# Novel apparatus for generating ground movements around sequential twin-tunnels in over-consolidated clay

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ABSTRACT: The tests consisted of a sequential twin-tunnel construction with varied centre-to-centre spacing in overconsolidated clay. Relatively complex apparatus facilitated a predefined volume loss whilst monitoring surface settlement, tunnel support pressures and pore-water pressures. The surface data were assessed against published estimation methods with the results highlighting some inconsistencies.

## 1 BACKGROUND

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 (O'Reilly & New, 1982). 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 (e.g. Addenbrooke & Potts, 2001).

This research programme aims 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 relatively complex apparatus to accurately simulate volume loss were carried out. This enabled the simulations of a single tunnel construction, followed by a pause representing a construction delay, and then a second separate tunnel.

## 2 EXPERIMENTAL TEST SERIES

### 2.1 *Model Geometries*

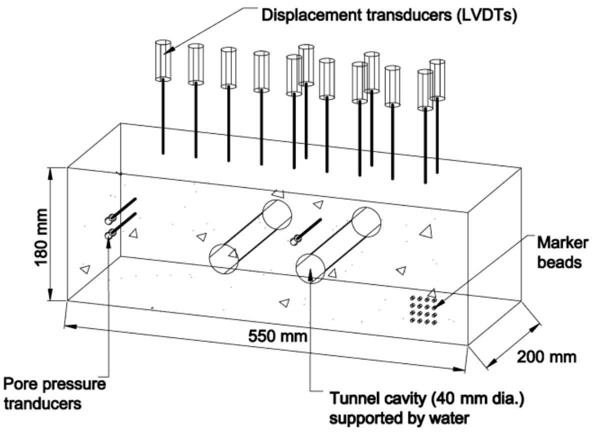
The use of a geotechnical centrifuge as a tool for examining geotechnical problems is well documented (Taylor, 1995). Three largely identical tests, only varying in the tunnel centre-to-centre spacing, have been conducted (Table 1).

| 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 |

Table 1 Tests performed

The tests were performed in a strong box at 100 g. Models consisted of preformed circular cavities in overconsolidated 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. The typical layout for the models is shown in Figure 1.

Figure 1 Schematic of a typical model




The newly developed 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 instrumentation of the models included Druck pore pressure transducers (PPTs), pressure transducers and Linear Variable Differential Transformers (LVDTs). A rack containing twelve LVDTs was bolted onto the top of the strong box to measure vertical surface settlement. The movements within the soil mass were also recorded via a digital image-processing system. The system monitored subsurface patterns of movement by tracking marker beads pressed into the front surface of the clay.

### 2.2 *Test Procedure*

After the acceleration had reached 100 g the tunnels were isolated from the standpipe using a plug valve controlled by a rotary solenoid. The centrifuge was left running 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 of three minutes was allowed between these events.

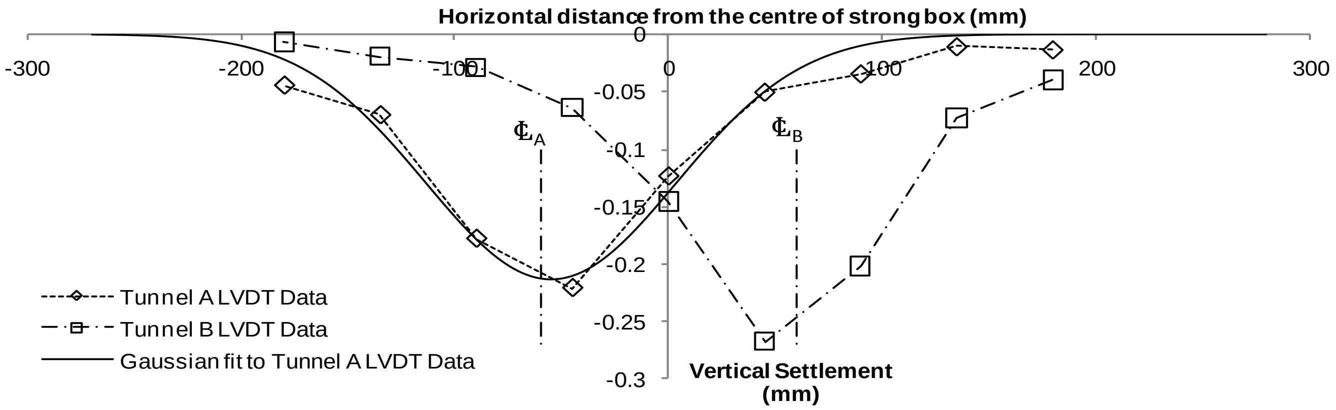



Figure 2 Tunnel A and Tunnel B settlements

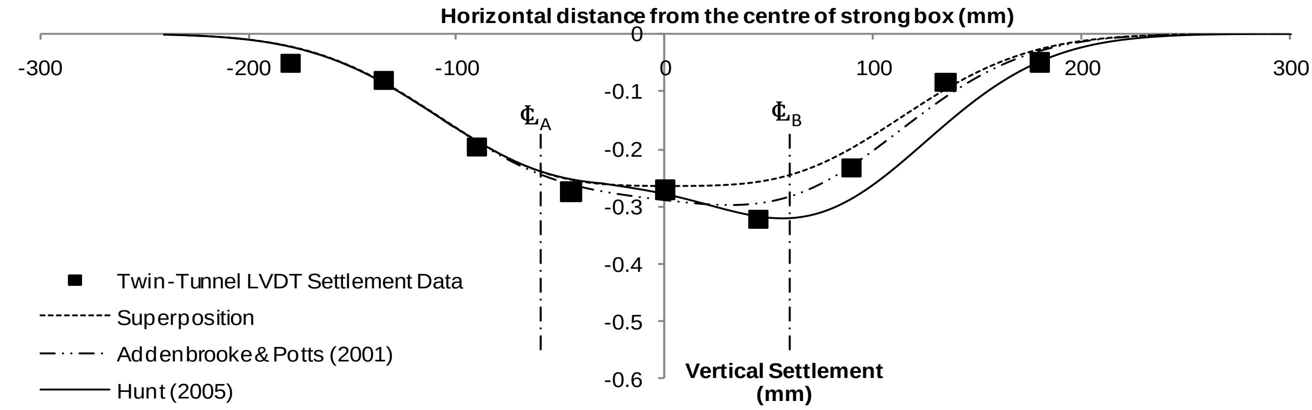



Figure 3 Twin-tunnel settlements

## 3 SURFACE SETTLEMENT DATA

Figures 2 and 3 show surface settlement data obtained from Test 2. In Figure 2 the individual settlement troughs are obtained by taking the surface readings before and after tunnel construction events. The surface settlement data associated with the first and second simulated tunnel constructions will be known as Tunnel A and B respectively.

As Tunnel A is excavated in what is effectively a greenfield site these are shown to have good agreement with the Gaussian fit. The settlements generated by Tunnel B show an increased magnitude as well a degree of asymmetry. This resulted in higher observed volume losses than in the case of Tunnel A. To examine this asymmetry, Gaussian curves can be 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 and a measure of asymmetry generated.

Figure 3 shows the total surface settlement after both tunnels have been excavated as well as some comparisons to existing predictive techniques.

## 4 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 has been shown to have some shortcomings although two recent numerical studies have shown a better fit with the experimental data.

Tunnel A surface settlements were as expected for greenfield construction, but Tunnel B surface settlements were not. The test series shows the closer the centres of the tunnels, the greater the added volume loss observed in the second bored tunnel. As the volume extracted from each tunnel is precisely controlled, the reasons for this are unclear at this time and are a topic for further investigation.

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