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Ground movement over three years at the Heathrow Express Trial Tunnel

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ABSTRACT: Measurements of ground deformation around the Heathrow Express Trial Tunnel have been taken over the three years since excavation, during which time only temporary support was installed. The observations show significant additional movements to have occurred after completion of construction; however, by the third year the rate of movement was greatly reduced. Analysis of these data suggests an empirical basis for the prediction of long term movements over other similar excavations and allows consideration of the effects of longer term tunnelling induced ground movements on overlying structures.

1 INTRODUCTION

The Heathrow Express Trial Tunnel, constructed in the first half of 1992, was the first excavation to test the "New Austrian Tunnelling Method" (NATM) in the London Clay. The project, promoted by BAA plc, provided an excellent opportunity both to evaluate a variety of construction sequences using sprayed concrete support and to develop methods of ground movement prediction (New and Bowers 1994).

After completion of the trial the permanent invert was not installed until mid 1994 and the remainder of the secondary lining was installed in mid 1995. This gave an opportunity to observe the behaviour of a tunnel in stiff clay with only sprayed concrete primary support over an unusually long period. Analysis of the data obtained suggests an empirical basis for the prediction of long term movements over other similar excavations and allows consideration of the effects of longer term tunnelling induced ground movements on overlying structures.

2 LONG TERM GROUND MOVEMENTS

The construction of a tunnel in soft ground normally results in ground movements as a direct result of the excavation process. For tunnels in clay, longer term primary consolidation movements may occur over some years until pore water pressure equilibrium is established. The nature of this equilibrium will depend on the boundary conditions imposed by the tunnel and in particular the permeability of the lining relative to the ground.

While short term ground movements above tunnels are often monitored routinely, there have been relatively few reported case histories of longer term ground movements. However, the increased use of sprayed concrete temporary works which may stand for prolonged periods without reaching complete equilibrium, and increasing concerns over environmental impacts, may mean the prediction of longer term ground movements becomes more important.

The best available long term monitoring data for clays are those reported by O'Reilly *et al* (1991) covering eleven years of surface settlement monitoring above the Haycroft Relief Sewer at Grimsby. This was a 3m diameter tunnel hand excavated through very soft marine clays at depths ranging between 5m and 8m. Short term maximum settlements showed a factor of two difference in magnitude between three measurement profiles, but the longer term movement increments, between one week and final equilibrium, were very similar. The short term settlement troughs were observed to be of Gaussian form, but in the longer term the troughs widened (by a factor of about three) and became less Gaussian. Ground movements continued for ten years at this site before an apparent final equilibrium was reached.

Finite element analyses of the Grimsby tunnel were undertaken by Mair *et al* (1992). Three models were investigated using different lining permeabilities, all of which indicated that primary consolidation would be completed in about five and a half years. The best agreement with the observed long term settlement data was achieved when it was assumed that the lining had a permeability of one tenth of that of the clay, although a better agreement might have been achieved if secondary consolidation effects had been considered. It is clear that while these models show some promise their extension to the much stiffer London Clay requires further validation.

3 THE HEATHROW EXPRESS TRIAL TUNNEL

3.1 *Construction history*

The trial tunnel was excavated between February and May of 1992. It consisted of three 30m long sections with an equivalent diameter of 8.66m and an axial depth of 21m, each constructed using a different sequence of subheadings (Figure 1). The trial sections were accessed through a 10m long heading driven from a shaft.

A secondary lining was not installed during the initial construction works (as would commonly be the case with tunnels of this type). Instead the tunnel stood unused for two years until mid 1994. At the end of that time an invert slab was cast and the tunnel was used for access to other tunnelling works. In mid 1995 a secondary lining of cast in-situ concrete was formed in the tunnel. This secondary structure included some backfilling to reduce the trial tunnel to running tunnel diameter. The most recent readings presented here were taken in October 1995, shortly after completion of this work.

3.2 *Instrumentation*

In addition to the normal NATM tunnel lining instrumentation the Transport Research Laboratory installed a comprehensive system of ground movement and stress monitoring equipment at the surface and in boreholes around the tunnel.

This instrumentation was arranged in a series of arrays including lines orientated parallel to and transverse to the tunnel axis at the centre of each of the three trial sections. This configuration allowed direct comparison of the effects of the three tunnelling sequences tested.

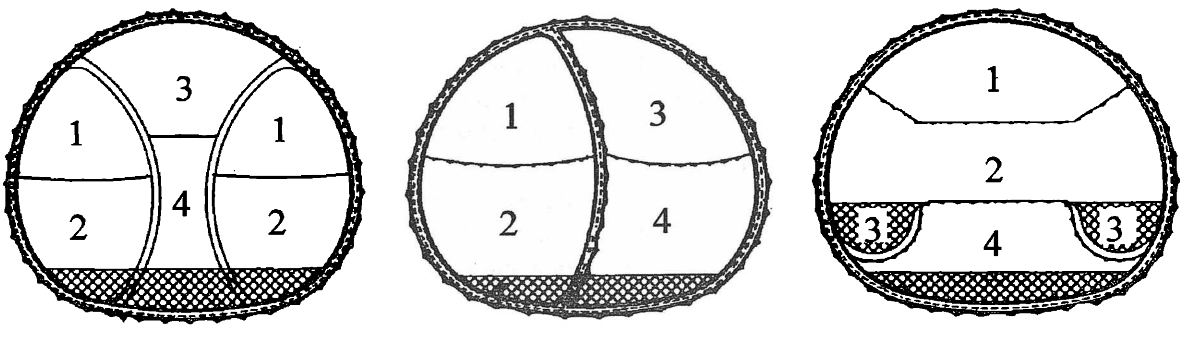
The surface instrumentation consisted of high precision digital levels, tape extensometers and Geomensor EDM equipment to measure vertical and horizontal displacements relative to remote reference stations. Subsurface settlements were monitored with magnetic ring extensometers using high precision micrometer reading heads and subsurface horizontal displacements were measured with inclinometers. These systems generally allowed critical ground movements to be measured with a precision of 0.25mm or better.

In addition to the movement instrumentation soil stress cells were installed around the tunnel to measure changes in horizontal ground stresses. Piezometers were installed both at the stress cell locations and elsewhere in the region of the expected settlement trough to allow determination of pore water pressure changes due to tunnelling.

The instrumentation and the results from the construction period monitoring, and the first year thereafter, have been reported previously (New and Bowers 1994). In the period since this work was reported, monitoring of the ground instrumentation has continued at a reduced rate and the results from this study are presented here.

4 RESULTS

Long term monitoring has shown significant continuing



Type one

Twin sidewall drifts

Type two

Single sidewall drifts

Type three

Crown bench & invert

Figure 1 The three excavation sequences at the Heathrow Express Trial Tunnel movements over the three years since excavation. However, by the end of this period the rate of movement was greatly reduced and in some areas tunnelling induced movements were becoming difficult to distinguish from the seasonal and other variations.

4.1 *Surface settlement*

The surface levelling data show that settlement has continued at a decreasing rate for the three years since completion of the tunnel (Figure 2). The variation in centreline settlement at the mid point of each trial section is summarised in Table 1 and the data may be compared in Figures 3, 4 and 5. It is apparent that the maximum settlements have tended to converge, with the type three section which had the greatest short term settlement having the smallest long term increment.

It is also apparent that there has been some effective widening of the settlement trough over time, arising principally from the overall increase in volume of the trough. This is illustrated by Figure 6 which shows the variation of the surface settlement over time above the mid point of the type two section. This figure also shows how, following completion of the tunnel, the rate of widening reduced and became approximately linear when plotted against the logarithm of time. Similar trends were demonstrated by the settlement profiles above the other sections of the tunnel.

4.2 *Subsurface displacement*

The magnetic ring extensometers indicate that subsurface settlements have continued and follow similar trends to the surface (Figure 2, lines D and E). The rate of settlement tended to be greatest at those points closest above the tunnel. Long term horizontal movements have also been apparent from the inclinometer results which show some continuing convergence of the ground on either side of the tunnel. However, the nature of this instrumentation and the small displacements recorded mean that these movements are approaching the practical resolution of the system and so more detailed analysis of trends is difficult.

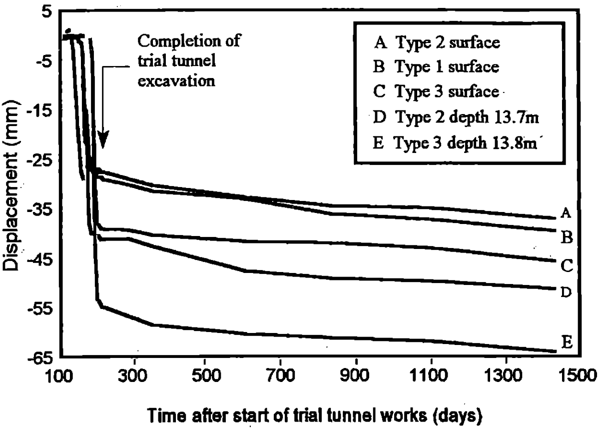


Figure 2 Centreline settlement time histories

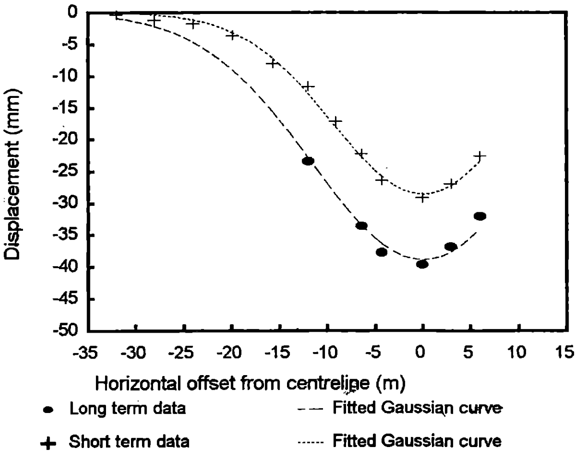


Figure 3 Type one: long and short term settlement

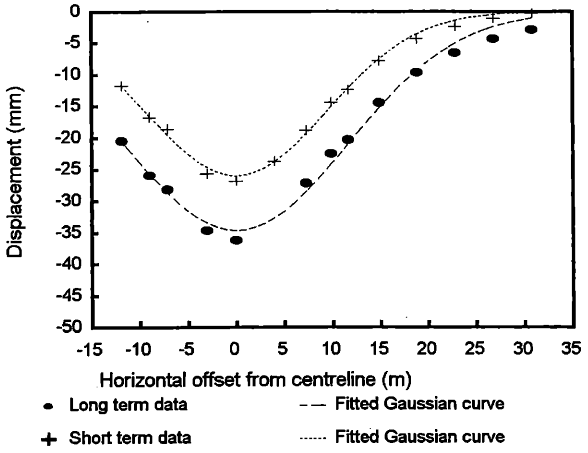


Figure 4 Type two: long and short term settlement

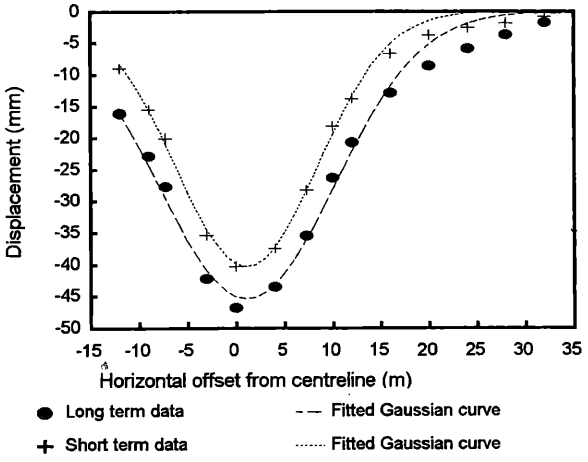


Figure 5 Type three: long and short term settlement

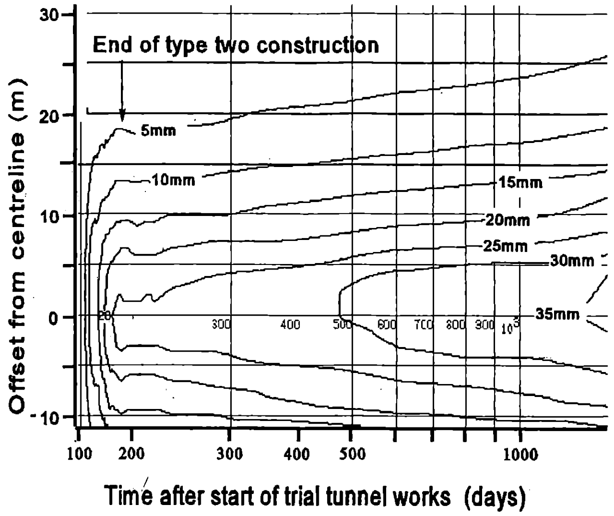


Figure 6 Variation of type two trough with time

Table 1 Summary of settlement troughs
*based on incomplete data.

Tunnel section	Max. settlement (mm) S_{MAX}	Volume loss (%) V_S	Trough width parameter K
Type one short term	27.9	1.15	0.45
Type one three years	39.6	1.9*	0.55*
% increase	42	68*	22*
Type two short term	26.8	1.05	0.45
Type two three year	36.2	1.7	0.55
% increase	35	63	22
Type three short term	40.3	1.26	0.35
Type three three years	46.8	1.8	0.43
% increase	16	40	23

4.3 *Ground stress and porewater pressure*

All the soil stress cells to either side of, and close above, the tunnel showed some increase in horizontal ground stress as the excavation approached the instrument location. After this the ground stresses fell rapidly to a level significantly below the initial state and then recovered to a new equilibrium state still somewhat below the pre-excavation condition. Over the three years since excavation there has been very little increase in these stress levels and thus no indication that the original stress state of the overconsolidated London Clay will be recovered.

Pore water pressures close to the tunnel boundary showed similar trends to the ground stress, with an initial construction phase increase followed by a drop to a lower than initial level and a slower partial recovery. Further from the tunnel boundary the pattern was somewhat different with a lesser change in pore water pressure followed by recovery over a few months to near original levels.

5 ANALYSIS

5.1 *Volume loss and trough width*

Non-linear regression analyses were carried out on the data from the surface settlement profiles and values for the volume loss and trough width were calculated for the derived curves. These are presented graphically in Figures 3 to 5. It can be seen that the Gaussian model which fitted reasonably well to the short term data has become a less good fit, particularly on the flanks of the settlement trough. This is compatible with the expectation that the dominant mechanism for the movements at this stage is primary consolidation of the low permeability London Clay. It should be noted that the loss of some levelling stations over the type one section means that analysis of that section is based on more limited data.

Table 1 summarises the analyses and quantifies the changes which have occurred in the longer term. The less good fit of the Gaussian curve in the longer term indicates that care should be taken in the use of the parameters to describe movements in the outer parts of the trough. As with the measured maximum settlements it is notable that the derived volume losses above the three tunnel types appear to be converging towards similar equilibrium states. Thus there was a smaller long term increment above the type three than had occurred over the other tunnel types, which had showed less short term settlement. This result contrasts with the observation by O'Reilly *et al* (1991) that the long term settlements at Grimsby were of a similar magnitude irrespective of the short term movements.

5.2 *Predictive modelling*

The data presented here provide an empirical basis for the prediction of future post construction movements over a similar time period and around similar openings in the London Clay, where primary consolidation is believed to be the dominant process.

It is established that movement due to primary consolidation processes tends to be linear against the logarithm of time and this is well supported by the current results. The rate of consolidation will depend on the geometry of the tunnel and the distance from the boundary towards which pore water pressure dissipation is occurring.

Thus for any surface point within the range of the present data let the settlement immediately after completion of the short term movements be S_A. This occurs at time after excavation, t_A, at which the rate of settlement becomes linear when plotted against the logarithm of time Let the settlement after a subsequent period of primary consolidation (time after excavation t_B) be S_B (Figure 7). This may be expressed as:

$$S_B = S_A+[\log(t_B/t_A).m] \tag{1}$$

where m (the gradient of the long term settlement line) is a constant for each particular surface location, and the value of S_A may be calculated by means of the Gaussian distribution model already validated at the trial tunnel site by New and Bowers (1994).

The value of m will be influenced by the bulk permeability of the ground, the stress regime, the distance from and geometry of the tunnel and the permeability of the lining, if the lining is less permeable than the ground. In the Heathrow case the latter factor may be disregarded because the sprayed concrete is of significantly higher permeability than the London Clay. The variation of m with horizontal offset from the tunnel centreline is illustrated by Figure 8.

A number of models were tested to relate the gradient to the distance from the tunnel. It was found that the best fit was obtained when the value of m_i (the value of m at surface location i) was expressed as

$$m_i = n / r_i^2 \tag{2}$$

where n is an empirical constant and r_i is the radial distance of point i from the tunnel axis. Thus equations (1) and (2) may be combined to give:

$$S_B = S_A+[\log(t_B/t_A).(n/ r_i^2)] \tag{3}$$

Inspection of the data indicated that t_A could reasonably be taken as 14 days for this London Clay site. Given this value, the value of n was found to be 2.3. Thus equation (3) may be re-expressed as follows:

$$S_B = S_A+[\log(t_B/14).(2.3/ r_i^2)] \tag{4}$$

where the units of S_A, S_B and r_i are metres and t_B is in days. This formulation results in an improved fit, particularly in the hogging regions of the trough (Figure 9). This empirical relationship would be expected to be valid for other tunnels of similar lining type, geometry and in similar ground conditions. However, due to the limited validation data care should be taken in extrapolation beyond the lateral extent of the trial tunnel data or over significantly longer time periods when the dominant settlement mechanism may change.

6 EFFECTS ON OVERLYING STRUCTURES

Damage to structures overlying tunnels is not due to displacement *per se* but rather to tensile ground strains and angular distortions. The data from the trial tunnel provide an indiction of how these parameters vary in the longer term.

Horizontal ground strain was measured directly over the trough flank and compared with that derived from the Gaussian curve fitted to the short term settlement data (Figure 10). The signs of the short term data agreed well with the model although the magnitudes tended to be somewhat less. The long term strain measurements are plotted on the same graph but show little significant change from the earlier values. Other profiles show similar trends.

Angular distortion effects may be considered in

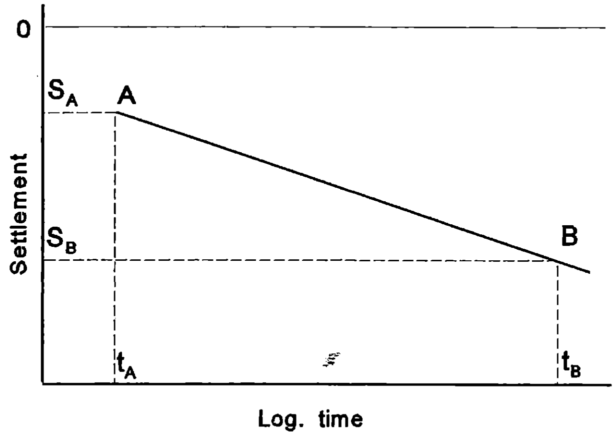


Figure 7 Consolidation settlement time relationship

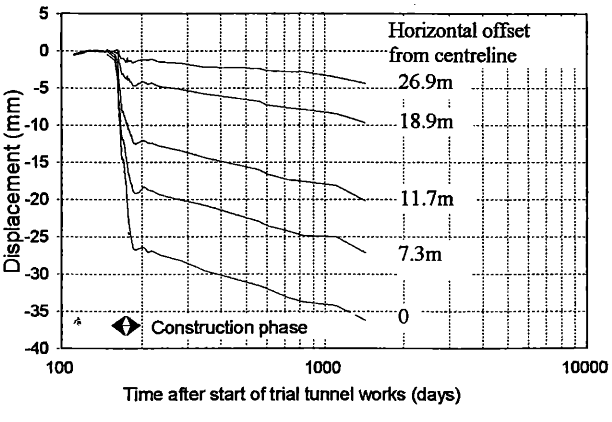


Figure 8 Settlement time relationship for type two

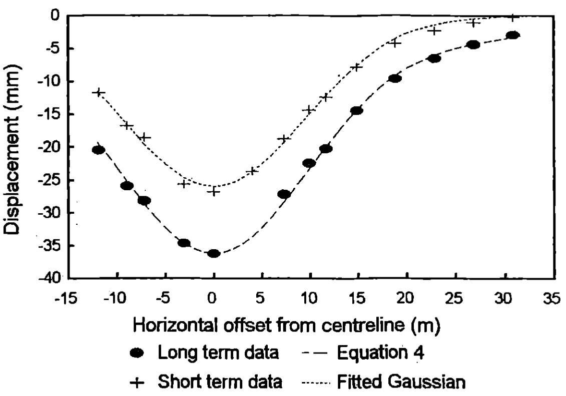


Figure 9 Revised long term model for type two

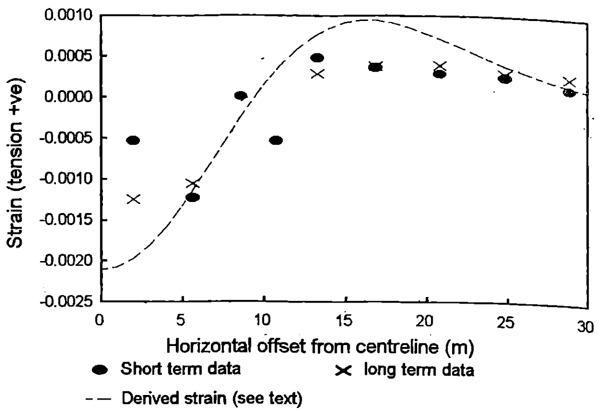


Figure 10 Horizontal strains over trial type two

terms of the ratio Δ/L where L is the length of the structure considered and Δ is the maximum differential deflection within the structure (Burland and Wroth 1974). Maximum values of Δ/L for a notional 1m beam structure were calculated for the hogging regions of the fitted curves illustrated in Figure 9. This analysis indicated only a minor increase of 7% in Δ/L from 1.62×10^{-5} to 1.74×10^{-5}.

Together these results indicate that the longer term increment in ground movement over the tunnel would have been unlikely to have had a significant additional impact on an overlying structure.

7 CONCLUSIONS

Monitoring of the ground instrumentation around the Heathrow Express Trial Tunnel has shown significant increases in ground displacements to have occurred since completion of the excavation and primary support. Maximum settlements increased by up to 42% and volume losses by up to 68%. There was also some convergence of the final trough magnitude over the three trial sections. Displacements occurred at a reducing rate and tended to be linear when plotted against the logarithm of time. This trend is compatible with a primary consolidation process.

The change in trough shape had not greatly altered the maximum tensile ground strains and distortions, although the widening of the trough slightly increased the affected area. Thus the movements in the three years since construction would have posed very little additional threat to any overlying structure. However, the continuing nature of the movements does indicate that the ground/lining system at Heathrow was not yet in full equilibrium.

The results and analysis presented here provide initial empirical guidance on the prediction of these effects over similar excavations in future, however, additional long term data from other sites are required to further develop and validate these methods.

8 ACKNOWLEDGEMENTS

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