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Ground movements generated by sequential twin-tunnelling in over-consolidated clay

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Abstract: The expansion of urban populations comes with an associated demand for increased public transport. An often utilised solution is to construct a rapid transit system within tunnels. Generally, a pair of tunnels are constructed within relative close proximity. The construction of these tunnels will generate ground movements which have the potential to cause damage to existing surface and subsurface structures. Modern tunnelling practice aims to reduce these movements to a minimum; however there is still a requirement for accurate assessment of settlements. For tunnels driven in clay, superposition of settlement predictions made by considering a single tunnel is an accepted method used to estimate movements around pairs of tunnels. This presumes that the movements generated from the construction of the second tunnel are not influenced in any way by the presence of the first tunnel. A series of plane strain centrifuge model tests have been conducted to explore the validity of superposition as a prediction method. The tests consisted of a sequential twin-tunnel construction with varied centre-to-centre spacing in over-consolidated clay. Relatively complex apparatus facilitated a predefined volume loss whilst monitoring surface settlement, tunnel support pressures and pore-water pressures. The measured data were assessed against superposition for surface vertical settlements in the plane perpendicular to an advancing tunnel face. The results highlight some inconsistencies with the superposition method.

Keywords: Centrifuge, tunnels and tunnelling, construction process, settlements

1 INTRODUCTION

In urban regions, where available surface space is restricted, tunnelling is used extensively and particularly for mass transit. When tunnelling systems are used in this way they are commonly constructed in pairs and this arrangement is known as twin-tunnelling. Stress changes in the soil mass from any underground construction can lead to ground movements. The propagation of these movements has the potential to cause damage to existing structures (Mair et al., 1996).

In construction using a Tunnel Boring Machine (TBM), the ground deformations towards a newly created cavity are often known as volume loss. Potential sources of tunnelling-induced ground deformation are described extensively by Mair & Taylor (1997). The product of these ground deformations is apparent at the surface as a transverse settlement trough which is usually assumed to fit a Gaussian distribution (Peck, 1969).

Tunnelling construction guidelines have been developed based, largely, 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 tunnel. Previous research, particularly numerical studies, has indicated that superposition may not necessarily be sufficient. Hunt (2005) explored the influence of constructing tunnels in close proximity using the finite element method and proposed a modification to current semi-empirical solutions to account for the presence of the first tunnel. Other numerical predictions (e.g. Addenbrooke & Potts, 2001) have also suggested that superposition is an inadequate method of prediction ground movements.

On a number of twin-tunnelling sites, such as St James Park in UK (Nyren, 1998), Lafayette Park in USA (Cording & Hansmire, 1975), and The Heathrow Express in UK (Cooper & Chapman, 1998), ground movements and tunnel behaviour have been monitored. The observed ground movements in these case studies show a difference in the relative settlements generated by the first and second tunnels.

The current research programme is to explore the ground movements in over-consolidated clay when constructing parallel tunnels with a small separation distance. A number of plane strain centrifuge tests, using complex apparatus to accurately simulate volume loss were carried out. The aims were to simulate a single tunnel construction, followed by a pause representing a construction delay, and then simulate a second separate tunnel construction. For a full discussion on the apparatus used see Divall & Goodey (2011). The test series consisted of three tests with equal diameter tunnels defined by their centre-to-centre spacing. The three tests were at spacings of 1.5D, 3D and 4.5D where D is the tunnel diameter. The results indicate asymmetry of ground movements in line with some previous numerical analysis (e.g. Hunt, 2005) and question the validity of superposition as a prediction tool.

2 CURRENT PRACTICE

2.1 Introduction

The assessment of potential effects on infrastructure is an essential aspect of the planning, design and construction of a tunnelling project in an urban environment. These assessments utilise the prediction of tunnelling-induced ground movements.

Predictions of tunnelling-induced ground movements were described in Peck (1969) as radial displacements towards the cross section and longitudinal displacements along the cross section of the cavity. These two sets of movements have been difficult to define and separate therefore displacements are usually simplified to a plane strain scenario.

In construction using a TBM the bored size of a tunnel will always be larger than the final size. This process explains the radial displacements towards the cavity and has been described by the term 'volume loss' (Peck, 1969). In the undrained case, the volume of 'lost ground' around a tunnel cavity should, in theory, be equal to the volume of any subsequent surface settlement trough. Mair & Taylor (1997) stated that whenever necessary the volume loss should be expressed in terms of the volume of surface settlement trough. It should be recognised that tunnelling naturally causes subsurface movements within the soil mass but only the surface settlements are discussed in this paper.

2.2 Single tunnel construction induced ground movements

It is accepted, that in order to predict single tunnelling-induced ground movements the ground movements are assumed to fit 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.

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

Where:

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

S_v = the theoretical settlement at a given horizontal distance from the tunnel centre-line
S_{max} = the theoretical 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 inflection in the Gaussian distribution curve
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:

$$i = K \cdot Z_0 \tag{3}$$

Where:
Z_0 = the vertical distance from the undeformed surface to the tunnel axis level
K = a dimensionless trough width parameter.

The average value of K was 0.5 for tunnels in moderately stiff clay. This agreed in general with the findings of Peck (1969) although the data presented varied between 0.4 and 0.6.

2.3 Twin-Tunnel construction induced ground movements

2.3.1 Method 1

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.

O'Reilly & New (1982) provided a formula for twin tunnels by superposition:

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

Where:
d = the lateral distance between the two tunnels centre-lines
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 interaction between the tunnels.

2.3.2 Method 2

Addenbrooke & Potts (2001) proposed a method for adjusting the predicted settlement profile associated with the second tunnel. This numerical study predicted that the shape of the second tunnel's settlement profile was not 'too dissimilar' to the first (greenfield) tunnel. Two design charts were produced to find, firstly, an eccentricity of the maximum settlement and, secondly, the increase in volume loss of the second tunnel's settlement profile (Figure 1). The plots indicated that the volume loss resulting from the second tunnel increases as the spacing between the tunnels decreases. Once the modified volume loss has been obtained the second tunnel settlements can be amended. The modified second tunnel settlements can then be summed with those of the unchanged first tunnel to predict the total settlement.

These design charts are plotted in terms of the parameter 'pillar width'. Pillar width is the horizontal distance between the tunnel's centre-lines minus the sum of their radii expressed as a ratio of the average tunnel diameter. However, caution should be taken when using this parameter as the shape of the second tunnel may distort towards the first tunnel when volume loss increases, hence, decreasing the overall pillar width.

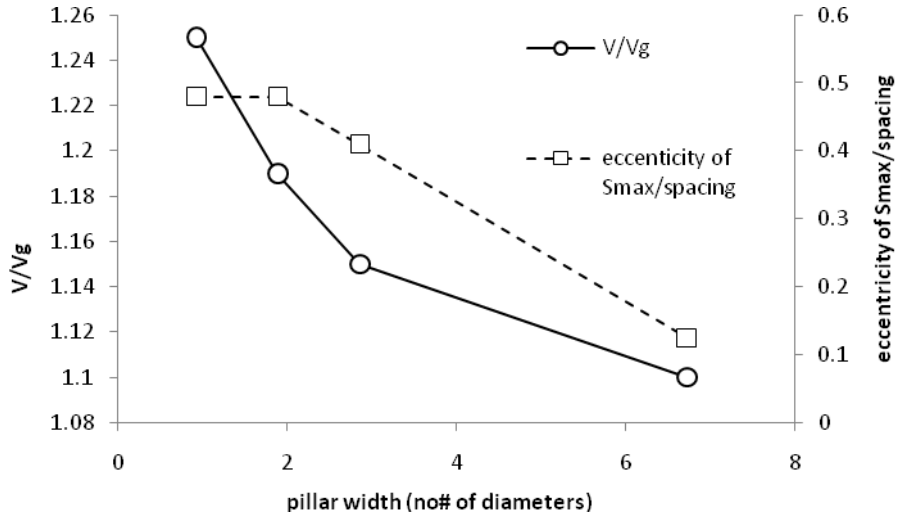

Figure 1: Design charts to find the increase in volume loss of the second tunnel's settlement profile (left) and an eccentricity of the maximum settlement (right). (After Addenbrooke & Potts, 2001).

2.3.3 Method 3

Another finite element study, conducted by Hunt (2005), proposed a different modification to the tunnelling-induced ground movements caused by the second tunnel. This method was based on modifying the ground movements of the second tunnel in an "overlapping zone", this is the soil assumed to have been previously disturbed by the creation of the first tunnel.

$$S_{\text{mod}} = FS_v \tag{5}$$

Where:
S_{mod} = the modified settlement and
S_v = the unmodified settlement above the second tunnel calculated by semi-empirical methods.

And:

$$F = \left\{1 + \left[M \left(1 - \frac{|d + x_A|}{AK_A Z^*} \right) \right] \right\} \tag{6}$$

Where:
$Z^* = (Z_0 - Z)$,
A = the multiple of the trough width parameter (usually taken as 2.5 or 3) in a half settlement trough,
d = the centre-to-centre spacing of the tunnels
K_A = the value of K in the region of the first bored tunnel
M = Maximum modification factor described in Chapman *et al.* (2006)

The maximum relative increase in settlement, M=1.0, is aligned with the centre-line of Tunnel A and reduces to zero at some lateral distance from Tunnel A. Hunt (2005) concluded that the maximum percentage increase in settlement was usually between 60 and 80 %.

As with Addenbrooke & Potts (2001) the method modifies the settlement profile above the second tunnel using Equations (5) and (6). The predicted total settlement is, again, to add the modified second tunnel settlement with the unmodified first.

3 CENTRIFUGE MODEL TESTS OF TWIN-TUNNEL CONSTRUCTION

3.1 Model Geometry

The use of a geotechnical centrifuge as a tool for examining geotechnical problems is well documented (Taylor, 1995). To investigate the ground movements around sequentially bored tunnels in clay a series of plane strain centrifuge tests have been conducted (Table 1). In this paper, three largely identical tests, only varying in the tunnel centre-to-centre spacing, are discussed.

Table 1: Tests performed

Test Name	Spacing (D)	Fluid volume extracted from each tunnel (%)
Test 1	1.5	3.0
Test 2	3.0	3.0
Test 3	4.5	3.0

The tests were performed in a plane strain strong box at 100 g. Models consisted of preformed circular cavities in over-consolidated clay. The twin-tunnels were bored equally spaced from the model centre-line. 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 strongbox. Relatively complex apparatus was developed in order to simulate sequential tunnel construction. The apparatus provided support to the tunnel cavities using a fluid that could be removed in order to simulate volume losses. The apparatus utilised a motorised Bishop ram as a syringe for removing the supporting fluid from within the tunnels. The support pressure in the tunnels is controlled by a standpipe and, as such, the pressure automatically increases with g. A full discussion of the apparatus details are given by Divall & Goodey (2011).

The typical layout for the models is shown in Figure 2. The instrumentation of the models included Druck pore pressure transducers (PPTs), pressure transducers and Linear Variable Differential Transformers (LVDTs). The PPTs were installed into the soil through ports present in the back-wall of the strong box, the pressure transducers were fitted to the tunnels fluid in-feed to monitor the tunnel support pressure and a rack containing LVDTs was bolted onto the top of the strong box to measure vertical surface settlement. The movements within the soil mass were also recorded, in conjunction with the LVDTs, via a second method. A digital image-processing system monitored subsurface patterns of movement by tracking marker beads pressed into the front surface of the clay although in this paper only the surface settlement data from the LVDTs will be presented.

3.2 The centrifuge

The geotechnical centrifuge used to carry out the series of test 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 in detail the facility including a description of the digital image-processing capability used for subsurface monitoring.

3.3 Test Procedure

In line with common practice in centrifuge testing procedures Speswhite kaolin clay slurry was prepared to a water content of 120 %. The slurry was placed in a hydraulic press, under a vertical stress of 500 kPa followed by a period of swelling to 250 kPa before any further in-flight reconsolidation.

The model making begins by removing the sample from the consolidation press. It is usual practice to seal the exposed surfaces of the clay before and during model making as quickly as possible with silicone oil in order to prevent drying. The front-wall of the strong box was removed to gain access to the clay front surface; where the excess clay was trimmed and the cavities were bored. Specially fabricated jigs, clamped to the front of the strong box, were used to ensure accuracy and repeatability. The tunnel cutter was a 40 mm diameter circular seamless tube. Once the tunnels were bored a separate guide was clamped to the front of the strong box so that image analysis target beads could be pressed into

the front surface of the clay. At this stage the preparation of the clay was complete and the apparatus was placed inside the tunnel cavities. Screwed to the back of the tunnel apparatus were fittings allowing for fluid in-feed. To enable the subsurface movements to be recorded by the CCD camera in flight, the front-wall was replaced by a Perspex window. Prior to being bolted to the front of the strong box the window was lubricated with a high viscosity, clear silicone oil to reduce interface friction. The fluid control apparatus was bolted securely to the strong box. The piping was connected and de-aired. Finally, using a syringe, the tunnel membranes were injected with water to completely fill the cavities. It should be noted that extreme care was taken to bleed air out of the tunnel support apparatus to ensure a stiff support was provided to the tunnel cavities during pore 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 the test. Once the power supplies, solenoid valves and transducers were connected the final checks were made and the test commenced.

After the acceleration had reached 100 g the tunnels were isolated from the standpipe using a plug valve controlled by a rotary solenoid. Once it had been ensured that the tunnels were not leaking support fluid which would be observed as a decrease in support pressure) the centrifuge was left overnight until pore pressure equilibrium had been reached in the model. Sequential tunnel constructions were simulated by operating the equipment to drain 3 % of the total volume of the support fluid from each of the tunnels. A time period representing a construction delay was allowed between these events. The centrifuge was usually run for at least an hour post-test to allow any longer term movements to develop.

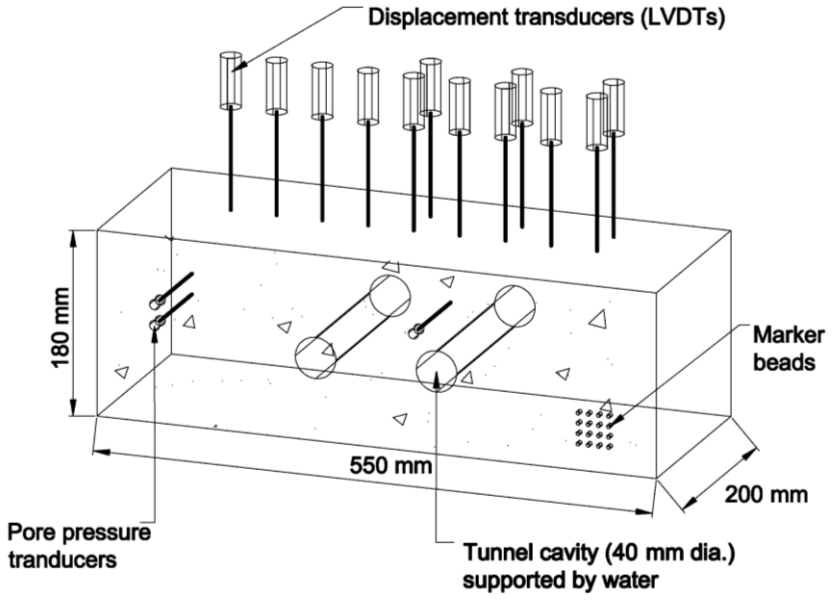

Figure 2: Schematic diagram of a typical plane strain centrifuge twin-tunnel model (not to scale)

4 RESULTS

4.1 Single Tunnel Settlement Data

Figures 3-5 show the settlement trough data for each test as measured by the LVDTs. The two settlement troughs are obtained by taking the surface readings before and after a tunnel construction event. The surface settlement data associated with the first and second simulated tunnel construction will be known as Tunnel A and B irrespective of whether the left hand or right hand tunnel was excavated first.

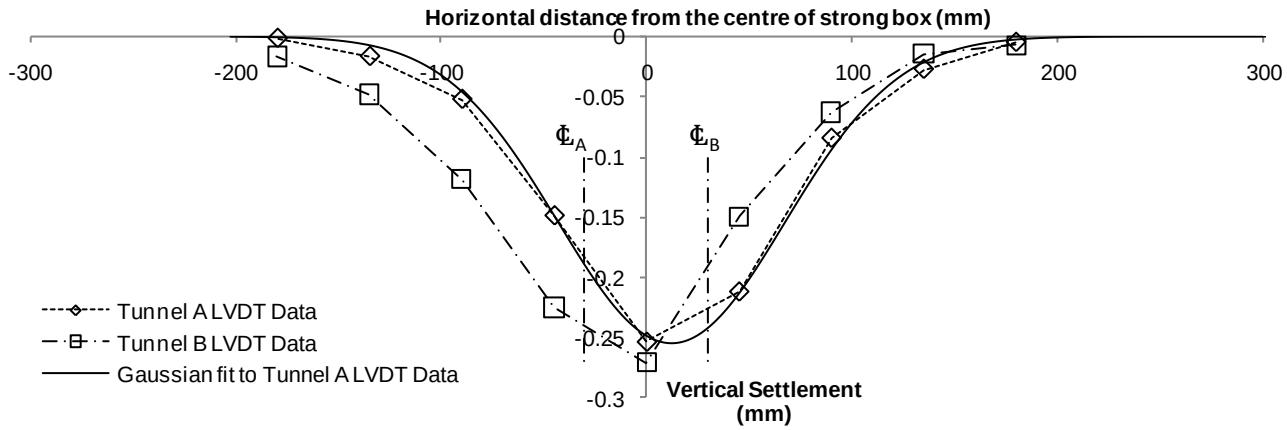

Figure 3: Individual single tunnel surface settlement measured by LVDTs in Test 1 (1.5D)

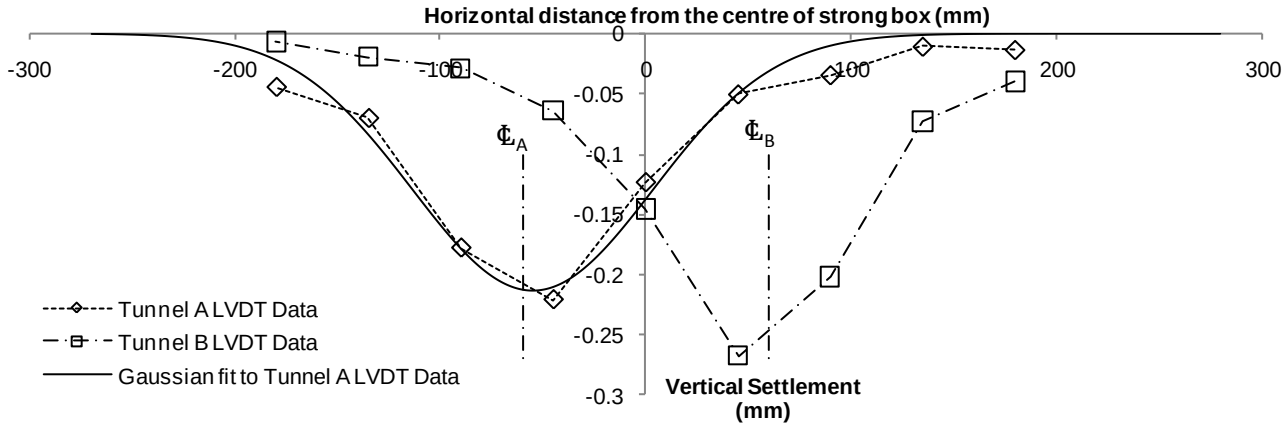

Figure 4: Individual single tunnel surface settlement measured by LVDTs in Test 2 (3D)

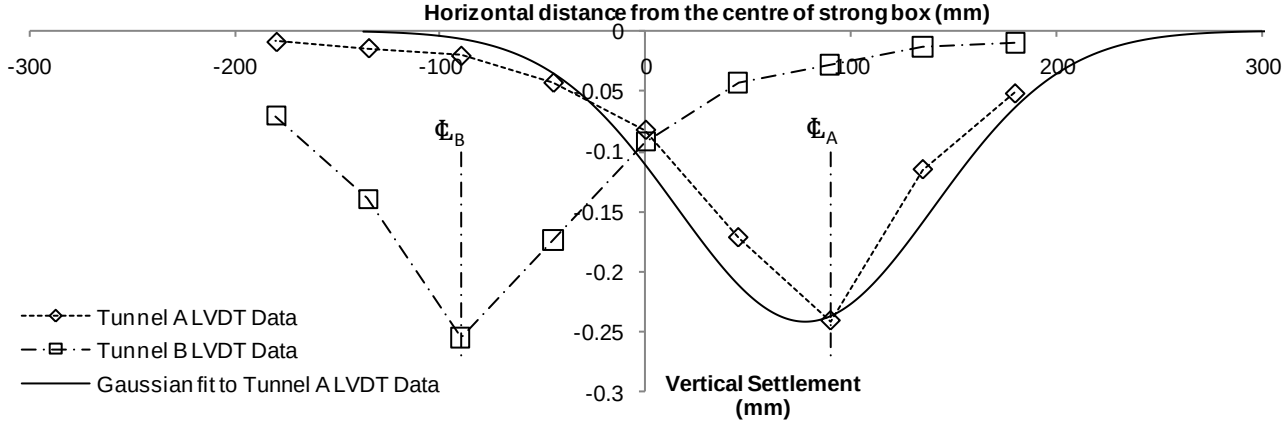

Figure 5: Individual single tunnel surface settlement measured by LVDTs in Test 3 (4.5D)

As Tunnel A is excavated in what is effectively a greenfield site, a Gaussian distribution has been fit to these data. These are shown to have good agreement with O'Reilly & New (1982). This expected behaviour was reflected in the Tunnel A settlements for all tests. Table 2 shows the volumes losses in the tests determined from both the curve fitting exercise and by a simple Simpson's rule. It should be noted that there is a slight variation in values compared with the 3 % volume extraction requested from the apparatus which was shown to be highly reliable and repeatable (Divall & Goodey, 2011). The

volume loss determined from Simpson's Rule shows a high level of agreement with the Gaussian curve fit.

The asymmetry of Tunnel B settlements and the increased magnitude of these settlements are also clear from Figures 3-5. This resulted in higher volume losses than in the case of Tunnel A. To examine this asymmetry, Gaussian curves were fit separately to the left and right-hand sides of the settlement trough data. The parameters i and K could then be calculated for Tunnel B settlements based on these lines of best fit. Table 2 clearly shows that i and K were not equal on the side of the trough towards Tunnel A compared with the side of the trough away from Tunnel A. The amount of asymmetry in this trough is influenced by the position and distance away from the centre-line of Tunnel A. To represent the extent of the asymmetry a ratio of i values was calculated as $i_{(towards\ A)}/i_{(away\ from\ A)}$. This measure of asymmetry is shown in Figure 6 along with the increase in volume loss of the second tunnel over the first. There is a clear trend showing that as the separation of the tunnels increases the effect on volume loss reduces but asymmetry of the second settlement trough is still affected.

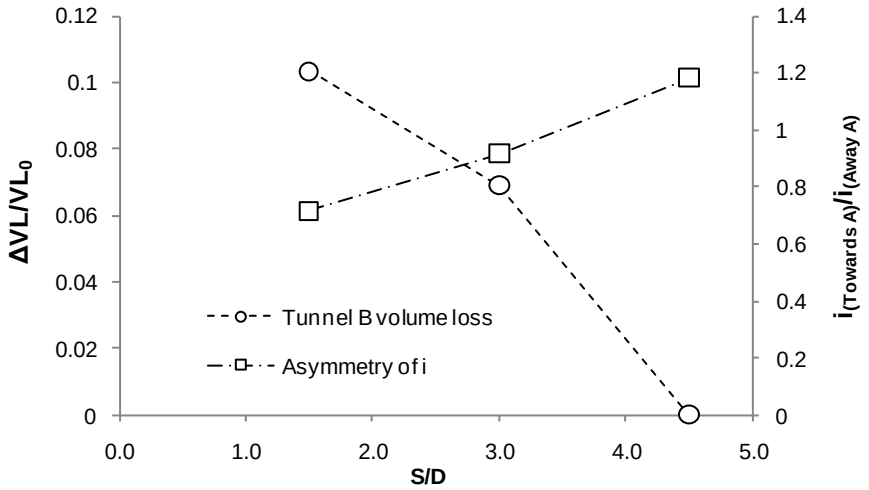

Figure 6: Effect on volume loss and asymmetry of settlements of Tunnel B construction

Table 2: Parameters determined from test results

Spacing	Volume	Tunnel A				Tunnel B					
D	Extracted	V_L *(Simpsons)*	V_L *(Gauss)*	*i (mm)*	*K*	V_L *(Simpsons)*	V_L *(Gauss)*	$i_{(towards\ A)}$	$i_{(away\ from\ A)}$	$K_{(towards\ A)}$	$K_{(away\ from\ A)}$
1.5	3.0%	2.9%	2.8%	55.2	0.552	3.2%	3.5%	53.8	77.3	0.538	0.773
3	3.0%	2.7%	2.5%	58.7	0.587	2.9%	3.2%	55.0	60.0	0.550	0.600
4.5	3.0%	2.8%	3.0%	62.5	0.625	2.8%	3.1%	65.0	55.0	0.650	0.550

4.2 Twin-Tunnel Settlement Data

Figures 7-9 show the final 'Twin-tunnel' settlement after both tunnel constructions have been simulated. The measured data has been compared with the prediction methods outlined earlier. It is clear that superposition does not take into account the repeated unloading of the soil and therefore, the curve does not represent the final displacement very well. The predictions of Addenbrooke & Potts (2001) tend to be in fairly good agreement with the experimental data at the extremities of the settlement trough. Hunt (2005) has shown to produce a good agreement with the results at both the extremities and the mid-points. However, this method tends to over predict the magnitude of settlements and the trough width. Both Addenbrooke & Potts (2001) and Hunt (2005) produce prediction methods that give fairly good correlation with the test data given the proviso for the extra volume loss in the simulation of a second tunnel construction.

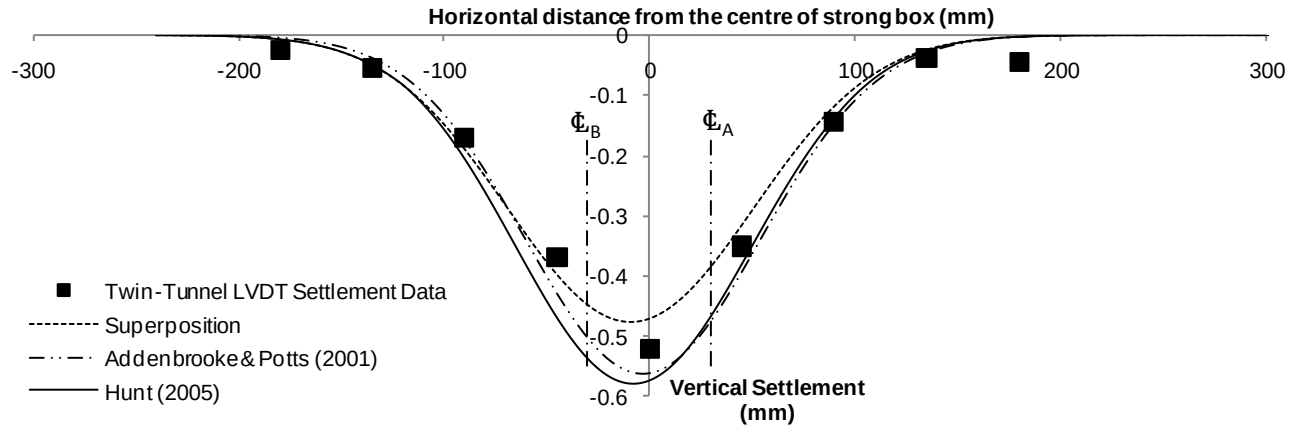

Figure 7: Twin-tunnel surface settlement measured by LVDTs in Test 1 (1.5D)

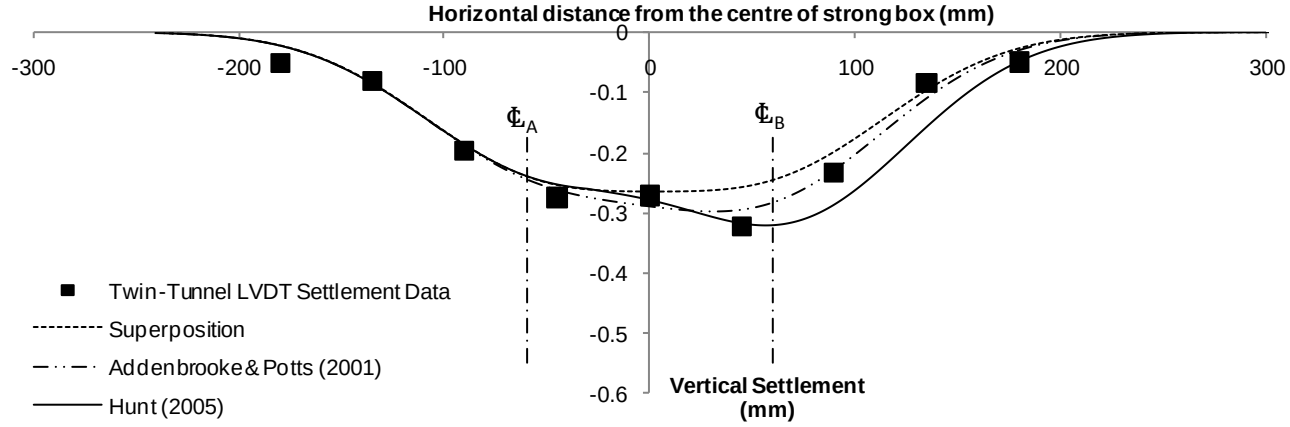

Figure 8: Twin-tunnel surface settlement measured by LVDTs in Test 2 (3D)

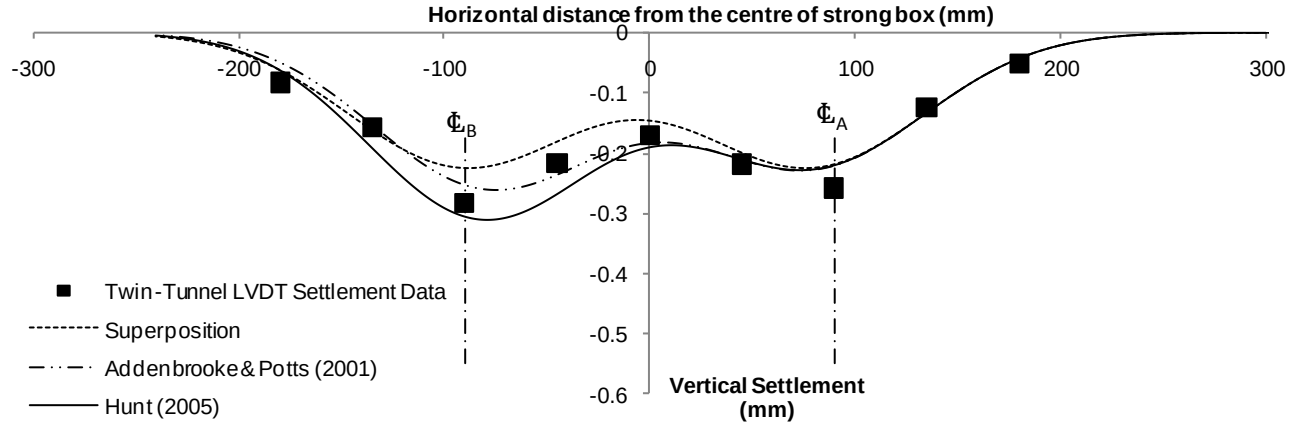

Figure 9: Twin-tunnel surface settlement measured by LVDTs in Test 3 (4.5D)

5 CONCLUSIONS

The centrifuge model tests described have provided the beginnings to some very interesting data examining the small strain movements around twin-tunnels. The accepted practice of superposition of settlement predictions has been shown to have some shortcomings although two recent numerical studies have shown a better fit with the experimental data.

The Tunnel A surface settlements were well represented by Gaussian distributions as might be expected for a greenfield construction, but Tunnel B surface settlement was not. Taking the parameter i as a measurement of the distribution of settlements at the surface shows that the left and right-hand sides of the settlement troughs were not equal i.e. not symmetrical. The extent to which the parameter i is affected is dependent on the position of the first bored tunnel with respect to the second. The closer the centres of the tunnels, the greater the added volume loss observed in the second bored tunnel. As the volume extracted from the tunnel is controlled, the reasons for this are unclear at this time and are a topic for further investigation.

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