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The influence of a time delay between sequential tunnel constructions

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ABSTRACT: In congested urban areas twin-tunnelling projects have an associated requirement for accurate predictions of any ground movements that may arise in order to minimize possible damage to existing structures. Much previous research has been carried out concerning the ground movements around single tunnels in greenfield conditions and this, along with field observations, forms the basis of most ground movement predictions. For twin-tunnel projects the prediction of overall ground movements is often based upon superposition of two equal settlement troughs. Previous research by the current authors has shown that this assumption may be invalid for most cases. The research presented in this paper considers the influence on observed ground movements of a construction process that involves a delay between the construction of each tunnel, compared with tunnels constructed simultaneously. A series of four centrifuge tests is described and the results are presented in terms of the ground movements measured at the surface.

1 INTRODUCTION

In urban areas surface space is often congested and to meet growing demands engineers have often utilised sub-surface space for various services. Tunneling is used extensively for mass rapid transit systems. Tunnels are often constructed in pairs for this function which is known as twin-tunnelling.

Any underground construction causes stress changes within the soil mass which can lead to ground movements. The propagation of these ground movements has the potential to cause damage to existing buildings and buried services (Mair *et al.*, 1996). The sources of the ground movements investigated in this study are those arising from construction using a Tunnel Boring Machine (TBM). The ground movements generated using this construction method are deformations towards the newly created cavity and are often characterized as volume loss. A full discussion and categorisation of these displacements is presented by Mair & Taylor (1997). These sub-surface movements are apparent at the surface as settlement trough. This is often divided into longitudinal and transverse settlements. In the case of single tunnels the transverse settlement trough has been shown to be well represented by a Gaussian distribution (Peck, 1969).

Many tunnelling construction guidelines have been developed based on research from single tunnel arrangements (e.g. Peck, 1969; Mair, 1979; Taylor, 1984 and Attwell & Yeates, 1984). Twin-tunnelling

surface settlement predictions are often the superposition of two single tunnel predictions. The assumption is that the construction of a second tunnel is unaffected by the presence of the first.

A number of field observations of twin-tunnelling sites have shown a relative difference between the monitored settlements generated during the first and second tunnel constructions. Such examples include St. James' Park (Nyren, 1998), Lafayette Park (Cording & Hansmire, 1975) and The Heathrow Express (Cooper & Chapman, 1998). Numerical studies have also shown the existence of this phenomenon and postulated that superposition may not necessarily be sufficient (Hunt, 2005 and Adenbrooke & Potts, 2001).

The current research programme is to explore the ground movements in overconsolidated clay when constructing parallel tunnels with a small separation distance. The current tests represent circumstances under which superposition may be considered appropriate. A number of plane strain centrifuge tests were carried out where two tunnels were constructed simultaneously. This would allow comparison with previous work where tunnels were constructed with a construction delay of 3 weeks at prototype scale (Divall, 2013). The current test series consisted of four experiments with equal centre-to-centre spacing and tunnel diameter. The results indicate the effect of any construction delay on the surface settlements.

2 CURRENT PRACTICE

2.1 Single tunnel prediction method

It is generally accepted that in order to predict tunnelling-induced ground movements above a single tunnel the displacements can be determined from a Gaussian distribution. This was proposed by Peck (1969) and verified by many site measurements and centrifuge tests (e.g. Mair *et al.*, 1993). Semi-empirical approaches have been adopted for calculating surface settlements and are usually expressed as:

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

$$S_{\max} = 0.313 \frac{V_L D^2}{i} \quad (2)$$

where S_v = the settlement at a given horizontal distance from the tunnel centre-line; $S_{\max}$ = the maximum settlement at the tunnel centre-line; x = the lateral distance from the tunnel centre-line; i = the lateral distance from the tunnel centre-line to the point of inflexion in the Gaussian distribution curve; and V_L = volume loss expressed as a ratio of the area of 'lost ground' to area of bored tunnel.

When considering the surface settlement trough above a tunnel, the volume loss is a measure of its magnitude and i a measure of its distribution. This implies that i controls the settlement trough width. O'Reilly & New (1982) proposed that:

$$i = K \cdot Z_0 \quad (3)$$

where Z_0 = the vertical distance from the undeformed surface to the tunnel axis level; and K = a dimensionless trough width parameter. An average value of $K = 0.5$ was determined for tunnels in moderately stiff clay. This agreed in general with the findings of Peck (1969).

2.2 Twin-tunnelling induced settlement prediction methods

2.2.1 Superposition

Superposition is a method for predicting surface settlement above any twin-tunnel arrangement. A Gaussian distribution is assumed for the first tunnel and positioned over its centre-line. The same distribution is then positioned over the centre-line of the second tunnel ignoring any influence from the first. The summation of these two overlapping curves describes the total settlement.

New & O'Reilly (1991) provided a formula for the prediction of the settlements above twin-tunnels by superposition:

$$S_v = S_{\max} \left[\exp\left(-\frac{x_A^2}{2i^2}\right) + \exp\left(-\frac{(x_A - d)^2}{2i^2}\right) \right] \quad (4)$$

where d = the lateral distance between the two tunnel's centre-lines; and x_A = the lateral distance from the centre-line of the first bored tunnel.

The expression above assumes the tunnels are parallel and have the same tunnel diameter, volume loss and settlement trough width. This expression implicitly ignores any effect on the boring of the second tunnel that the existing (first) tunnel may have.

2.2.2 Accounting for asymmetry in settlements

During a series of 18 centrifuge experiments Divall (2013) varied the centre-to-centre spacing of twin-tunnel constructions. All these tests were conducted at 100 g. In this work the delay between the construction of each tunnel was 3 minutes at model scale and therefore analogous (in terms of consolidation) to a construction delay of 3 weeks at prototype scale. Detailed analysis contained within this work proposed a relative difference in the magnitude of ground movements between the first and second tunnel owing to the spacing and construction delay.

Figure 1 describes the relative increase (as a percentage) of the volume loss of the second tunnel when compared with the first tunnel (effectively the greenfield case). The horizontal axis shows the centre-to-centre spacing of the tunnels normalised against the tunnel diameter. Substituting the modified value of volume loss from Figure 1 and the dimensions for the second bored tunnel into Equations (1) and (2) would give a better prediction of the settlements solely from this tunnel construction. The predicted total settlement would therefore be the summation of the unaltered first tunnel and the modified second tunnel settlements.

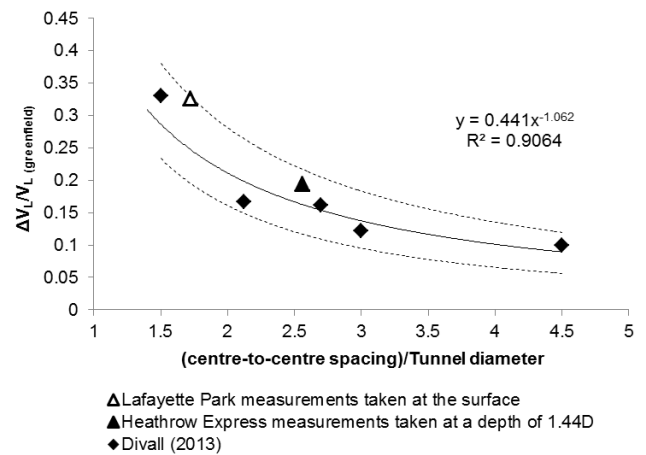


Figure 1. Relative increases in volume loss for a second bored tunnel with respect to the spacing to the first (after Divall, 2013).

3 CENTRIFUGE MODEL TESTS OF TWIN-TUNNEL CONSTRUCTION

3.1 Model Geometry

A series of plane strain centrifuge tests (Table 1) were conducted in order to investigate the influence of a construction delay on the ground movements.

Table 1. Tests performed.

Test Name	Volume loss	Construction delay
SD11*	3 %	3 minutes
SD14*	5 %	3 minutes
DG01	3 %	0 minutes
DG02	5 %	0 minutes

* results taken from Divall (2013).

In this paper, four largely identical tests, varying only in volume loss and the time delay between the constructions are discussed. All of the models in Table 1 comprised preformed circular cavities in overconsolidated clay. The twin-tunnels were bored equally spaced from the model centre-line with a centre-to-centre spacing of 3D. All models had a cover to diameter ratio (C/D) equal to 2 and the tunnel axis level was approximately 80 mm above the base of the model (Figure 2). The tests were performed in a plane strain strong box at 100 g.

Relatively complex apparatus was developed (described in Divall & Goodey, 2012) to simulate sequential tunnel constructions. The function of this apparatus was to provide support to the cavities via a virtually incompressible fluid (water) during testing in a centrifuge model. Utilising water then allows for the simulation of the volume loss effect by removal of the fluid. The same apparatus was used in the test representing simultaneous tunnel construction. A full discussion of the apparatus details are given in Divall & Goodey (2012).

The instrumentation used included Druck pore pressure transducers (PPTs), standard pressure transducers (PTs) and Linear Variable Differential Transformers (LVDTs). A rack of LVDTs was bolted to the top of the strong-box for measuring vertical displacement at the surface. A row of nine LVDTs were placed along the transverse centre-line of the model at distances of 0, ± 45 , ± 90 , ± 135 and ± 180 mm from the midpoint of the box. Holes are present in the back wall of the strong box for the installation of the PPTs within the model and the fluid feed for the tunnels. The PPTs were installed in the space between the tunnels and close to the boundaries. Two PPTs were positioned 75mm from the boundary at heights of 82 and 62mm from the base of the model. The standard pressure transducers were fitted to monitor the tunnel support pressure at

the tunnel axis level. The movements within the soil mass were also recorded via a digital image-processing system. Sub-surface patterns of movement were monitored by tracking marker beads pressed into the front surface of the clay however, only the surface settlement data will be discussed in this paper.

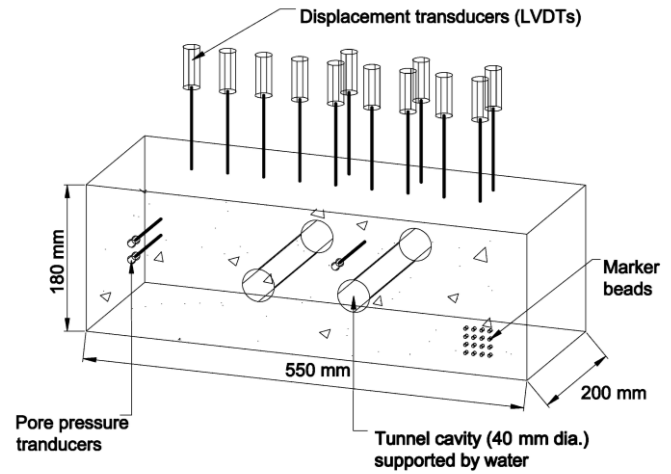


Figure 2. Typical plane strain centrifuge twin-tunnel model (Divall *et al.*, 2012)

3.2 The centrifuge

The use of a geotechnical centrifuge as a tool for examining geotechnical problems is well documented (Taylor, 1995). The geotechnical centrifuge used to carry out the series of tests was an Acutronic 661 available at City University London. This machine has a radius of 1.8 m and the capacity to test models weighing up to 200 kg at 200 g. Grant (1998) describes the facility in detail.

3.3 Model preparation

The model preparation process was standardised across all the tests and is discussed in detail by Divall & Goodey (2012). The significant features of the process are described below.

The Speswhite kaolin clay powder was mixed with distilled water to produce slurry with a water content of 120 %. The slurry was prepared in an industrial ribbon blade mixer. The slurry was placed within a strong box sandwiched between sheets of porous plastic and filter paper. A loading platen attached to a computer controlled pneumatic/hydraulic press was used to consolidate the clay slurry. The maximum vertical stress reached was 500 kPa followed by a 24 hour period of swelling at 250 kPa before any further in-flight reconsolidation. Drainage was allowed via holes in the bottom plate of the strong box and holes in the loading platen. The PPTs were installed during the swelling stage.

The model making begins by removing the sample from the consolidation press. The front-wall of the strong box was removed to gain access to the clay front surface. It is usual practice, at this point, to seal the exposed surfaces of the clay with silicone oil in order to prevent the sample drying out. A specially fabricated jig was clamped to the front of the strong box and a sharpened aluminium box cutter used to trim excess clay from the surface. To bore the tunnels a frame was fitted to the front of the strong box and corresponding plugged holes in the back wall removed. The use of these jigs ensured accuracy and repeatability. The tunnel cavities were cut with a 40 mm diameter circular seamless tube.

After the cavities were bored the tunnelling apparatus was placed inside. Every precaution was taken to bleed any air from of the tunnelling systems before placement. Screwed to the back of the tunnel apparatus were fittings allowing for fluid in-feed. The fluid control apparatus was bolted securely to the strong box. The piping was connected and de-aired. The support window was lubricated with a high viscosity, clear silicone oil to reduce interface friction a bolted in place between the observation window and the strong box.

Finally, using a syringe, the tunnel membranes were injected with water to completely fill the cavities. This ensured a stiff support was provided to the tunnel cavities during pore-water pressure equalisation. The assembled model was weighed and placed on the centrifuge swing. 450 ml of silicone oil was poured onto the top surface to prevent evaporation of pore-water from the clay during testing. Once the power supplies, solenoid valves and transducers were connected the test commenced.

3.4 Test Procedures

After the acceleration had reached 100 g the tunnels were isolated from the feed standpipe using a plug valve controlled by a rotary solenoid. The tunnels were checked to ensure no leaks were evident in the membranes or piping. This was apparent from a constant tunnel support pressure reading. Assuming no leakage, the centrifuge could be left overnight until pore-water pressure equilibrium had been reached in the model.

Simultaneous tunnel constructions were performed by operation of the equipment to drain 3 or 5 % of the total volume of the cavities. The sequential simulated constructions followed the procedure outlined in Divall & Goodey (2012). Essentially, a series of plug valves controlled by rotary solenoids could isolate individual parts of the fluid control system. When the simulation of Tunnel A was required, the valve to Tunnel A was opened and fluid

was extracted. A similar procedure was repeated for Tunnel B. In every test the same amount of fluid was extracted from both tunnels. A 3 minute construction delay was adhered to in the sequentially tunnelling tests. The centrifuge was usually run for at least an hour post-test to allow any longer term movements to develop.

4 RESULTS

Each figure presented below allows for the comparison of the results from the tests with simultaneous tunnel constructions with data from tests with sequential tunnel constructions.

Figure 3 and Figure 4 shows the surface settlement data comparing volume losses of 3 % and 5 %, respectively. The data shown are taken immediately upon completion of both tunnel constructions. The horizontal axes are distance from the centre-line of the model normalised against a tunnel diameter. The vertical axes are vertical settlement normalised against a predicted maximum settlement for a single tunnel constructed in a greenfield site ($S_{max\ predicted}$).

The predicted maximum settlements used in Figure 3 and Figure 4 are calculated from the single tunnel Gaussian settlement distributions using Equation (2). The parameters required to calculate $S_{max\ predicted}$ are i (or K) and V_L . The volume of fluid extracted from the tunnel is known and therefore V_L is known. The value of K is based on the typical value measured by Divall (2013) for movements using this apparatus ($K = 0.55$). For clarity, the position of the centre-line of each tunnel is shown with the labels T_A and T_B .

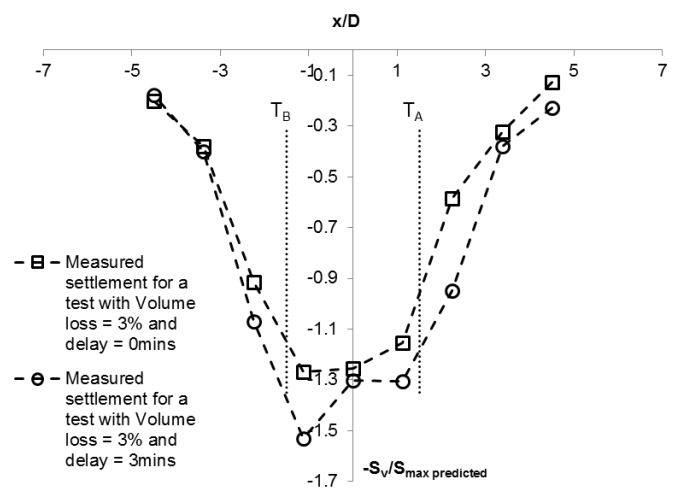


Figure 3. Twin-tunnelling settlement at 3% volume loss at a centre-to-centre spacing of 3D.

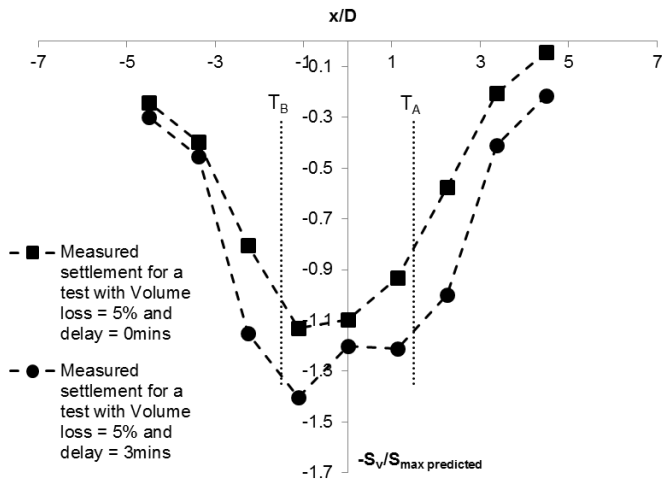


Figure 4. Twin-tunnelling settlement at 5% volume loss at a centre-to-centre spacing of 3D.

In Figure 3 and Figure 4 there is a markedly different shape observed between the settlement troughs obtained. The main difference observed is a level of asymmetry in the final settlement for tests where there is a delay between tunnel constructions. However, it should be noted that the data from tests with a construction delay also resulted in relatively larger settlements compared with those from tests with no construction delay.

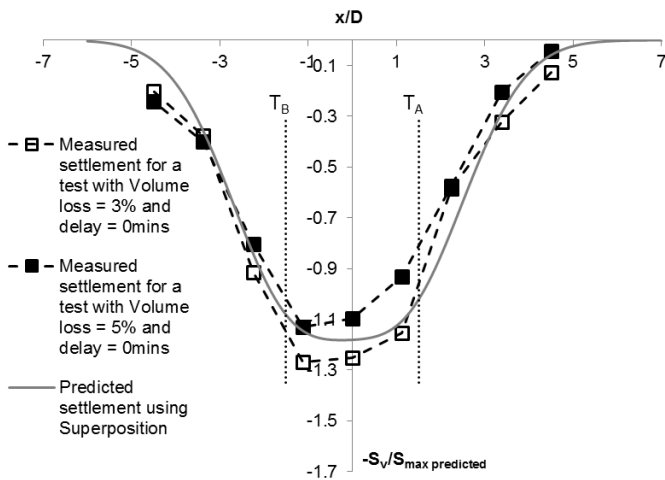


Figure 5. Twin-tunnelling settlement where no construction delay was observed and at a centre-to-centre spacing of 3D.

Figure 5 compares the total settlement for the 3 % and 5 % volume loss tests where the time between the constructions was zero. The same axes as in Figures 3 and 4 were used. Grant (1998) showed the shape of tunnelling-induced settlements are equal for Volume losses ranging from 2 % - 20 %. Therefore, the settlements resulting from these different Volume losses (normalised against their respective maximum settlement) should be equal in Figure 5. This figure also shows the Superposition prediction curve. This curve is the average of the 3 % and 5 % Volume loss cases calculated using Equation (4).

The Superposition curve is shown to be in good agreement with both data sets.

There is some slight variation between the left and right sides of the settlement which are due to small differences in the initial positions of the LVDT footing. If these footings rest on areas of high curvature the readings can be marginally affected. Overall however, the settlements are still largely symmetrical.

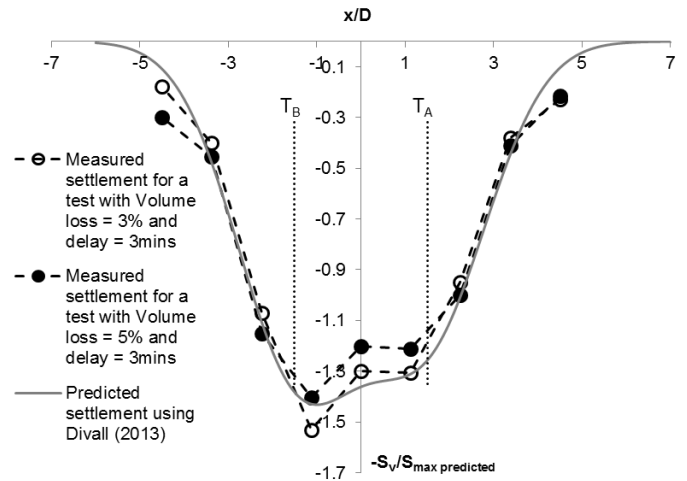


Figure 6. Twin-tunnelling settlement where a construction delay was observed and at a centre-to-centre spacing of 3D.

Figure 6 shows the total settlement for the 3 % and 5 % volume loss tests where the construction delay was equal to 3 minutes. In Figure 6 the Superposition predicted curve was modified in order to achieve a better fit to these data sets.

Initially, a greenfield settlement curve was generated for the prediction of settlements associated with the first tunnel construction. The trend in Figure 3 implies that for a centre-to-centre spacing of 3D the Volume loss associated with the second tunnel construction would be approximately 13 % larger than the greenfield equivalent. Therefore, an identical settlement curve to the first tunnel was used to represent the settlement from the second tunnel but modified in Equation (2) by substituting in this new value of Volume loss. The summation of the unaltered first tunnel and the modified second tunnel settlements produces the asymmetric total settlement prediction shown in Figure 6. Averages were taken of the 3 % and 5 % cases, similar that shown in Figure 5. This modified curve, using Figure 3 is in good agreement with the both sets of experimental data.

5 CONCLUSIONS AND FURTHER WORK

The centrifuge model tests described have provided some interesting data examining the movements around twin-tunnels. The accepted practice of using superposition of settlement predictions has been

shown to be adequate where both tunnels are constructed simultaneously. However, superposition has been shown to have some shortcomings if there is a construction delay between the tunnels.

Further research is required in order to fully understand the extent this construction delay has on the settlements. Future tests will investigate the effect on the tunnelling-induced settlements caused by a greater variation in the time between the simulated tunnel constructions.

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