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# The response of full-scale piles to tunnelling

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**ABSTRACT:** The construction of the new Channel Tunnel Rail Link (CTRL) in the UK provided a unique opportunity to monitor the response of full-scale piles to tunnelling-induced movements. This paper presents the results of a full-scale trial, which took place during the construction of CTRL Contract 250 in Dagenham, Essex, UK. The contract involved the construction of 5.2 km of twin 8 m diameter bored tunnels using a Lovat Earth Pressure Balance shield with tail-skin grouting. Well ahead of tunnel excavation four instrumented driven cast-in-situ reinforced concrete piles were installed above and at an offset from the two tunnels. All four piles were loaded using kentledge to loads of up to 50% of their ultimate carrying capacity. The intention was to maintain these loads during tunnelling which at the site of interest took place through London Clay. The study also included the installation of several surface settlement monitoring stations to measure the profile of 'greenfield' ground surface displacement. This paper discusses the resulting changes in the pile base load and the associated pile settlement due to tunnel construction. The comparison of ground and pile surface settlements due to tunnelling indicated that three zones of influence exist around a tunnel in which pile settlement can be correlated to 'greenfield' ground surface settlement.

## 1 INTRODUCTION

### 1.1 Introduction

The construction of the new Channel Tunnel Rail Link (CTRL) in the UK provided a unique opportunity to monitor the response of full-scale piles to tunnelling-induced movements. This paper presents the results of a full-scale trial, which took place during the construction of CTRL Contract 250 in Dagenham, Essex, UK. The study involved the installation and loading of four instrumented piles along the route of two 8 m diameter bored tunnels. The overall aim of the study was to monitor the response of the four piles and the surrounding ground during tunnel construction and compare the 'greenfield' ground response with the corresponding pile behaviour.

The objective of this paper is to present the resulting pile settlement due to tunnelling in comparison with the corresponding ground surface settlement. The paper also discusses the changes in the pile base load during tunnel construction.

### 1.2 Earlier work

The subject of tunnelling near piled foundations has received particular attention lately. The North/South Line in Amsterdam and the proposed Crossrail in London are project where there is a need to gain better insights into the response of piled structures to tunnelling. Although there is considerable experience of the assessment of tunnelling in 'greenfield' ground and buildings founded on shallow foundations there is a scarcity of well-documented studies showing the influence of tunnelling on piled foundations. Two notable exceptions include the Heinenoord full-scale trial near Rotterdam (Kaalberg et al., 1999) and the study by Coutts and Wang (2000).

In the Heinenoord study the response of 38 timber piles and 18 concrete piles was monitored during construction of 8.3 m diameter twin tunnels through both Holocene deposits (layers of soft clay and peat) and Pleistocene dense sand. Field observations showed that pile settlement could be classified into three categories, depending on the position of the pile toe relative

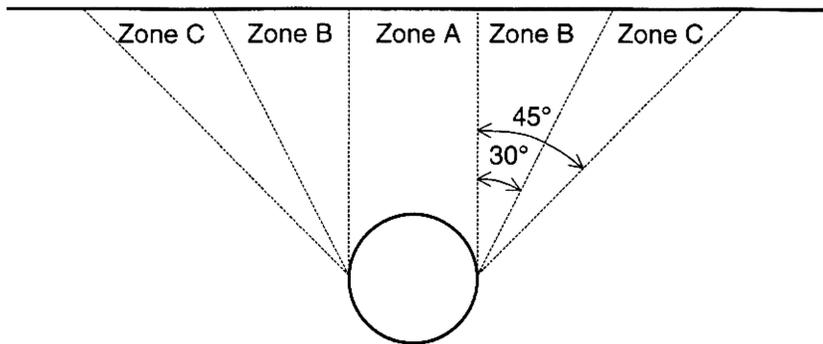


Figure 1. Zones of pile movement around a tunnel driven through soft clays and dense sands after the Heinenoord full-scale trial (Kaalberg et al., 1999).

to the tunnel axis (see Figure 1). In particular piles with their bases in Zone A settled more than the ground surface, piles in Zones B settled approximately by the same amount as the ground surface and piles founded in Zones C settled less than the ground surface.

Jacobsz et al. (2001) describe the results from a number of centrifuge model tests investigating the form of these zones of influence for the case of tunnelling near axially loaded piles driven in dry sand. Similar zones of influence in which pile settlements could be correlated with surface movements were identified from these tests.

Other model studies include the work of Bezuijen and Van der Schrier (1994) and Loganathan et al. (2000). The subject has also been studied numerically (Vermeer and Bonnier, 1991; Mroueh and Shahrou, 2002), and analytically (Chen et al., 1999).

## 2 PROJECT DETAILS

### 2.1 Tunnelling details

CTRL Contract 250 involved the construction of 5.2 km of twin 8 m diameter bored tunnels using two Lovat Earth Pressure Balance (EPB) machines with tail-skin grouting. The length of the shields, i.e. the distance between the face of the Tunnel Boring Machine (TBM) and the last segment constructed was approximately 8 m (this length varies depending on the operation of the propulsion jacks up to a maximum of 10 m). The tunnel lining consisted of prefabricated reinforced concrete segments 1.5 m in length.

The two 8 m diameter tunnels were excavated at separate times. The first TBM (Up-Line) passed beneath the monitoring section one month prior to the second TBM (Down-Line). The spacing of the two tunnel centre-lines at this section was 16 m and the depth to the tunnel axes was 18.9 m. At the site tunnelling took place through London Clay.

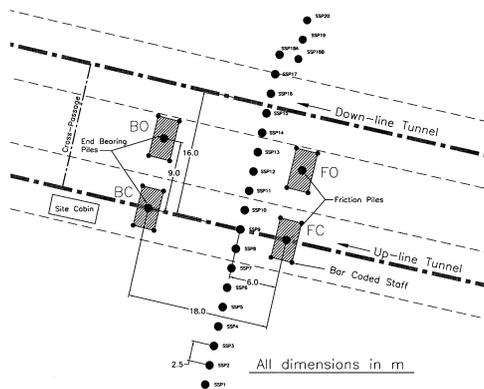


Figure 2. Plan view of instrumented piles and surface settlement points (SSPs) relative to tunnel alignments.

### 2.2 Ground conditions

The ground conditions consist of 3 m of Made Ground overlying about 4.5 m of soft Alluvium of fibrous peat and silty clay. Beneath this Alluvium lies 3.7 m of dense Terrace Gravels with Standard Penetration Test (SPT) values up to  $N = 50$ . The Terrace Gravels overlie about 15 m of very stiff London Clay. The groundwater level is 4 m below the ground surface.

### 2.3 Instrumentation details

At a site situated about 1 km from the TBM launch area, four instrumented piles were installed well in advance of tunnelling activities. Figure 2 shows the surface positions of the four piles relative to the twin tunnel alignments. Also shown is the line of 21 surface settlement points (SSPs) installed perpendicular to both tunnel axes. The SSPs consisted of extended BRE sockets (BRE Digest 386, 1993) embedded into a 1.0 m deep concrete column (~150 mm in diameter).

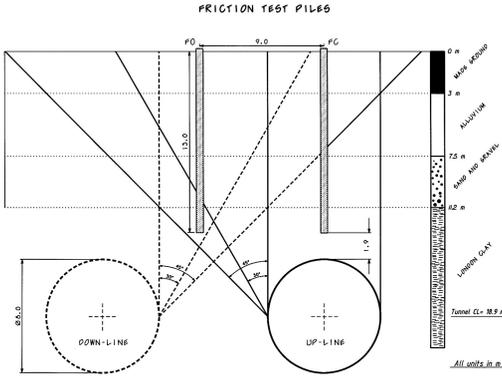


Figure 3. Cross-section of 'friction' piles relative to tunnels.

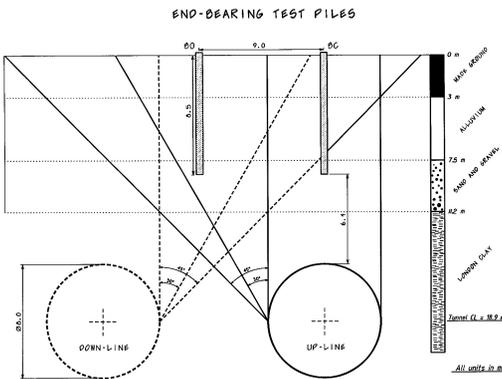


Figure 4. Cross-section of end-bearing piles relative to tunnels.

The vertical displacement of the SSPs was measured by precise levelling using a digital Leica NA3003 precise level with a 2 m invar bar-coded staff.

The piles were driven cast-in-situ with a nominal diameter of 480 mm. Two of these piles were end-bearing (BC and BO) in the Terrace Gravels with a total length of 8.5 m, while the other two piles, referred to as 'friction' piles, (FC and FO) were 13 m in length and founded in London Clay. The cross-sections on Figures 3 and 4 show the positions of the pairs of end-bearing and friction piles, respectively, relative to the two tunnels and soil stratigraphy. Piles BC and FC were installed directly above the Up-Line tunnel centre-line and piles BO and FO at an offset of 9 m from it. These pile locations were strategically selected to investigate the zones of influence described by Jacobsz et al. (2001).

One month prior to the arrival of the first TBM all four piles were loaded up to approximately 50% of their ultimate capacity using kentledge reaction platforms. Four automatically controlled hydraulic pumps

were used to maintain constant pile loading during tunnel construction. Each of the end-bearing piles was loaded with 650 kN and a load of 240 kN was applied to each of the 'friction' piles.

The displacement of each pile relative to the ground surface was monitored by means of four Potentiometric Displacement Transducers (PDTs) set up at the head of each pile. The PDTs were mounted on reference beams supported on stakes driven a minimum of five pile diameters from each pile. Changes in the level of the reference beams during tunnelling were monitored by precise levelling onto bar-coded strips attached to the stakes (see Figure 2).

The pile base load cells used in this study have been developed by BRE (see, for example, Crilly and Driscoll, 2000). Each load cell consists of three or four vibrating wire (VW) sensing units housed between two steel plates. The VW units are covered with a soft rubber membrane which forms a break in the concrete enabling the load to be transmitted entirely through the sensing units. The load cells are pre-cast into a concrete block of 400 mm diameter and attached to the bottom of the reinforcement cage. Near the base and around the circumference of the load cell there is an inflatable tube which is pressurised once the pile is installed in order to prevent any transfer of load through the pile concrete surrounding it.

### 3 MONITORING RESULTS

#### 3.1 Ground surface settlement

Figures 5a and 5b show the profiles of transverse surface vertical displacement due to construction of the Up-Line and Down-Line tunnels. In both tunnelling events the settlement profiles can be well described by the form of a Gaussian curve. These troughs relate to ground surface settlements after the TBM face had passed the monitoring section by more than 50 m. The construction of the Up-Line and Down-Line tunnels caused maximum settlements of 5.2 mm and 12.7 mm respectively. The difference between the two values is probably associated with the difference in the applied EPB face pressures. The volume loss values for the Up-Line and Down-Line settlement troughs shown below were 0.2% and 0.5% respectively. These values of volume loss are typical for good construction practice using EPB shield tunnelling in London Clay.

#### 3.2 Pile settlement

This section presents the pile settlement during the Up-Line tunnel construction expressed as the difference between the pile head displacement and the surrounding ground surface displacement. Figure 6 shows the development of this Differential Pile Settlement (DPS) for the four piles (FC, FO, BC and BO)

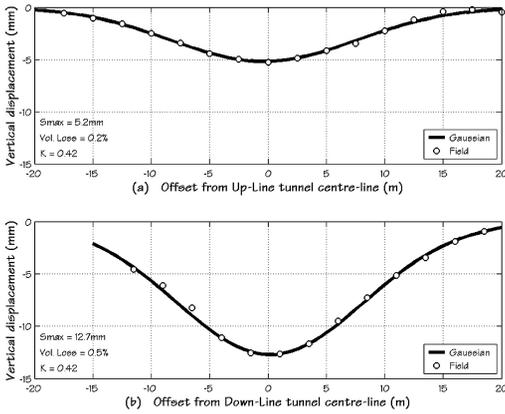


Figure 5. Transverse vertical displacement profiles from precise levelling on Surface Settlement Points (SSPs) due to construction of (a) Up-Line and (b) Down-Line tunnels.

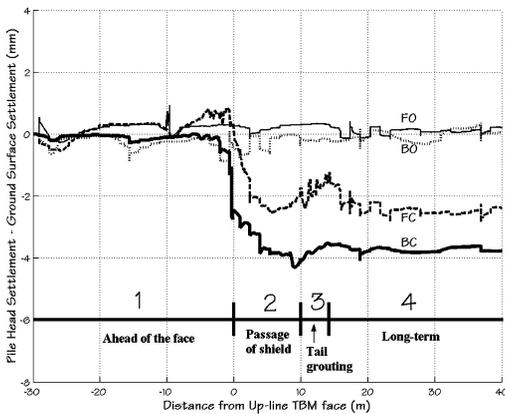


Figure 6. Development of Differential Pile Settlement (DPS) during the Up-Line tunnel construction.

with changing distance between the TBM face and the piles. The four lines of data correspond to the average of the readings recorded by the PDTs installed at each pile head. Close inspection of the field measurements indicates some diurnal movements, independent of tunnelling activity, which are primarily due to thermal effects. The response of the four piles is discussed below in relation to four construction phases, the extent of which is also shown in Figure 6, namely (1) ahead of the face, (2) the passage of the TBM shield, (3) tail grouting, and (4) the long-term effects.

The first observation to be made here is that piles FO and BO (at an offset of 9 m from the tunnel centre-line) experienced essentially no DPS during tunnel construction. For these piles the ratio of pile head settlement to ground surface settlement, defined here as  $R$ , was for most practical purposes equal to 1. In

contrast piles FC and BC (directly above the tunnel centre-line) settled more than the ground (i.e.  $R > 1$ ) following the passage of the TBM face. These piles showed some distinctive responses during the four construction phases which are now discussed.

Pile FC initially experienced some slight differential heave at a distance of about 4 m from the TBM face followed by a slight DPS just before the TBM face passed underneath the pile. This initial heave is hardly surprising in view of the clearance of only 1.9 m between the pile tip and the tunnel crown (see Figure 3) and the high EPB pressures applied at the face of the excavation. In comparison pile BC, with a clearance of 6.4 m from the tunnel crown, showed only some slight DPS at a distance of about 2 m from the TBM face. The EPB type of tunnelling is shown here to be very efficient in minimising the amount of DPS ahead of the face. However, when the TBM face is just beneath the piles a sudden increase of DPS takes place.

During the second phase corresponding to the passage of the TBM face, piles FC and BC settled more than the ground. This DPS took place over a distance of about 10 m, corresponding to the length of the EPB shield. During this stage both piles experience a reduction in their base load which is compensated by mobilisation of reserve shaft capacity, hence resulting in differential pile settlement relative to the ground. In particular, Pile FC (with a length of 13 m) experienced 2.5 mm of DPS while pile BC (with a length of 8.5 m) settled 4 mm in excess of the surrounding ground. This difference can be attributed partly to the different loads applied at the top of each pile and partly to the difference in the length of the piles, i.e. a longer pile would settle less to mobilise the same amount of shaft friction compared to a shorter pile of the same diameter. The results suggest that this second phase during which the shield passes beneath the pile is the most critical in terms of the impact on adjacent structures, as it induces the main differential movements.

Following the passage of the shield a sand-bentonite-cement grout was injected behind the shield under high pressure to fill the void between the most recently placed ring segment and the ground. This caused some slight differential heave of about 0.5 mm for piles FC and BC. After completion of the tail-grouting phase there was a small amount of DPS, almost bringing the piles to the same level prior to grouting. In the long-term there was essentially no DPS with time.

During construction of the Down-Line tunnel, piles FO and BO (in this case at an offset of 7 m from the tunnel centre-line) experienced zero differential pile settlement, i.e. the settlement of the piles was identical to the vertical displacement of the surrounding ground ( $R = 1$ ). In the case of piles FC and BC, located at an offset of 16 m from the tunnel centre-line, the surrounding ground settled slightly more than

the piles (i.e.  $R < 1$ ) indicating some negative shaft friction along the length of these piles.

### 3.3 Pile base load changes

The overall pile response to tunnelling was found to be very sensitive to changes in the pile base load which was strongly influenced by the position of the pile base relative to the tunnel axis. Although the intention was to maintain constant loads to the top of the piles during tunnel construction it was found that temperature changes and mostly differential pile settlement and TBM tail grouting gave rise to variations in loading at the top of the piles. The two cases that are examined here are piles FC and BC which were directly above the Up-Line tunnel and experienced the largest changes in their base loads and differential pile settlement.

Figure 7 shows the variation of applied load at the top of the pile and base load in pile FC during the Up-Line tunnel construction. In this case the load applied at the top of the pile is shown to remain constant within  $\pm 5$  kN and this small variation does not affect the base load of the pile. The pile base load began to gradually increase from when the TBM face is about 10 m away from the pile. This increase in the base load is associated with the large TBM pressures applied at the face of the excavation. For this pile the distance between its base and the tunnel crown is just less than 2 m. The base load continued to increase up to a maximum of 25 kN when the TBM face was within a metre of the pile.

As the TBM shield passed beneath the pile there was a marked reduction in the base load of about  $-55$  kN, bringing the net change to a value of  $-30$  kN. Following this reduction in base load there was an increase of  $+40$  kN due to the grouting pressures applied behind the shield. This resulted in a net change to the base load of  $+10$  kN with the TBM face 10 m beyond the pile. With time the base load gradually reduced until it reached a steady value at a distance of 40 m from the TBM face, corresponding to a net change of  $-7$  kN.

The changes in the applied load and base load of pile BC during construction of the Up-Line tunnel are shown in Figure 8. In this case the applied load at the pile head showed some significant variations. This is particularly evident during the tail grouting stage when the applied load suddenly increased by as much as 150 kN followed by a dramatic reduction to its original value when the TBM face was about 20 m beyond the pile. These changes in the applied load had a marked influence on the base load response and therefore 'masked' some of the effects of tunnel construction at this stage. However, initially when the TBM phase approached the pile and subsequently when the shield passed beneath the pile there was a similar base load response to that of pile FC.

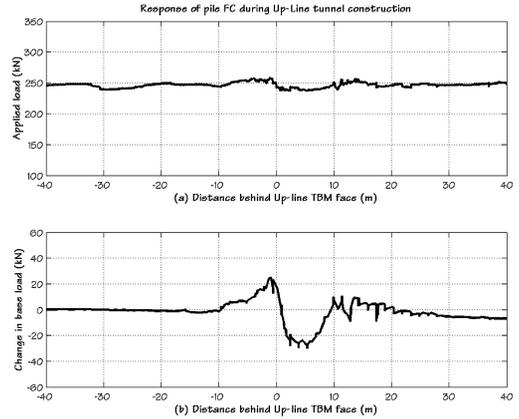


Figure 7. Change in (a) applied load at pile head and (b) base load in pile FC during the Up-Line tunnel construction.

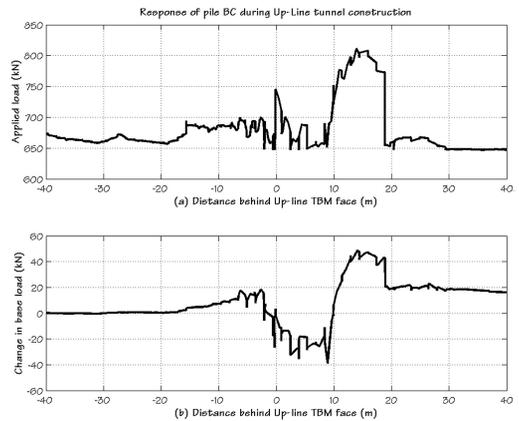


Figure 8. Change in (a) applied load at pile head and (b) base load in pile BC during the Up-Line tunnel construction.

In particular the base load in pile BC gradually increased by up to 18 kN when the TBM face was 2 to 3 metres in front of the pile. This is followed by significant reduction in the base load by  $-57$  kN as the TBM shield passed beneath the pile, resulting in a net decrease of  $-39$  kN. At this point, due to a slow response of the pile loading system at ground level, the actual applied load significantly increased due to the tail grouting pressures, resulting in an increase in the base load. Based on the response of pile FC an increase in the pile base load would be expected at this stage, although not of the same magnitude.

During the Down-Line tunnel construction the changes in the base loads of all piles were small, as shown in Figure 9. Piles FO and BO (at an offset of

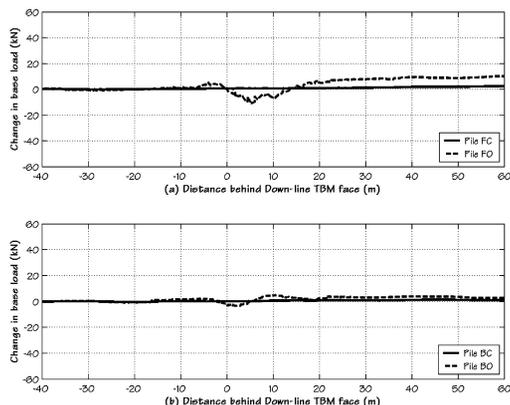


Figure 9. Change in pile base load during the Down-Line tunnel construction.

7 m from the Down-Line tunnel centre-line) showed a small reduction followed by a gradual increase in the base load bringing the load to a value slightly higher than the original value. Piles FC and BC (at an offset of 16 m from the Down-Line tunnel centre-line) showed a very slight gradual increase in their base loads with time due to negative shaft friction, induced by soil movement. This negative shaft friction and subsequent increase in the pile base load with time was slightly larger in magnitude in the case of the ‘friction’ piles FC and FO, as might be expected.

#### 4 LESSONS LEARNED

The displacements presented in this paper can be generalised in the framework shown in Figure 10. There is evidence to suggest the existence of three zones around an EPB tunnel in London Clay, similar to those presented in previous studies (see [Kaalberg et al. 1999](#) and [Jacobsz et al. 2001](#)), in which pile head and ground surface settlements can be correlated. In summary, piles with their bases located in Zone A were shown to settle 2–4 mm more than the ground surface ( $R > 1$ ). Piles with their bases in Zones B (defined by an angle of 45° between Zones A and C) settled by the same amount as the surface ( $R = 1$ ). Finally, piles with their bases in Zones C were found to settle less than the surface ( $R < 1$ ). Therefore for most practical applications reasonable predictions of pile settlement could be made by using the Gaussian curve as a reference frame.

The critical zone is Zone A in which piles are likely to settle more than the ground due to the reduction in their base load. To counterbalance this loss in the base load the piles settled in order to mobilise the required shaft friction.

It is important to appreciate that the boundaries of Zone B are simplified here by simply drawing two

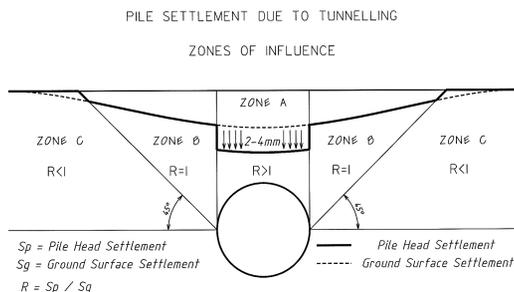


Figure 10. Zones of influence of piled settlement due to Earth Pressure Balance (EPB) shield tunnelling in London Clay.

straight lines from the spring-line of the tunnel. The angle between Zones A and C is probably a function of the shearing resistance of the soil and the tunnelling volume loss and therefore is not likely to be constant.

#### 5 CONCLUSIONS

This paper has described the results of a full-scale trial investigating the influence of close-face tunnelling on the settlement and base load of piles. Three zones of influence were identified in which pile head settlements were correlated to surface ground settlements (as shown in Figure 10):

1. Piles in Zone A settled 2–4 mm more than the ground surface.
2. Piles in Zone B settled by the same amount as the ground surface.
3. Piles in Zone C settled less than the ground.
4. The well-established Gaussian curve describing the magnitude of ground surface settlement due to tunnelling may be used as a reference frame for the assessment of pile settlement due to tunnelling.
5. Piles with their bases in Zone A experienced a marked reduction in their base loads during passage of the TBM shield of about 50 kN, accompanied by differential pile settlement.
6. Piles with their bases in Zones B and C experienced small changes in their base loads. The base loads of these piles showed a net gradual increase with time due to the ground-induced negative shaft friction.

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## REFERENCES

- Bezuijen, A. and Van der Schrier, J. S. (1994). The influence of a bored tunnel on pile foundations. *Proc. Int. Conf. Centrifuge 94*, Singapore: 681–686, Rotterdam: Balkema.
- Building Research Establishment (1993). Digest 386: Monitoring building and ground movement by precise levelling.
- Chen, L. T., Poulos, H. G. and Loganathan, N. (1999). Pile responses caused by tunnelling. *ASCE J. Geotech. and Geo-environmental Engng.* Vol. 125 (3): 207–215.
- Coutts, D. R. and Wang, J. (2000). Monitoring of reinforced concrete piles under horizontal and vertical loads due to tunnelling. In *Tunnels and Underground Structures*, (eds. Zhao, Shirlaw and Krishnan), Singapore: 541–546, Rotterdam: Balkema.
- Crilly, M. S. and Driscoll, R. M. C. (2000). The behaviour of lightly loaded piles in swelling ground and implications for their design. *Proc. Instn Civ. Engrs Geotech. Engng.*, 143: 3–16.
- Jacobsz, S.W., Standing, J.R., Mair, R.J., Soga, K., Hagiwara, T. and Sugiyama, T. (2001). Tunnelling effects on driven piles. *Proc. Int. Conf. on Response of Buildings to Excavation-Induced Ground Movements*, London: 337–348, Ciria.
- Kaalberg, F. J., Lengkeek, H. J. and Teunissen, E. A. H. (1999). Evaluatie van de meetresultaten van het proefpalenproject ter plaatse van de tweede Heinenoordtunnel (in Dutch). Adviesbureau Noord/Zuidlijn Report no. R981382, Amsterdam.
- Loganathan, N., Poulos, H. G. and Stewart, D. P. (2000). Centrifuge model testing of tunnelling-induced ground and pile deformations. *Géotechnique* 50, No. 3: 283–294.
- Mroueh, H. and Shahrouh, I. (2002). Three-dimensional finite element analysis of the interaction between tunnelling and pile foundations. *Int. J. Numer. Anal. Meth. Goemech.* Vol. 26: 217–230.
- Vermeer, P.A. and Bonnier, P.G. (1991). Pile settlements due to tunneling. *Proc 10th European Conference on Soil Mechanics and Foundation Engineering*, Florence, Vol. 2: 869–872, Rotterdam: Balkema.