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# The influence of tunnelling and deep excavation on piled foundations

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**ABSTRACT:** The paper addresses the effects of tunnelling and deep excavations on piled foundations. It focuses particularly on cases where tunnels are constructed beneath pile toes; it also discusses deep excavations adjacent to buildings for which the depth of excavation extends significantly below the piles. Case histories are reviewed and some new ones are presented. For friction piles the settlement was generally observed to be similar to the settlement of the ground surface at the position of the pile head. Some results of recent centrifuge modelling of tunnelling beneath bored piles in stiff clays are presented; these elucidate the detailed behaviour of piles subject to tunnel volume loss, particularly in relation to settlement, load distribution and shaft friction. Comments are made on numerical modelling, analytical methods and empirical methods used in practice. Field observations of the effects of deep excavations on piled buildings are also presented.

## 1 INTRODUCTION

For underground construction projects in urban areas it is becoming increasingly common for tunnels and deep excavations to be located close to piled foundations. It is important to be able to assess the effects of constructing tunnels and deep excavations on piled foundations. This paper focuses mainly on the effects of bored tunnelling on piled foundations. Later in the paper the effects of deep excavations are also discussed, with particular reference to recent experiences in Amsterdam (Korff 2012).

In the case of tunnelling, it is useful to consider the issue in two distinct categories:

1. Tunnelling adjacent to piles
2. Tunnelling beneath piles

Tunnelling adjacent to piles has been covered by a number of authors (e.g. Mair 1993, Loganathan et al. 2001, Pang et al. 2005). In general the experience has been that the effects are generally minor, with some lateral displacement of the piles being caused (with associated additional induced bending moments). Generally very little pile settlements occur.

In contrast, much less is known about the effects of tunnelling directly beneath piled foundations, and in particular how much settlement is caused. This subject has seen very little research from physical, numerical and analytical modelling perspectives, and there are very few documented field case histories.

Previous work investigating the effects of tunnelling on piled foundations can be categorised into the following:

1. Case Histories
2. Full Scale Field Trials

3. Centrifuge Modelling
4. Laboratory Studies
5. Numerical Modelling
6. Analytical Methods
7. Empirical Models Used in Practice

This paper does not cover all of these seven categories. It focuses principally on items 1 and 3, Case Histories and Centrifuge Modelling, relating to tunnelling beneath piled foundations. Towards the end of the paper comments are made on items 5, 6 and 7, Numerical Modelling, Analytical Methods and Empirical Models Used in Practice.

## 2 CASE HISTORIES OF TUNNELLING BENEATH PILED FOUNDATIONS

### 2.1 CTRL tunnels, UK

Jacobsz et al. (2005) describe three case histories relating to tunnelling beneath piled foundations. Figure 1 illustrates twin 8.2 m OD tunnels constructed for the UK Channel Tunnel Rail Link (CTRL) beneath driven piles supporting a road bridge. The piles are driven through soft alluvium and peats and are acting as end-bearing piles founded in a gravel layer. The tunnels were constructed with Earth Pressure Balance (EPB) tunnelling machines in London Clay, close to the top of the stratum, with the clear distance of the tunnel crowns beneath the toes of the piles being around 3 m. The observed volume loss for each tunnel was around 1%. The measured settlement of the bridge was very similar to the predicted greenfield settlement at the level of the pile toes.

Figure 2 illustrates the twin 8.2 m OD CTRL tunnels constructed very close beneath the toes of both driven

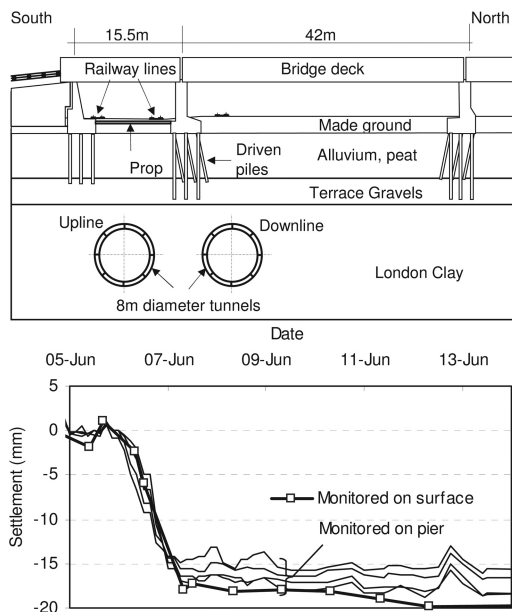


Figure 1. Tunnelling for CTRL beneath end-bearing piles at Renwick Road Bridge (Jacobsz et al. 2005).

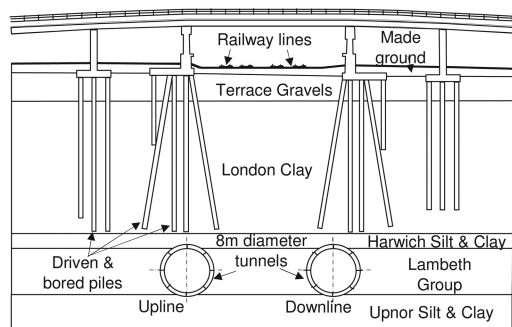


Figure 2. Tunnelling for CTRL beneath friction piles at Ripple Road Flyover (Jacobsz et al. 2005).

and bored piles in London Clay supporting the Ripple Road Flyover. The closest pile toe is only 1 m above the tunnel crown. The piles are acting primarily as friction piles, with only a very small endbearing component. As a precaution the Terrace Gravels beneath the pile caps were grouted. Both tunnels were constructed with observed volume losses of less than 1%. The measured pile settlements were 8 mm above the Upline tunnel and 10 mm below the Downline tunnel; these were very similar to the settlements at the ground surface at the locations of the pile caps. Similar behaviour was observed for the A406 viaduct supported by friction piles constructed as bored piles mainly in very stiff to hard clays, illustrated in Figure 3.

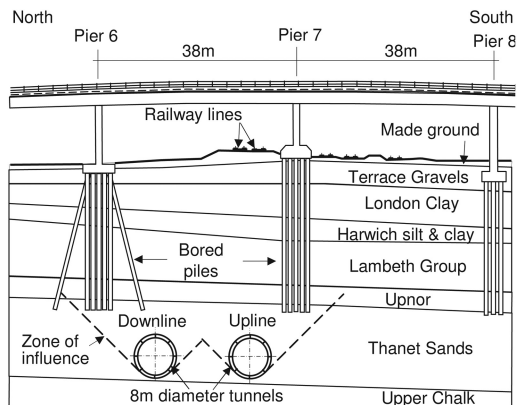


Figure 3. Tunnelling for CTRL beneath friction piles at A406 viaduct (Jacobsz et al. 2005).

## 2.2 Crossrail running tunnels, UK

Twin running tunnels of 7.1 m OD were constructed for the Crossrail project in London using Earth Pressure Balance (EPB) TBM's. The 4–18 BBR building is framed with masonry cladding, constructed in 1932/1933, and largely consists of six storeys with a single basement. The pile foundations are mainly driven vibro piles of 432 mm diameter connected to pile caps supporting the columns of the building. The pile caps were founded on London Clay. Estimation of the pile toe depths was undertaken by means of parallel seismic and magnetometer testing, and from the known design loads. A cross-section through the tunnels and pile foundations is shown in Figure 4; the tunnels were constructed in London Clay with the crown of the tunnels within 3 m of the estimated pile toe levels.

The tunnels were constructed in London Clay. Detailed measurements were made of both the greenfield ground surface settlements and the settlements of the piled building. The greenfield measurements indicated the volume losses for the Westbound (WB) tunnel, which was constructed first, to be 0.46%; in the case of the Eastbound (EB) tunnel, constructed second, the observed volume loss was 1.02% (Williamson, 2014). The corresponding values of the trough width parameter  $K$  were 0.42 and 0.59.

The observed building settlement was found to be very similar to the greenfield ground surface settlement, as shown in Figure 5.

## 2.3 Crossrail station tunnels, UK

Station tunnels for the Crossrail project were constructed using sprayed concrete linings. A piled building influenced by such tunnelling is shown in relation to the layout of the tunnels in Figure 6. The building consists of two separate four storey structures (an 'L-shaped' part and a curved part) constructed in 1996 comprising load bearing masonry. The

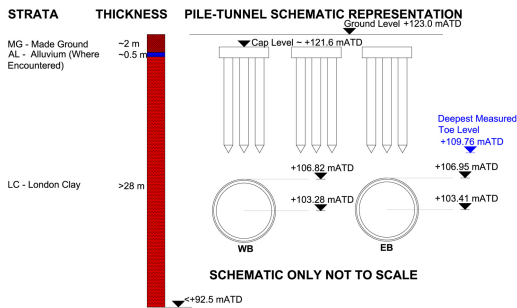


Figure 4. Tunnelling beneath 4–18 BBR piled building for Crossrail, London (Williamson 2014).

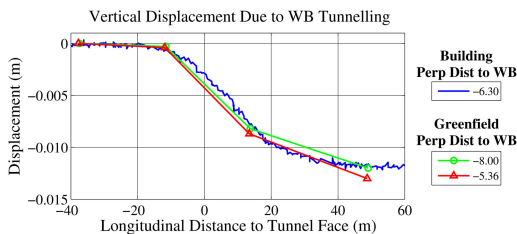


Figure 5. Comparison of observed settlement of 4–18 BBR piled building and greenfield ground surface settlement caused by westbound tunnel construction for Crossrail, London (Williamson 2014).

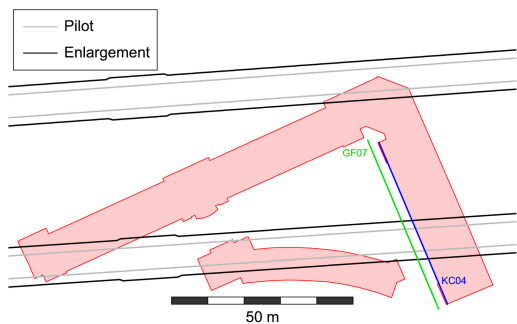


Figure 6. Layout of piled building KC in relation to station tunnels on Crossrail project.

building is supported by 350 mm diameter continuous flight auger (CFA) piled foundations supporting 500 mm  $\times$  600 mm deep reinforced concrete ground beams (with some local variation) upon which all walls are constructed. Figure 7 shows a representative cross-section through one of the 10.7 m diameter platform tunnels (showing the 6.3 m diameter pilot tunnel) and the building's pile foundations; the tunnels were constructed in London Clay with the crown of the tunnels very close to the pile toe levels.

Observed greenfield volume losses for the pilot tunnel and subsequent enlargement were 1.29% and 1.22% respectively. As for the 4–18 BBR piled building data presented in section 2.2, a typical observed

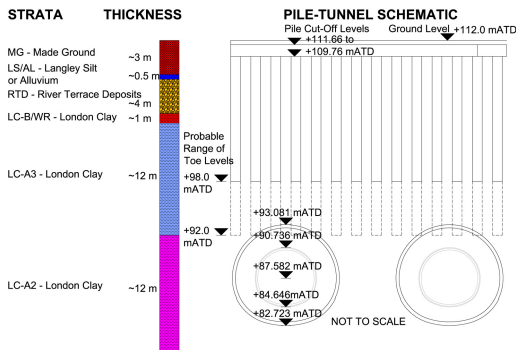


Figure 7. Tunnelling beneath KC piled building for Crossrail, London (Williamson 2014).

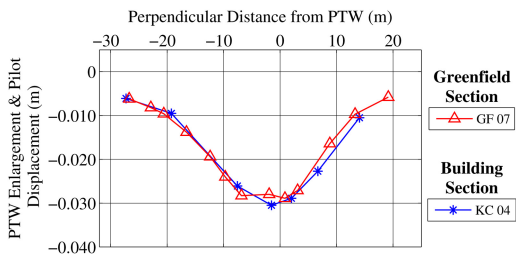


Figure 8. Comparison of observed settlement of KC piled building and greenfield ground surface settlements caused by tunnel construction for Crossrail station, London (Williamson 2014).

building settlement profile for the KC piled building was found to be very similar to the greenfield ground surface settlement profile, as shown in Figure 8. There is very little difference in the shape, magnitude or width of the settlement trough and the building displacement closely follows the greenfield ground surface settlement profile; the building exhibits fully flexible behaviour.

## 2.4 Field trials

Full scale field trials were conducted on the Second Heinenoordtunnel (Kaalberg et al. 2005, Van Hasselt et al. 1999, Bakker et al. 1999). The field trials were conducted in strata consisting of a layer of 4 m of soft clay underlain by fine sand. The twin tunnels were 8.3 m OD with a centre to centre spacing of 16.3 m constructed using a slurry tunnel boring machine. The cover above the tunnel varied between 12 and 13 m. The piles were driven within 2 m diameter clay columns pre-installed to simulate the 10–13 m of soft clay in Amsterdam. 130 mm timber and 250–350 mm concrete square piles, either as single piles, pairs of piles or pile groups, were driven in various locations between  $0.25D_t$  and  $2.5D_t$  from the tunnels (each of diameter  $D_t$ ). The piles were loaded to give factors of safety of 1.5 and 2.0 for the timber and concrete piles respectively. The results showed significant movements due to stress relief only at pile toe distances

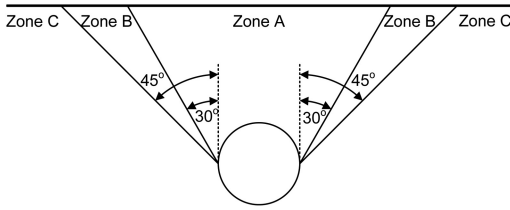


Figure 9. Influence of pile toe locations on observed pile settlements in Second Heinenoordtunnel field trials (Kaalberg et al. 2005).

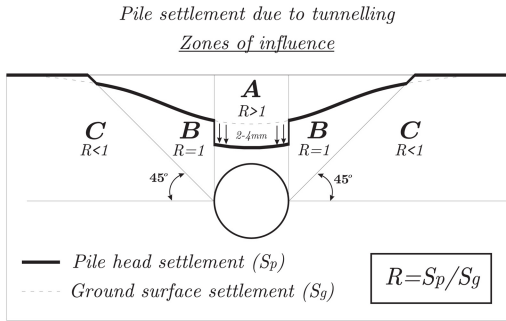


Figure 10. Influence of pile toe locations on observed pile settlements in CTRL field trials (Selemetas et al. 2005).

from the tunnel extrados of  $<0.25D_t$ . Figure 9 shows the influence of the pile toe location on the induced settlement with results as follows:

1. Zone A – Piles will move equal to, or slightly more, than the surface level settlement.
2. Zone B – Piles will move equal to the surface level settlement.
3. Zone C – Piles will move less than the surface level settlement.

Field measurements of the effects of tunnelling beneath piles were also reported, for the CTRL project in London, by Selemetas et al. (2005) and Selemetas (2005). The tunnels were twin bored Earth Pressure Balance (EPB) machines of 8.15 m OD ( $D_t$ ) at a centre to centre distance of 16.0 m and at a depth of 18.9 m to tunnel axis ( $z_t$ ). Four 480 mm diameter piles were constructed; two were friction piles and two were end-bearing piles. All the piles were constructed by driving a steel tube into the ground, excavating the soil inside, filling the cavity with concrete, removing the tube and placing the reinforcing cage.

The piles were loaded to 50% of their ultimate design capacity and the load was maintained with hydraulic jacks attached to the kentledge reaction platform. The observed pile settlements were very small (a few millimetres) due to the low volume losses experienced (0.2% and 0.5% for the first and second tunnels respectively). The results of the field trial are summarised in Figure 10, in a similar diagram to that of Figure 9 presented by Kaalberg et al. (2005).

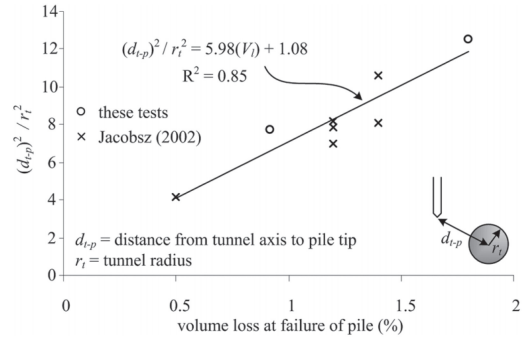


Figure 11. Observed tunnel volume loss at pile failure (taken as 20 mm at prototype scale) in relation to the normalised distance of the pile toe from the tunnel centrifuge models of tunnelling beneath driven/jacked piles in sand (Marshall & Mair 2011).

### 3 CENTRIFUGE MODELLING OF TUNNELLING BENEATH PILE FOUNDATIONS

#### 3.1 Previous centrifuge studies

Bezuijen & Van der Schrier (1994) and Hergarden et al. (1996) describe a series of centrifuge experiments investigating the effects of tunnelling beneath piles. Prior to the tunnel volume loss phase the model piles were driven in flight through a clay layer to found in an underlying sand layer. The following results were noted:

1. The stress reduction due to the tunnel cavity, resulting in the change in principal stress direction and its interaction with the existing driven pile stress bulb in the sand layer, was the main cause of settlement and reduction in base capacity.
2. Generally large settlements occur when the pile toes are within 0.25 to 1.0  $D_t$  of the tunnel extrados in any geometric configuration.
3. Settlements of piles with toes greater than 2.0  $D_t$  from the tunnel showed little displacement.

Centrifuge tests on the effects of tunnelling beneath driven/jacked piles and pile groups in uniformly graded silica sand were reported by Jacobsz (2002) and Jacobsz et al. (2004). Similar tests on driven/jacked piles were reported by Marshall & Mair (2011) and Marshall (2012). These were conducted with tunnelling movements conducted under plane strain conditions and the piles installed along a 'frictionless' plane of symmetry of a perspex window, thereby enabling Particle Image Velocimetry (PIV) (White et al. 2003) to measure soil and pile displacements. Figure 11 shows the volume loss at pile failure (taken as a settlement of 20 mm at prototype scale) in relation to the normalised distance of the pile toe from the tunnel; results from Jacobsz (2002) are also shown. The linear relationship with the square of the normalised distance from the tunnel axis is consistent with cylindrical cavity contraction theory, which predicts

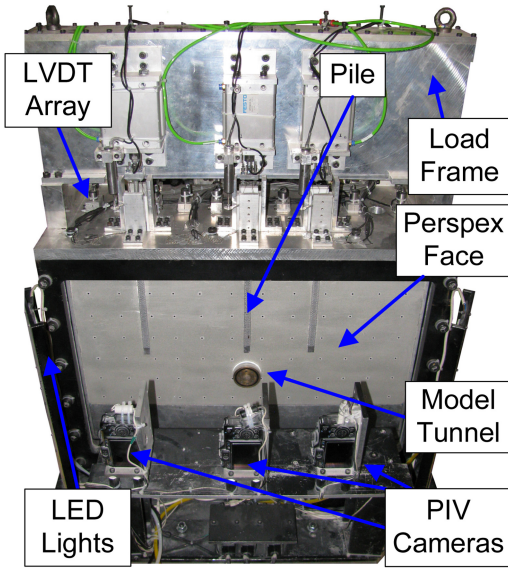


Figure 12. Centrifuge models for investigating effects of tunnels on bored piles in clay (Williamson 2014).

a reduction in stress with the square of the distance from the cavity (tunnel). Marshall (2012) extends this to analyse the volume loss at which pile base capacity for end-bearing piles would be expected to be significantly affected by cavity contraction in sand.

Ng et al. (2013) describe a series of experiments to simulate the 3D aspects of tunnelling on a bored pile in sand in the centrifuge. The tests investigated the influence of twin tunnelling either side of the pile. In cases where the pile toe was above the tunnel, the pile load before and after the tunnelling works was found to be nearly identical, though varying as the tunnel ‘passes’ the pile location for the first tunnel. Larger variation from the initial load was observed as the second tunnel ‘passes’ with both the soil settlements and stress variation increasing.

### 3.2 Centrifuge tests on bored piles in clay

Centrifuge model tests of the effects of tunnelling beneath bored piles in clay have been reported by Williamson (2014). The test set-up is illustrated in Figure 12. A greenfield package was first used to investigate the detailed ground movement mechanisms for the tunnel construction in stiff clay. Speswhite kaolin clay was consolidated to 800 kPa in a consolidometer, the model tunnel was then installed, and the clay was then allowed to swell on the centrifuge at 75 g with the pressure in the tunnel maintained equal to the total overburden pressure. The tunnel consisted of an inner brass mandrel, with a 1 mm thick latex sleeve on the outside. The tunnel cavity between the mandrel and the latex sleeve was filled with water.

After the clay had swelled and reached equilibrium (after approximately 10 hours) the tunnel volume loss

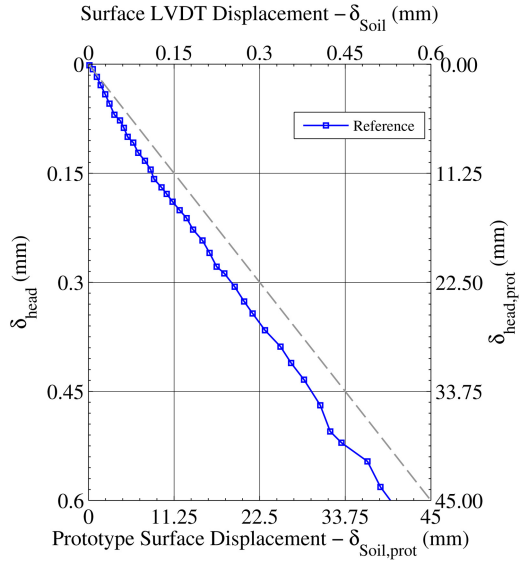


Figure 13. Comparison of pile head settlement and ground surface displacement for a centrifuge model test (Williamson 2014).

was simulated by extracting well-defined volumes of water from the annulus surrounding the tunnel. For the pile-tunnel test package (Figure 12) the piles were semi-circular in cross-section, and installed up against the perspex window (with measures taken to reduce the friction to very low values). Realistic pile loads were applied to the pile heads after the swelling clay had reached equilibrium. Separate pile load tests at 75 g were also undertaken to establish the detailed load-displacement behaviour of the piles.

Four different pile-tunnel tests were undertaken as follows:

1. A reference test (reported in this paper)
2. A test to investigate the effect of a lower pile factor of safety
3. A test to investigate the effect of lower soil strength and stiffness
4. A test to investigate the effect of pile offset from the tunnel

Figure 13 illustrates the comparison of pile head settlement and ground surface displacement for the reference test for tunnel volume loss value increasing steadily from 0 to 5%. The pile was directly above the tunnel crown (the pile toe being  $0.5D$  above the tunnel crown.). It can be seen that the observed pile head settlement was very similar and slightly larger than the ground surface settlement at the position of the pile head.

The observed changes in load distribution in the pile is shown in Figure 14, and the corresponding changes in shaft friction in Figure 15. The observed sub-surface displacements of both the clay and the pile for a volume loss = 2% are shown in Figure 16.

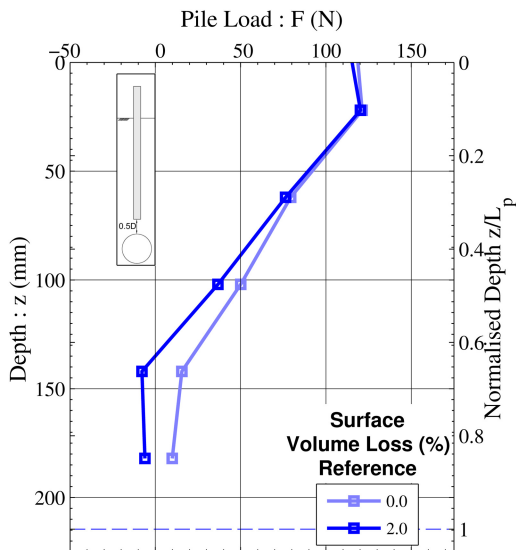


Figure 14. Observed load distribution in pile for centrifuge model tests (Williamson 2014).

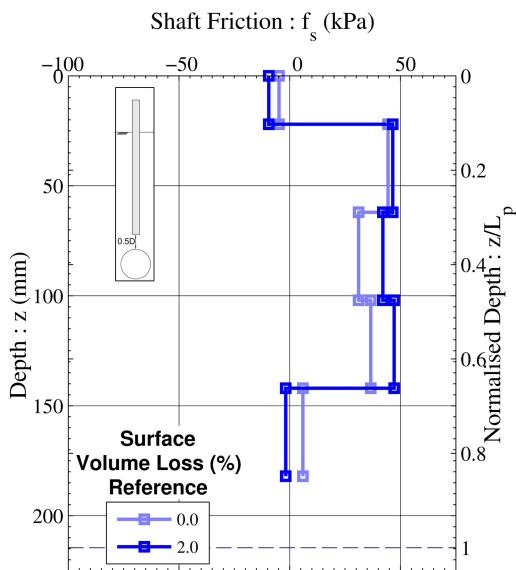


Figure 15. Observed changes in shaft friction distribution in pile for centrifuge model test (Williamson 2014).

The principal conclusions from the centrifuge model testing reported in this paper are as follows:

1. Piles above the tunnel centreline in response to tunnel volume loss show displacements greater than the soil surface settlement at the pile head.
2. The piles show relatively small changes in load when subjected to tunnelling induced settlements.
3. Piles show a reduction in skin friction when subjected to negative relative displacements and an

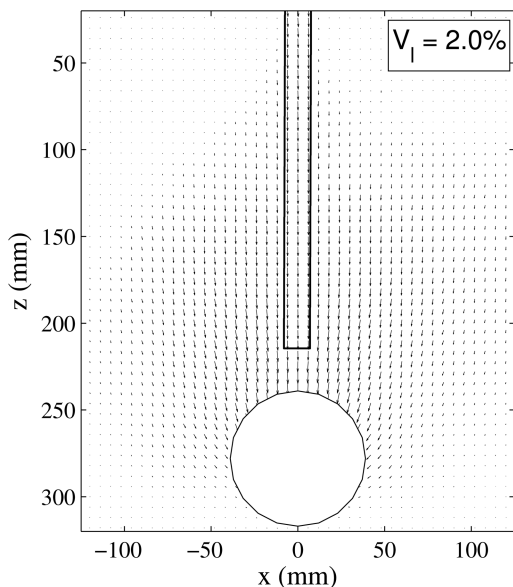


Figure 16. Observed sub-surface displacements for volume loss = 2% (Williamson 2014).

increase in skin friction when subjected to positive relative displacement.

4. Pile failure does not occur, even at high tunnel volume loss. The pile simply experiences increasing settlement so that sufficient positive friction is generated to maintain equilibrium.
5. There is little or no loss of capacity of the piles, hence the concept of ‘loss of capacity’ is not generally applicable. In cases where the end-bearing component is a significant element of the working load of the pile, there may be some reduction of this end-bearing component associated with the tunnel volume loss; however the consequence is likely to be settlement of the pile in order to remobilize this end-bearing component.

## 4 DEEP EXCAVATIONS

### 4.1 Field measurements in Amsterdam (Korff 2012, Korff & Mair 2013a, Korff & Mair 2013b)

An important difference between tunnelling and deep excavations in relation to their effects on piled foundations is the ground settlement profile. In the case of tunnelling the ground settlement generally decreases from the tunnel up to the ground surface, whereas in the case of deep excavations the ground settlement generally decreases from the ground surface with depth.

Similar to the case of tunnelling beneath piles, the Amsterdam case histories referred to in this paper relate to deep excavations adjacent to buildings on pile foundations for which the depth of excavation extends significantly below the pile toes. A typical cross-section through a station (Ceintuurbaan) for the



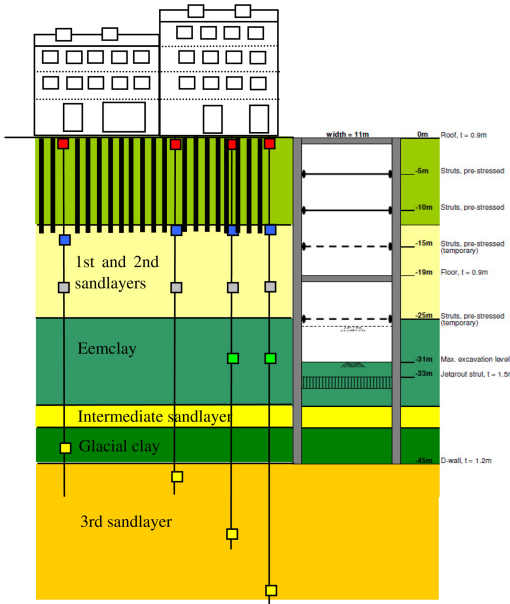


Figure 17. Cross-section through Ceintuurbaan station, Amsterdam (Korff & Mair 2013a).

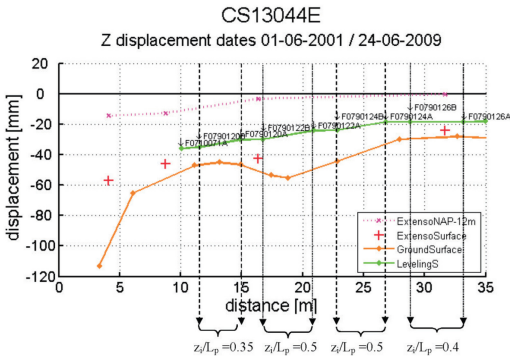


Figure 18. Observed settlement of piled building and greenfield ground surface settlements and settlements at pile toe levels for Govert Flinckstraat caused by construction of Ceintuurbaan station, Amsterdam (Korff 2012, Korff & Mair 2013b).

North South Metro line in Amsterdam is shown in Figure 17. Many of the buildings are founded on timber piles driven through approximately 12 m of soft Holocene clay to found in the first sand layer. Two sections relating to this station are shown in Figures 18 and 19. Figure 18 shows the building displacements (LevellingS) compared to the soil displacements at the ground surface (GroundSurface) and pile toe level (ExtensioNAP-12m). The building settlement is equal to the soil settlement at approximately  $0.3-0.5 L_p$  (where  $L_p$  = pile length); within the Holocene soft clay a linear settlement profile between the ground surface and the first sand layer (on which the piles are founded) has been assumed.

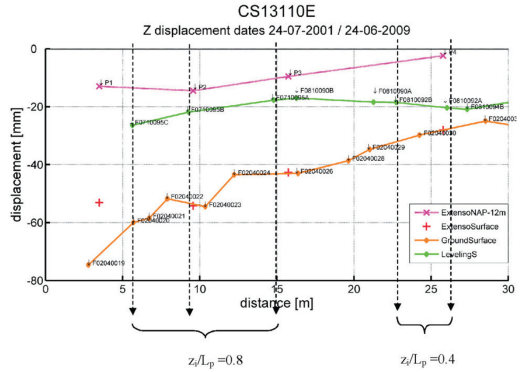


Figure 19. Observed settlement of piled building and greenfield ground surface settlements and settlements at pile toe levels for Ferdinand Bolstraat 95 and 1e Jan van der Heijdenstraat 90-92 caused by construction of Ceintuurbaan station, Amsterdam (Korff 2012, Korff & Mair 2013b).

Correspondingly, Figure 19 shows the response of a building founded on more modern pile foundations comprising old timber piles with renovation steel piles. For the renewed steel pile foundations, the depth at which the pile and soil settlements are equal is found to be approximately  $0.8-1.0L_p$ .

## 5 NUMERICAL MODELLING, ANALYTICAL METHODS AND EMPIRICAL MODELS USED IN PRATICE

### 5.1 Numerical modelling

Numerical modelling of tunnelling beneath piles in 3D has been reported by a number of authors including Mroueh & Shahrour (2002), Yoo & Kim (2008), Yoo & Wu (2012), Lee (2012) and Lee (2013). The work has compared the effects of single piles with pile groups and has generally shown the effect of shielding or pile interaction to be beneficial in reducing pile settlements and axial loads. Lee (2013) showed a markedly different result for pile groups entirely within the zone of influence (where the displacement profile is always increasing with depth) with much greater group displacement than for single piles.

### 5.2 Analytical modelling

The use of a two-step approach method (TSAM) for estimating the effect of tunnelling movements on pile displacements and axial load distribution is a popular analytical technique. The greenfield sub-surface soil movements are estimated using either elastic settlement models, empirical models or FE models and these are applied to a boundary element (Chen et al. 1999; Loganathan et al. 2001; Xu & Poulos 2001 and Basile 2012) or t-z model (Kitiyodom et al. 2005; Huang et al. 2009; Zhang et al. 2011; Korff 2012; Zhang et al. 2013; Williamson 2014) of the pile.



Boundary element methods have generally shown increased pile load and settlements when compared with t-z models for single piles, due to node-node interaction effects. Both methods have shown that the effects of tunnelling on single piles are generally conservative when compared with those of pile groups, though the majority of analyses have dealt with tunnelling adjacent to and not beneath piles.

The importance of limiting skin friction to these models have been shown by Chen et al. (1999), Devriendt & Williamson (2011), Zhang et al. (2013) and Williamson (2014) to prevent overestimation of axial response both in terms of load and settlement.

Recent work by Basile (2012), Zhang et al. (2011), Zhang et al. (2013) and Korff (2012) have applied non-linearity to these problems in an attempt to better model the pile behaviour both upon initial loading and secondary soil induced loading. Basile (2012) showed reduced axial pile loading due to the non-linear soil modelling when compared with that of linear elastic soil models.

### 5.3 Empirical modelling

Simplistic bounding of the settlements caused by tunnelling beneath piles is often applied in engineering practice. This is most commonly applied to tunnelling beneath driven piled foundations, where the greenfield displacements at the pile base is taken as the pile head settlement, as shown by Jacobsz et al. (2005). The other bound would generally be the greenfield displacement at the pile head.

Such approaches are generally conservative for displacements of single piles as the maximum of the chosen bounds is taken as the pile head settlement. Though conservative, such an approach would result in the same predicted displacements of piles with both high and low factors of safety, which has been shown based on centrifuge modelling (Lee & Chiang 2007) and the TSAM above to be inappropriate for piles deriving a large component of their load from shaft friction.

## 6 CONCLUSIONS

Very little is known about the effects of tunnelling beneath piled foundations, and in particular how much settlement is caused. Case histories referred to in this paper indicate the following:

1. There is a clear distinction between a pile that is primarily end-bearing and one that is primarily a friction pile.
2. For end-bearing piles the settlement is likely to be similar to the greenfield settlement of the ground at the level of the pile toe.
3. For friction piles the settlement is generally observed to be similar to the settlement of the ground surface at the position of the pile head. This was also found in the two recent case histories from

the Crossrail project in London presented in this paper.

Centrifuge model testing by Williamson (2014) has elucidated the behaviour of single bored piles in stiff clay subjected to tunnel construction beneath the pile toes, as follows:

1. The centrifuge modelling shows that a single pile above the tunnel centreline settles by a greater amount than the soil surface settlement at the pile head.
2. There are only relatively small changes in load distribution in the pile.
3. The centrifuge modelling clearly show a reduction in skin friction acting on a pile when it is subjected to negative relative displacements and an increase in skin friction when it is subjected to positive relative displacement.
4. Pile failure does not occur even at high tunnel volume loss. There is little or no loss of capacity of the piles.

Numerical modelling of tunnelling beneath piles has generally shown beneficial effects for pile groups when compared with single piles, with the exception of pile groups entirely within the zone of influence.

The TSAM approach to modelling piles has generally been validated against scenarios of tunnelling adjacent to piles. Therefore some caution should be applied when these methods are used for the case of tunnelling beneath piles, especially regarding group versus single pile effects, particularly given the results from FE models.

The use of bounding between the maximum and minimum greenfield settlement is generally conservative.

Deep excavations adjacent to buildings on pile foundations, where the depth of excavation extends significantly below the pile toes, are more likely to cause settlements of the piles rather than inducing significant bending moments. As shown by the case histories in Amsterdam (Korff 2012; Korff & Mair 2013b) summarized in this paper, such piled buildings settle by an amount between the settlement at the ground surface and the value at the pile toe. In the case of old timber piles the building settlement was found to be equal to the soil settlement at approximately  $0.3-0.5L_p$  (where  $L_p$  = pile length); for newer steel pile foundations the depth at which the pile and soil settlements are equal was found to be approximately  $0.8-1.0L_p$ .

## ACKNOWLEDGEMENTS

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