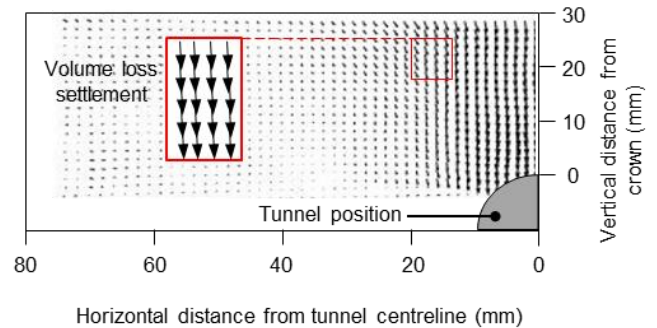

Figure 4. PIV soil displacement vectors.

4.1 *Image based observations*

Figure 4 presents an example of the PIV output achieved using the miniature GoPro camera system for the test conducted at C/D = 1.6 at a volume loss of 3.5%. Initial observations confirm that the soil tracking and calibration process were highly successful owing to the consistency of the soil trajectory vector field (i.e. no 'wild vectors') and the expected vertical soil displacement above the tunnel. Furthermore, even prior to intimate scrutiny of the displacement data, this observation offers considerable reassurance as to the successful development and implantation of the miniature tunnel and volume control systems. As expected, it is clear from the observations that the largest settlement displacements occur along the vertical centre line of the tunnel, diminishing with increased horizontal distance.

4.2 *Surface settlement performance*

Using the analytical equations of Peck (1969) and others reported in Section 1.2.1, curve fitting was conducted to compare the analytical solutions to the centrifuge experimental data obtained in this study. The results are shown in Figure 5 for C/D = 1.6 at increasing volume loss of 2.1%, 3.1%, 3.6%.
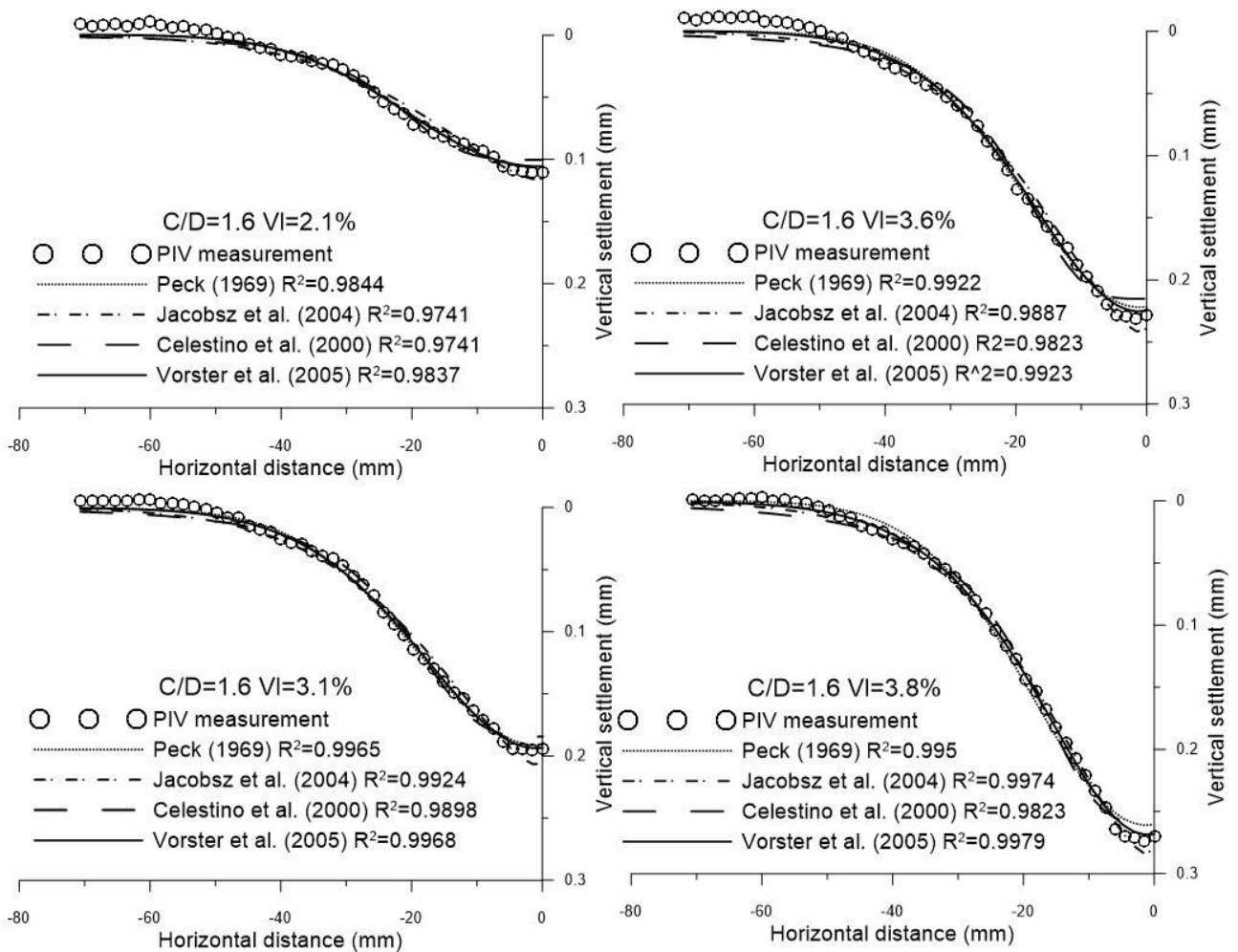
Figure 5. Surface settlement for a tunnel C/D = 1.6 at volume loss 2.1%, 3.1%, 3.6% and 3.8%.3.8%.

Gaussian formulation of Peck (1969) and subsequent analytical solutions published by Celestino et al. (2000), Jacobsz et al. (2004) and Vorster et al. (2005); confirmed by the least square regression (R^2) correlation. Observations include: (i) increased levels of maximum settlement and (ii) a changing point of inflection of the Gaussian settlement curve occur with increased volume loss; both of which are concurrent with existing literature.

Figure 6 shows the surface settlement trough at various C/D ratios correlated with Peck (1969). A strong correlation exists at increased C/D ratios for the maximum settlement at the crown of the tunnel; however, some small variations are evident at the extreme ends of the settlement profile curves, especially for the deepest tunnel. This is attributed to the infringement of the settlement trough with the rigid lateral boundaries of the strongbox owing to is reduced size. Nevertheless, the primary settlement response remains reasonably unaffected by the conditions occurring at the strong box boundary and hence this effect is not considered intolerable.
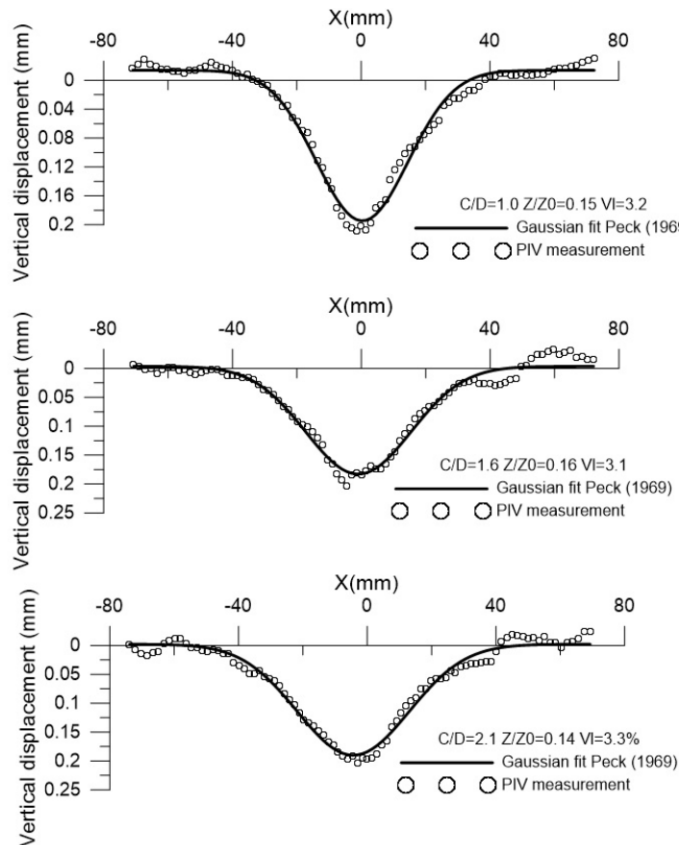

Figure 6. Surface settlement for a tunnel C/D = 1.0, 1.6 and 2.1 at volume loss equivalent to 3%.

The data fit between the current experiments and existing literature provides confidence in the quality of the preparation methodologies established, but also confirms the viability of the small scale centrifuge facility to conduct pre-cursive tunnel tests to inform large scale tests.

5 CONCLUSIONS

The purpose of this paper was to evaluate the performance of a small scale centrifuge test facility to model tunnel boundary value loss problems for the purpose of informing strategies for more complex larger scale tests. The tunnel volume simulation using an inflatable membrane tube approach, with external pressure and volume system, proved suitable to control volume loss. High quality soil displacement observations generated using a miniature 12MP GoPro camera proved highly successful and provided suitable resolution and image quality to examine the surface and sub-surface settlement profile.

The three soil cover to diameter ratios considered, C/D = 1.0, 1.6 and 2.5, were examined up to volume losses of 4% and the results of the surface and subsurface settlement curves showed strong correlation with (i) previous published data in terms of the maximum settlement observed and (ii) shape of the overall Gaussian curve parameters. Some errors were observed at the extreme ends owing to boundary effects although these did not significantly affect the overall performance.

The successful outcome of the tests confirms the potential of smaller scale centrifuge facilities to investigate tunnel induced ground settlements for the purpose of (i) conducting preliminary scoping trials to inform larger scale tests, (ii) student training and (iii) possible integration of tunnel design within the undergraduate taught curriculum using experimental observation.

6 ACKNOWLEDGEMENTS

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