Geotechnical Aspects of Underground Construction in Soft Ground, Kastner, Emeriault, Dias, Guilloux (eds)
© 2002 Spécifique, Lyon. ISBN 2-9510416-3-2

Recent Experiences of the Measurement of Tunnelling Induced Ground Movements

C. Pound & J. P. Beveridge
Mott MacDonald Ltd, St Anne House, 20-26 Wellesley Road, Croydon, Surrey, CR9 2UL, United Kingdom

ABSTRACT: The ability to predict ground movements caused by tunnelling is becoming increasingly important as more tunnels are constructed in urban areas. This paper presents measurements of the ground movements caused by tunnelling on the A20 Round Hill tunnels, which were constructed by NATM in Chalk, and on the Heathrow Express running tunnels, which were excavated by conventional shields in London Clay. The surface settlement of both tunnels was found to be well represented by gaussian curves, although the troughs for the tunnels in Chalk were narrow and represented a small volume loss. One key finding was the marked variation of volume loss over short distances in similar ground conditions and using the same construction methodology. The measurements from the Heathrow Express project also provided data on the interaction of settlement troughs from two adjacent tunnels.

1 INTRODUCTION

The prediction of ground movements is very important during the planning phase of any tunnel construction project in an urban area. This prediction is used to identify the risk of damage to adjacent structures and utilities and to assess whether the proposed construction method needs to be modified. It can also be used to highlight where mitigation measures may be necessary in advance or during tunnel construction.

The prediction of settlements is normally based on empirical methods (O'Reilly & New 1982, Macklin 1999). The method is based on settlement data from a large number of tunnels from around the world. However, the method is difficult to apply when the ground conditions or construction method is unusual or more than one tunnel is present. Many attempts have been made to use numerical methods to predict ground movements due to tunnelling but almost without exception the analyses have predicted unrealistic surface settlement troughs.

This paper presents measured settlements from two tunnels constructed using different methods and in different ground conditions.

2 A20 ROUNDHILL TUNNEL

The A20 Round Hill tunnel was constructed between 1991 and 1994 as part of the upgrading of the A20 between Folkestone and Dover, Kent. The work involved the construction of twin 11.25m diameter, 400m long tunnels in Lower Chalk using NATM techniques (Murphy, 1991). The cover varied from about 8m at the tunnel portals to a maximum 40m in the middle of the hill. The tunnels were constructed as top heading, bench and invert, with the top heading excavated along the full length of the tunnels before removal of the bench and invert with only a short delay. Both tunnels were excavated from the northern portal although short drives were constructed from the southern portals prior to tunnel breakthrough.

The Chalk was generally Grade IV and III (Spink et al 1990) with localised areas of Grade II. The face was logged on most advances, both in the top heading and in the bench, to provide data for selection of the appropriate primary support. The contract specified the range of Q values (Barton, 1974) for which each support class was designed.

Instrumentation was installed within the tunnels as part of the NATM method. This comprised combined convergence and settlement pins at changes in support class and at a pre-defined spacing thereafter. The convergence arrays were installed in the top

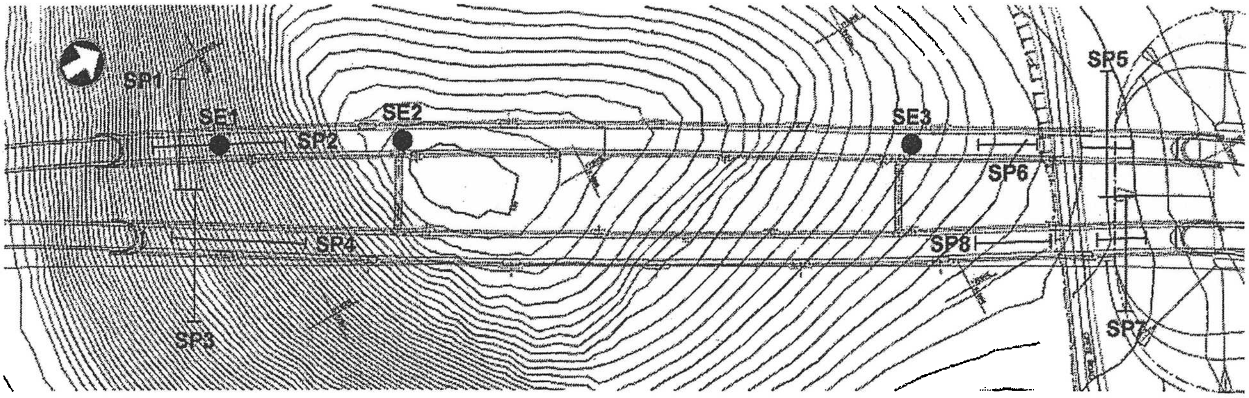

Figure 1 Location of surface monitoring

heading and later extended during bench excavation. On three sections, two nine metre long multiple point rod extensometers were installed immediately after top heading excavation. An extensometer was installed in each tunnel shoulder inclined at 60° to the horizontal and comprised rods with anchors at 3m, 6m and 9m depth from the tunnel profile.

In addition to the in-tunnel monitoring, surface settlement monitoring pins were installed in arrays above each portal and three magnetic extensometers were installed above the eastbound tunnel. The location of the surface monitoring pins and magnetic extensometers is shown in Figure 1.

The surface settlement pins were monitored generally on a weekly basis. The typical settlement on a transverse monitoring line is shown in Figure 2. Two sets of settlement data are shown; one following top heading excavation and one following excavation of the bench and invert when the tunnel was complete.

It is generally recognised that the settlement trough above tunnels follows a gaussian curve (Peck, 1969). The gaussian curve has the following form:

$$S = S_{\max} e^{-\frac{x^2}{2i^2}} \qquad (1)$$

where S is the settlement at a point x metres from the tunnel centre-line, S_{max} is the settlement above the tunnel centre-line and i is the value of x at the point of inflection of the trough. The volume loss, V_L, is defined as the area of the surface settlement divided by the cross-sectional area, A, of the tunnel. For a gaussian curve the volume loss is related to the maximum settlement by the following equation:

$$V_L = \frac{\sqrt{2\pi} i S_{\max}}{A} \qquad (2)$$

Often a trough width factor, K, is defined which is related to parameter i by the following equation:

$$i = Kz_0 \qquad (3)$$

where z_0 is the depth to tunnel axis below ground level.

Also shown in Figure 2 are best-fit gaussian curves to the settlement data. It can be seen that the gaussian curve fits the settlement data well. Table 1 shows the gaussian curve data for the transverse settlement arrays above each of the tunnel portals. At the North portal it was possible to distinguish between the settlements caused by top heading, and bench and invert excavation. However, this was not possible at the south portal because there was only a short delay between the two operations and therefore only results for the completed tunnel are presented.

Table 1. Settlement data

		North Portal		South Portal	
		East-bound	West-bound	East-bound	West-bound
Top heading	V_L	0.691	0.127	-	-
	K	0.263	0.326	-	-
Complete	V_L	0.538	0.105	0.251	0.219
	K	0.285	0.304	0.249	0.293

The data in Table 1 shows only a small variation in trough width factor, K, but there is a significant variation in volume loss, V_L. The value of K of

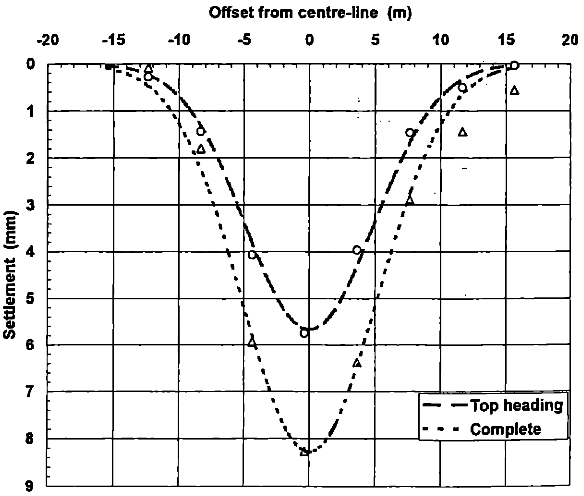

Figure 2 Surface settlement trough

around 0.3 is similar to that suggested by Schmidt for rocks. The low value of *K* in rocks is thought to be due to the tendency for the settlement to occur due to slip on subvertical discontinuities. The variation in volume loss is difficult to explain because there was not a marked variation in the geological conditions within the tunnels.

As expected the volume loss associated with excavation of the top heading is greater than that for excavation of the bench and invert. The volume loss due to excavation of the bench and invert alone was 0.36% and 0.08% for the eastbound and westbound tunnels respectively.

Figure 3 shows the development of the surface settlement with time above the centre-line of the eastbound tunnel at the north portal. The data clearly shows the passage of the top heading beneath the monitoring points in May 1991 and of the bench and invert in December 1991. Movements stabilise quickly after the heading passes suggesting minimal or very slow creep deformations in the Chalk. Point 8/8 is closest to the tunnel portal. The data also shows that the surface settlement increases with increasing distance from the tunnel portal. This is surprising as the amount of cover above the tunnel crown is progressively increasing and therefore it would be expected that the ability of the rock to form an arch would be improved. One of the factors found to have a significant impact on the settlement of the tunnel crown was the quality of construction of the top heading footings. Where these were constructed to the highest standards, crown settlements were reduced.

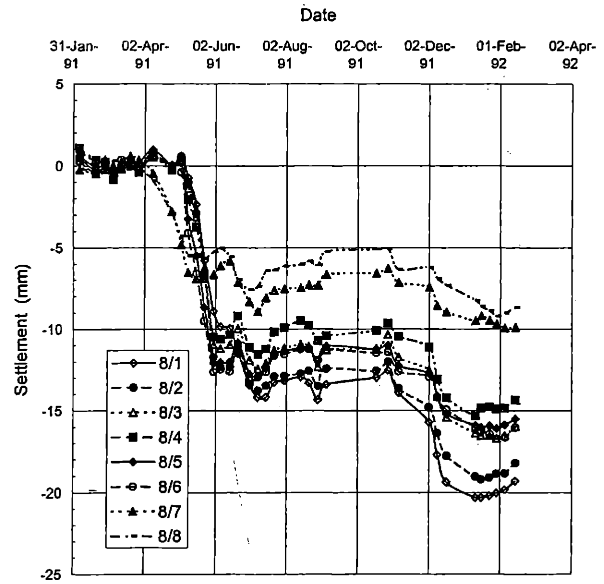

Figure 3 Settlements on longitudinal profile 8

The data from the settlement points along the tunnel centre-line can be used to derive a volume loss assuming a trough width factor. Based on the data from the transverse lines a trough width factor, *K*, of 0.29 has been adopted. The resultant range of volume losses measured by the longitudinal surface settlement lines is shown in Table 2.

Table 2. Longitudinal settlement arrays

	North Portal		South Portal	
	East	West	East	West
Max settlement (mm)	30.6-41.6	9.6-20.1	21.1-36.1	20.5-25.0
Volume Loss (%)	0.47-0.54	0.11-0.28	0.25-0.44	0.16-0.47

The results indicate that the volume loss is typically between 0.1 and 0.5%.

The magnetic extensometers were installed well in advance of tunnelling and good base readings were obtained. The deepest magnet was located about 0.6m above the theoretical excavation profile of the tunnel crown in SE1 and about 2m above the theoretical excavated profile of the tunnel crown in SE2 and SE3. Unfortunately, the lowest magnet in SE1 was damaged during tunnel excavation and no subsequent readings could be obtained. Measurements of the settlement of the magnets were made relative to the head of the extensometer tubing which was located at ground level. Unfortunately surveying of the head of the extensometers was not as reliable as the standard surface settlement monitoring and therefore no definite surface settlement can be quoted. However assuming a volume loss of 0.2% the surface settlements would be around 17mm, 7mm and 14mm for SE1, SE2 and SE3 respectively. The vertical settlement profile on completion of tunnel excavation for each of the magnetic extensometers is shown in Figure 4. The results

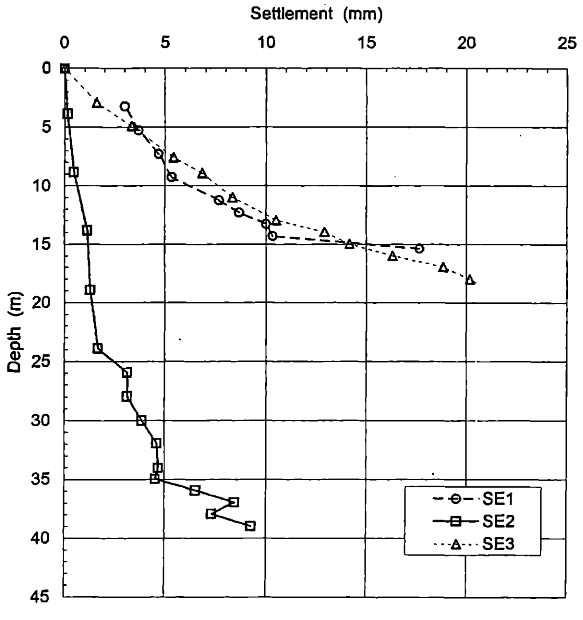

Figure 4 Extensometer Results

show a clear pattern of increasing settlement with proximity to the tunnel crown. The settlement of the crown of the tunnel relative to the ground surface is considerably greater for the two extensometers located close to the tunnel portals (SE1 and SE3) than for the extensometer located near the point of highest cover (SE2). This is believed to be because of the significantly better ground conditions beneath the deepest part of the hill.

The extensometer data can be used to define the vertical strains in the ground above the tunnel. Best-fit curves were derived for each of the extensometers and these curves were used to determine the strains in the tunnel crown. These are shown in Figure 5. The strain between the two magnets closest to the tunnel varies from about 0.1% for extensometer SE2 to 0.23% for extensometer SE1 and SE3.

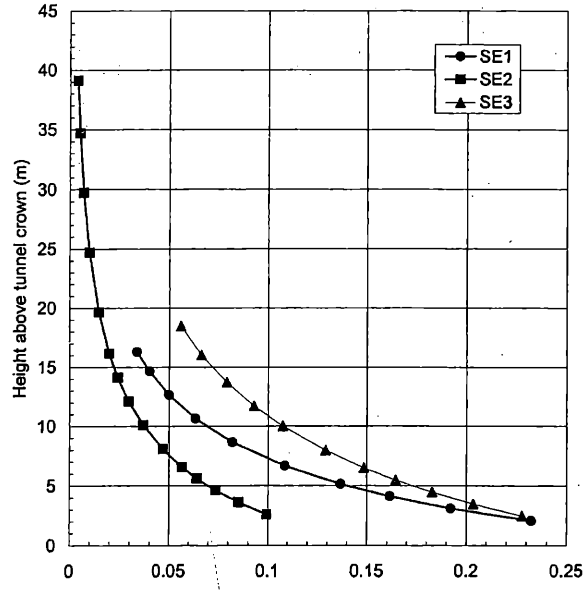

Figure 5 Vertical strain from extensometer data

3 HEATHROW EXPRESS BORED TUNNELS

The Heathrow Express project at Heathrow Airport, London involved the construction of twin bored running tunnels between the existing West Coast Mainline and the Central Terminal Area (CTA) and a single bored running tunnel between the CTA and Terminal 4 (Deane, 1997) (see Figure 6). The tunnels had an excavated diameter of 6.12m, and in the twin tunnel section the tunnel spacing was typically 18 metres. The tunnels were bored in London Clay throughout which is a stiff fissured silty clay, although along most of the route the London Clay is overlain by between 4 and 6m of Terrace Gravel. The depth to the tunnel axes varies from about 16 metres in the north to 22 metres beneath the airport.

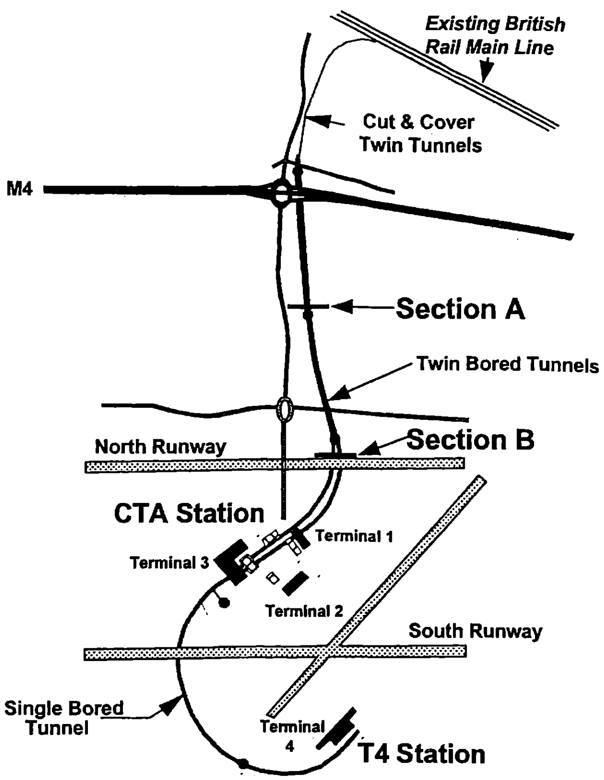

Figure 6 Heathrow Express Layout

The tunnels were excavated by digger-shield with a seven segment expanded lining being installed immediately behind the 6m long shield.

Surface settlement pins were installed on profile lines at locations where the tunnels passed beneath roads, services or utilities. Some of these surface settlement arrays ran oblique to the tunnel, but the data has been corrected to show the correct perpendicular offset from the tunnel centre-line. The settlement arrays contained between 7 and 25 points depending on the importance of the structure, although typically around 11 was used. Full details of the monitoring strategy adopted are given in Sam (2002).

Figure 6 shows the location of two key settlement profiles along the route of the bored tunnel. Figure 7 shows the settlement data at chainage 226S0m (Section B in Figure 6) where the tunnels are at a depth of 22.0m, but the tunnel separation is increased to 38m as it approaches the CTA station. The settlement profile shows a prominent double low point due to the interaction of the settlement troughs from the two tunnels. Also shown on the figure is a best-fit gaussian curve for the settlement of each tunnel. The fit is good suggesting that it is reasonable to superimpose the settlement due to one tunnel on the settlement of an adjacent tunnel. The volume loss for the two tunnels is similar at 1.0% and 1.15% and the trough width factor is also similar at 0.5 and 0.55 for the two tunnels.

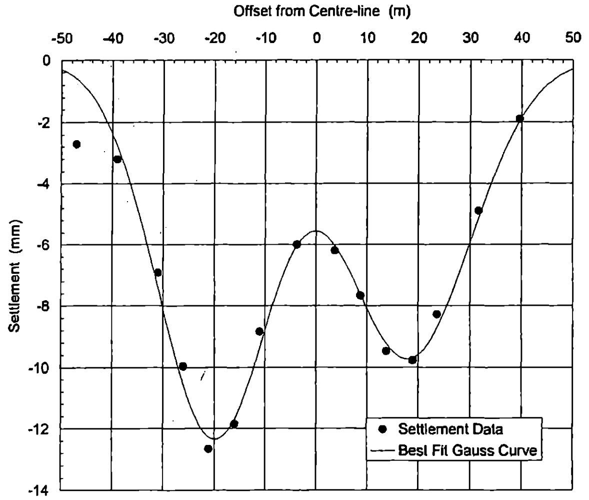

Figure 7 Settlement data for chainage 22670m

At other locations to the north of the CTA station a single broad settlement trough results from the construction of the two tunnels. From simple manipulation of the gaussian curve it is possible to show that for a K value of 0.5, a single broad settlement trough will be observed where the tunnel depth exceeds the tunnel centre-line spacing, otherwise a double trough will be observed. More generally, a single broad trough will be observed where the following equation applies:

$$x_0 < 2Kz_0 \quad (4)$$

Where x_0 is the centre-line spacing of the two tunnels.

Figure 8 shows the settlement trough at the end of construction along the profile line at chainage 21320 (Section A in Figure 6). At this point the tunnel axes are located at a depth of 20.8m with a centre-line separation of 18.0m and as expected a single broad trough is observed. Also shown on this figure is a best-fit gaussian curve for the settlement caused by each tunnel. With the single broad settlement troughs it was generally not practical to separate the settlement associated with each tunnel unless the volume loss was very different and therefore a single value of V_L and K was used for both tunnels. The fit to the data is generally good although towards the edges of the trough in the hogging zone the data points are seen to fall somewhat below the gaussian curve. This was seen on a number of the monitoring sections suggesting that this may be a typical response. Also points just above the right-hand tunnel fall slightly below the gaussian curve maybe suggesting slightly higher volume losses for the right-hand tunnel.

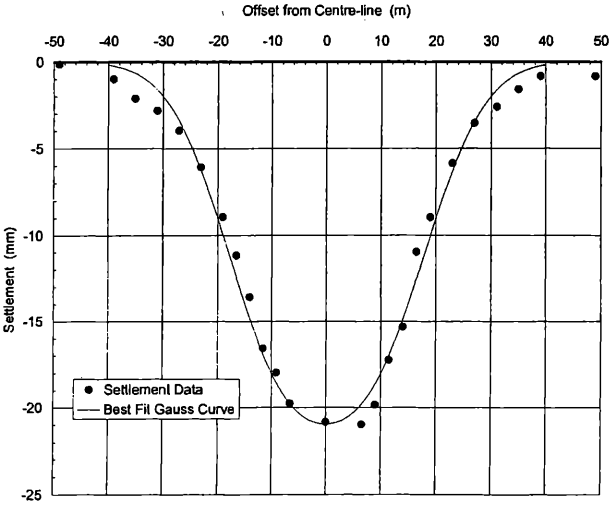

Figure 8 Settlement data for chainage 21320m

The back analysis of the settlement troughs for each of the monitoring sections is given in Table 3.

Table 3 Summary of settlement trough parameters

Chainage	Depth (m)	Settlement (mm)	V_L (%)	K
20630	16.0	30.9	1.30	0.45
20730	18.2	17.8	0.90	0.5
20740	17.5	23.8	1.50	0.65
21320	20.8	21.0	1.35	0.5
22300	22.4	28.5	2.10	0.52
22670	22.0	9.7	1.00	0.55
		12.7	1.15	0.50
24500	22.4	7.1	0.68	0.50*
24600	22.0	7.4	0.82	0.52
24640	22.1	6.8	0.64	0.50*
24720	21.9	10.2	0.88	0.44
24850	22.3	9.7	0.92	0.50*
24950	21.6	13.6	1.25	0.50*

*Assumed trough width factor,

The results indicate a trough width factor, K, between 0.45 and 0.55 with a volume loss generally varying from 0.7 to 1.5%. Of particular note is the marked variation in the volume loss over relatively short distances. For example, the volume loss approximately doubles from around 1.1% to 2.1% between chainages 22300 and 22670. The settlement trough at chainage 22300 was symmetrical suggesting that both tunnels suffered essentially the same volume loss. There were no records of poorer ground conditions at chainage 22670 and the profile at chainage 22300 was located on a bend where the volume loss is traditionally expected to be larger. The volume loss to the south of the CTA is also generally lower than that to the north. This rapid variation of volume loss data confirms the suggestion by Burland (2001) that we should be referring not to the *prediction* of ground movements due to tunnelling, but their *estimation*.

4 CONCLUSIONS

Monitoring data from two tunnels shows settlement troughs which are well represented by a gaussian curve. The data from the A20 tunnels in Chalk shows a relatively narrow trough. Data from both the A20 and Heathrow tunnels shows rapid changes in volume loss over relatively short distances. The data also suggests that where two tunnels are in close proximity the surface settlement trough can still be represented by two overlapping gaussian curves.

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