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TECHNICAL NOTE

A Review On The Laboratory Model Tests Of Tunnels In Soft Soils

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Abstract: Tunnelling through densely populated areas is usually associated with undesirable ground movement and damage to adjacent buildings. Consequently, it is essential to investigate the mechanism of the soil movements around the tunnel as well as ground surface. Laboratory model tests provide comprehensive understanding of the soil movements induced by tunnelling and failure mechanism as well. This paper presents a review on the laboratory model test of tunnels in soft soils

Keywords: *Laboratory model tests, tunnelling, soft soils, ground movements.*

1.0 Introduction

The growth of the urban areas has resulted in increased demand for infrastructures. Subsurface tunnels became definitive choice to overcome the congestion at the ground surface. With the increasing number of tunnels, it is essential to have a comprehensive understanding of the displacements and stresses induced by tunnelling and the effects of tunnelling on surface and subsurface structures. Several empirically derived relationships have been introduced by researchers to investigate the ground movements induced by tunnelling and the soil movements pattern around the tunnels by Peck (1969), Cording and Hansmire (1975), O'Reilly and New (1982), and Attewell and Woodman (1982). In addition to empirical methods, several research have been conducted to predict ground movements by means of analytical methods as in Sagaseta (1987), Verruijt and Booker (1996), Loganathan and Poulos (1998) and Park (2004). In the last decades, numerical methods have been developed due to increasing in powerful computers beside the capability of the numerical methods in analysing the complex geometrical conditions. Extensive researches have been conducted to estimate tunnelling-induced ground movements using numerical analysis such as in Lee *et al*. (1992), Vermeer *et al*. (2002) and Alessandra *et al*. (2009).

In addition to the aforementioned methods, several researches were also conducted by other researchers (e.g. Atkinson *et al*., 1977, Love, 1984; Mair *et al*. 1993; Kim, 1996; Nomoto *et al*., 1999; Wu and Lee, 2003; Lee *et al*., 2004; Hunt, 2005; Lee *et al*., 2006; Lee, 2009;Aklik *et al*., 2010; Ahmed and Iskander, 2011; He *et al*., 2012) to investigate the effects of tunnelling on ground movements, tunnel face stability, and soil movements pattern using physical modelling under single gravity or multiple gravities. Laboratory model tests provide an appreciated investigation of the ground behavior due to tunnelling. In addition, face stability as well as effects of face pressure can be investigated using laboratory model tests in 1g or centrifuge tests. A review on the selected laboratory model tests of tunnels in soft soils is presented in this paper.

2.0 Physical Modelling of Tunnels in Soft Soils

Physical modelling of tunnels helps to recognize different phenomena associated with tunnelling, such as, ground deformation pattern around the tunnel as well as failure mechanisms. Physical modelling of tunnels in soft soils are usually carried out under single gravity (1g) or under multiple gravities in centrifuge modelling. 1g models have been widely utilized in physical modelling of tunnels in soft soil. These techniques provide an investigation of complex systems in a controlled environment and are considered to be more economical compared to centrifuge or field investigations (Meguid *et al*., 2008). However, in-situ stresses are not realistically simulated in 1g models. Centrifuge modelling provide an applicable control up to failure and therefore, have been widely used in physical modelling of tunnels in soft soils.

3.0 Laboratory Model Test Techniques

Various laboratory model tests have been conducted by previous researchers to investigate the ground movements and collapse mechanism induced by tunnelling in different types of soil. Laboratory model tests are carried out under single gravity (1g) or under multiple gravities in centrifuge modelling to investigate the most relevant factors influencing the ground-tunnel behaviour. Tunnelling procedure is modelled by either placing soil around a pre-installed tube as a tunnel and controlling the supporting pressure or pre-cutting the tunnel opening and installing a lining system. In physical modelling, the tunnel-ground responses are investigated by means of a variety of techniques including the trap door, rigid tube, pressurized air bags, polystyrene foam and organic solvent. Following sections describe the laboratory model test techniques.

3.1 Single Gravity (1g)

Sterpi *et al*. (1996) conducted large scale three-dimensional 1g model to investigate the tunnel face stability in horse-shoe-shaped tunnels. The air pressure was utilized to support the tunnel face. The air pressure was reduced to record the failure pattern throughout the test, as shown in Figure1.

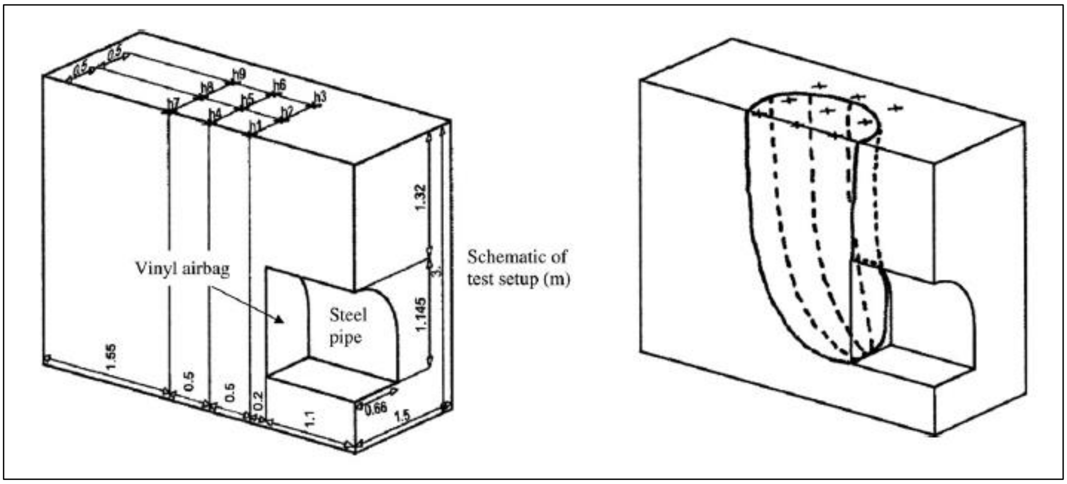

Figure 1: Test setup and failure mechanism resulting from air pressure reduction at the tunnel face (Sterpi *et al*., 1996)

In order to examine the effects of tunnelling on inclined soil layers, a series of 1g trap door experiments have been conducted by Park *et al*. (1999). They simulated the tunnelling procedure by lowering the trap door via a control jack. The results demonstrated that the inclination angle has a significant effect on surface settlement trough. Hagiwara *et al*. (1999) conducted several centrifuge tests to investigate the tunnelling-induced ground movement in multi-layer grounds by modelling several tunnels in clay overlain by sand. They demonstrated that the stiffness of the upper sand strata significantly affects the soil movements in the lower clay layer.

Sharma *et al*. (2001) used the polystyrene foam and organic solvent in order to simulate tunnel excavation using centrifuge model test. They placed a stiff tube of polystyrene foam into the soil. In order to model the procedure of tunnel advancement, they controlled the flow of organic solvent into the tunnel. Figure 2 shows the progressive development of the settlement trough obtained by polystyrene foam in their model test.

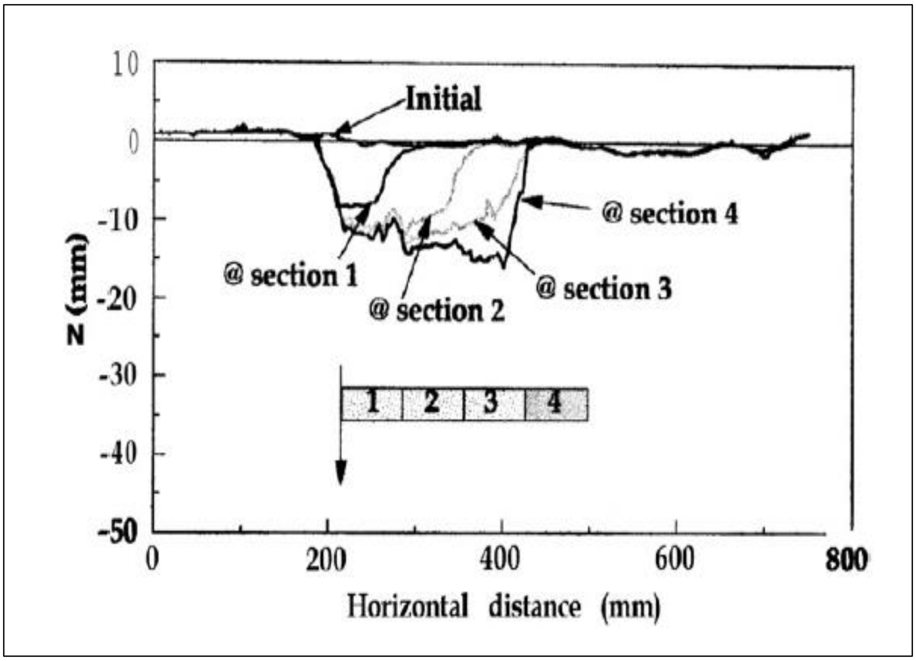

Figure 2: Progressive development of settlement trough obtained by polystyrene foam in model test (Sharma *et al*., 2001)

Adachi *et al*. (2003) conducted an axi-symmetric trap door experiments under 1g and centrifugal conditions. A tunnel was simulated using a circular trap door with 5 cm diameter and lowered by a screw jack. They measured earth pressure and displacements around the trap door placed in sand. They found that the ground displacements increased as the ratio of tunnel depth/tunnel diameter decreased.

Champan *et al*. (2006) utilized a small soil auger to excavate two parallel tunnels in clay. They used a water bag to provide surcharge pressure on the soil surface. Figure 3 shows the surface settlement trough resulting from the excavation of two parallel tunnels in clay. They concluded that the simply summing individual normal probability curves provide a correct reflection of the ground movements to estimate surface settlement above the closely spaced tunnel excavated in clay.

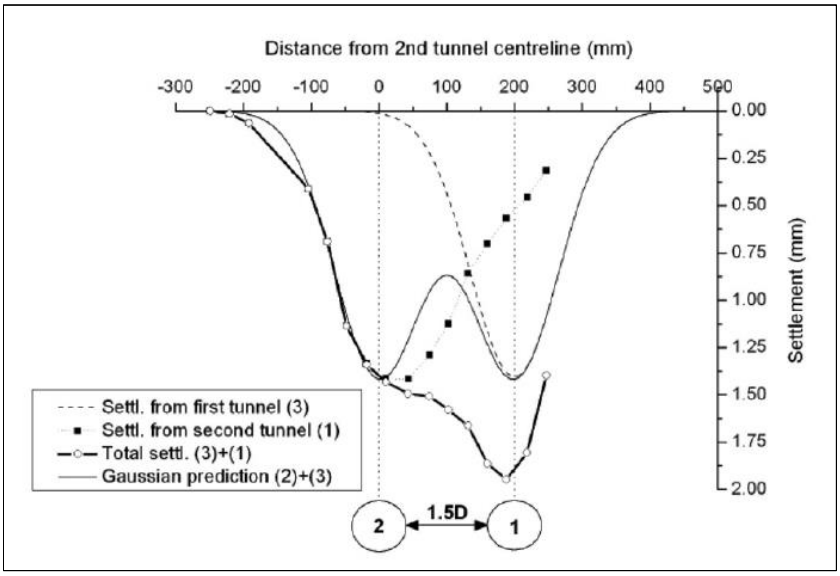

Figure 3: Settlement troughs developed from the construction of two parallel tunnels (Champan *et al*., 2006)

3.2 Multiple Gravities in Centrifuge Modelling

A series of centrifuge tests have been conducted by Chambon *et al*. (1991) and Chambon and Corte (1994) to analyse the stability of the tunnel face in different types of soil. The tunnel face was represented using latex membrane, as shown in Figure 4. The latex membrane was left slack to prevent mechanical influences on the displacement of the tunnel face and a displacement transducer was utilized to record the face movements. Throughout the tests, pressure in the tunnel was gradually decreased until failure occurred. When the internal pressure was decreased (between 32 kPa and 36 kPa) face movements were observed, as shown in Figure 5. However, the figure shows no significant vertical movements of the ground surface due to the decrement of the tunnel internal pressure.

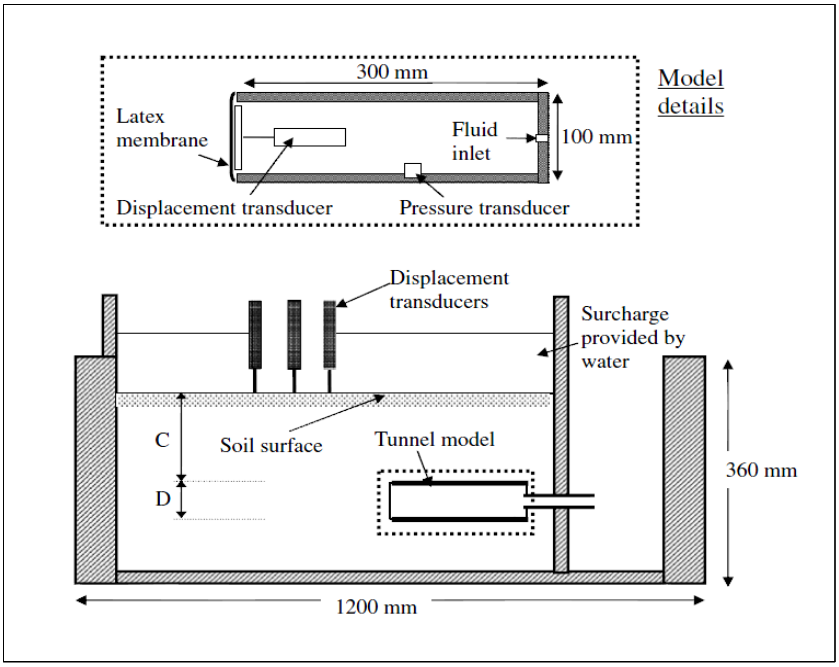

Figure 4: Centrifuge tunnel modelling (Chambon and Corte, 1994)

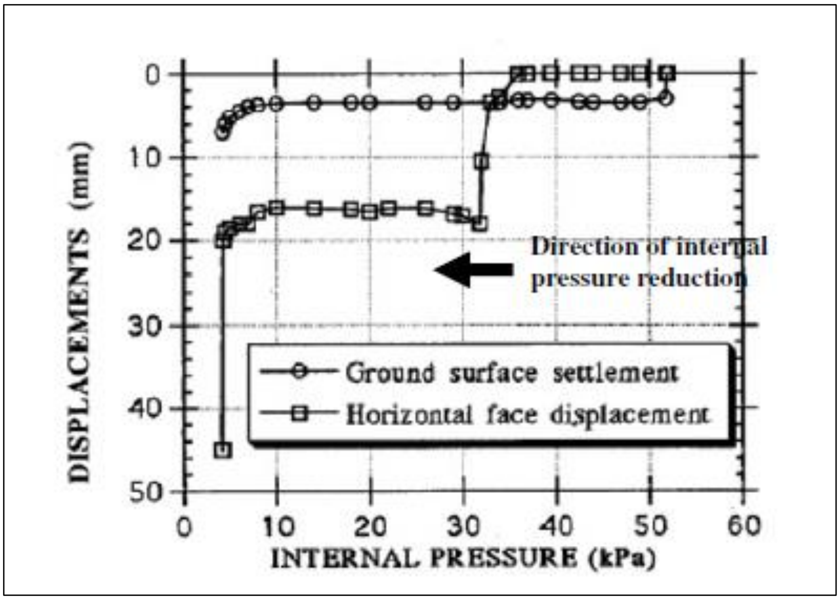

Figure 5: Displacement versus internal tunnel pressure from centrifuge tunnel modelling (Chambon and Corte, 1994)

Kamata and Masimo (2003) conducted a physical modelling to determine the effects of face reinforcement on the stability of the tunnel face in shallow depths. They supported the tunnel face in the model using a movable aluminium plate. The stability of the tunnel face was observed by pulling the aluminum plate. Figure 6 shows the failure pattern when the centrifuge acceleration reached 30g.

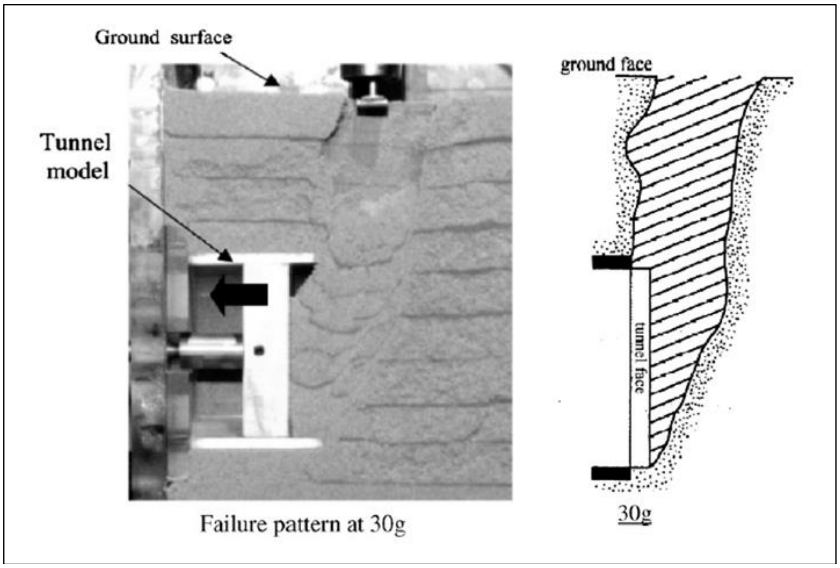

Figure 6: Observed failure pattern from centrifuge test (Kamata and Masimo, 2003)

Juneja *et al*. (2010) conducted several centrifuge tests to determine the effects of face bolting and fore poling on tunnel face stability. They demonstrated that the fore-poles reduced the length of settlement trough ahead of the tunnel face, whereas the width of the settlement trough remained unaffected. A series of plain strain centrifuge model tests were designed by Divall and Goodey (2012) to determine the validity of superposition as a prediction method. They conducted the test in overconsolidated clay for parallel twin tunnels. The results demonstrated some inconsistencies with the superposition method, as shown in Figure 7.

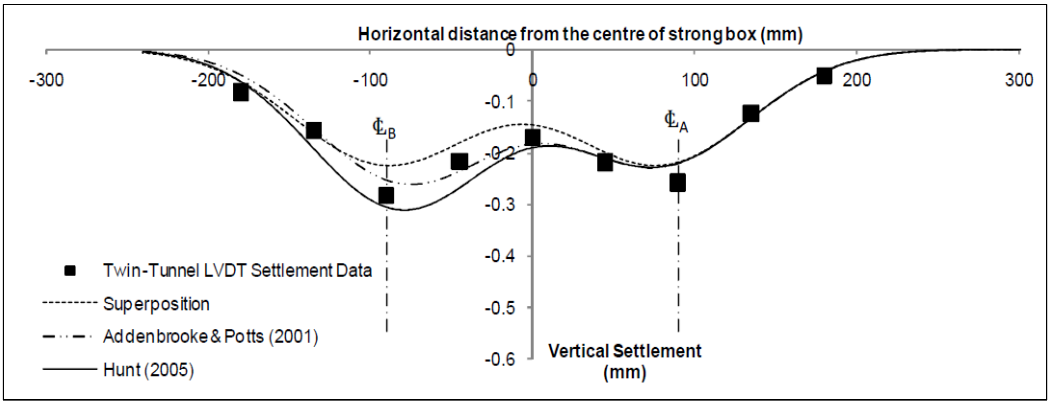

Figure 7: Measured and predicted surface settlement induced by twin-tunnel in overconsolidated clay (Divall and Goodey, 2012)

4.0 Conclusion

A review has been conducted on the methods of laboratory model test of tunnels in soft soils. These techniques are conducted under single gravity (1g) or under multiple gravities in centrifuge modelling. Tunnelling procedure is modelled by either placing soil around a pre-installed tube as a tunnel and controlling the supporting pressure or pre-cutting the tunnel opening and installing a lining system. Although physical modelling under single gravity are more economical compared to centrifuge modelling, in-situ stresses are not realistically simulated in single gravity models. Review on the findings of laboratory model tests demonstrates that these methods are more appropriate for investigating the mechanism of ground movements induced by tunnelling rather than the amount of ground movements.

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