Geotechnical Aspects of Underground Construction in Soft Ground, Mair & Taylor (eds)
© 1996 Balkema, Rotterdam. ISBN 90 5410 856 8

Construction of low-level tunnels below Waterloo Station with compensation grouting for the Jubilee Line Extension

D.I.Harris & C.O.Menkiti
Geotechnical Consulting Group, London, UK

A.J.Pooley
G.Maunsell & Partners, Beckenham, UK

J.A.Stephenson
Soil Mechanics Limited, Wokingham, UK

ABSTRACT: A new station on the Jubilee Line Extension is under construction beneath the existing main line railway station at Waterloo. The complex of tunnels includes two platform tunnels at low level which are connected to higher level tunnels linking to existing London Underground stations by two banks of escalators via central concourse tunnels. Total greenfield site settlements of 200mm were predicted based on volume losses of 2%. Compensation grouting was specified to enable the maximum settlement to be reduced below 25mm. This Paper describes the performance to date of the tunnelling, grouting and structure movements.

1 INTRODUCTION

A new station at Waterloo is under construction by Balfour Beatty Amec JV (BBA) as part of Contract 102 of the Jubilee Line Extension (JLE). The station complex is of traditional London Underground (LU) design comprising two platform tunnels at low level which are connected to higher level tunnels linking to the existing main line railway station and other LU lines by two banks of escalators via central concourse tunnels. Ventilation and emergency escape tunnels at the low level are also included. The total short term settlement associated with the construction of these tunnels was conservatively estimated to be 200mm using greenfield site calculations with a volume loss of 2%.

The new station is located beneath the existing main line Waterloo Station and the viaduct carrying trains to Charing Cross Station via Hungerford Bridge. Settlements of the magnitude predicted were deemed unacceptable and compensation grouting was specified as a mandatory protective measure in the Contract. Compensation grouting had only recently been introduced to the UK on a previous tunelling Contract at Waterloo (Harris et al., 1994; Mair et al., 1994), although there has been experience of its use elsewhere (Mair and Hight, 1994).

This paper details the construction of the platform and associated low level tunnels completed to date. The implementation of compensation grouting is described. The performance to date is presented as contours of predicted and actual settlement together with contours of the intensity of grout injected.

2 TUNNEL CONSTRUCTION

Construction to date (December 1995) has concentrated on the low level tunnels. The layout of the lower level tunnels and the construction progress to date are shown in Figure 1(a). A cross section is shown in Figure 1(b). The underside of the foundations of the existing station structure is at approximately 98m APD at the top of the Thames Gravels. The tunnels are wholly within London Clay which extends from around 94m APD to 64m APD and are underlain by Woolwich and Reading Beds.

The 791m of 5.3m i.d. running tunnel to the boundary of the contract have been completed. This length includes 284m of pilot tunnel to the platform tunnels (at the same size) and 66m of enlarged (7.0m i.d.) tunnel at intersections with vent and escape tunnels. Enlargement of the pilot tunnel to the final platform tunnel diameter (7.0m i.d.) has been completed for a length of 122m on the

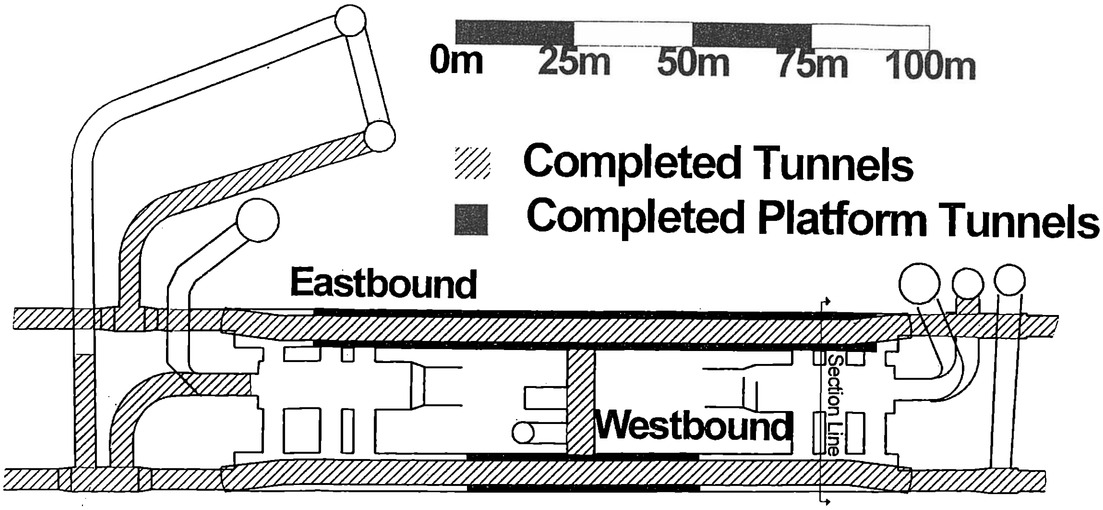

Figure 1(a) Layout and progress of the low level tunnels

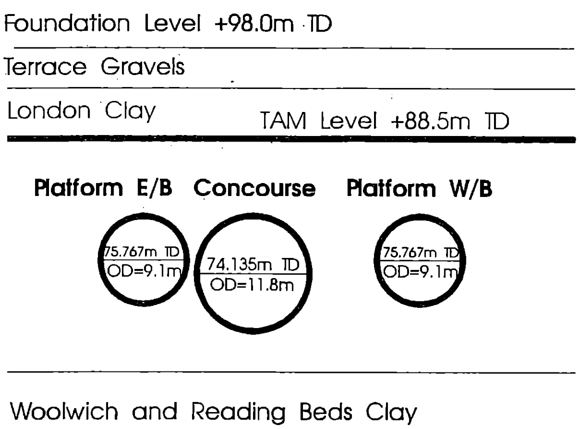

Figure 1(b) Cross section of low level tunnels

Eastbound tunnel and 88m on the Westbound tunnel; 92m of 5.3m i.d. ventilation tunnel have also been completed.

The tunnels have all been supported by temporary shotcrete linings (NATM), and will ultimately be lined with cast in-situ reinforced concrete permanent linings. The tunnels have been constructed full face in a heading and bench sequence. The platform tunnels have been constructed around the concentric pilot tunnel using a similar sequence. The heading is advanced in 1m lengths and the bench in 2m lengths. The maximum lead of the heading has been restricted to 4m. Shotcrete thicknesses of 150mm has generally been adopted for running tunnels, 200mm thickness for pilot tunnels and 300mm for platform tunnels with localised thickening at tunnel intersections.

Advance rates have averaged 25m/week for 5.3m i.d. tunnels and 11m/week for platform tunnels.

There have been numerous other construction activities carried out concurrently with the tunnelling which have induced ground movements, either settlement or heave, or both. The most important of these are shaft sinking, drilling to install compensation and permeation grouting arrays, permeation grouting, shallow bulk excavation, piling and dewatering.

Time dependent, consolidation settlements following tunnelling and the other construction activities have made a significant contribution to the total movements observed.

3 COMPENSATION GROUTING

The area to be protected by the provision of compensation grouting was defined in the Contract. All compensation grouting on C102 has been carried out through tubes a manchettes (TAMs). The plan extent of the arrays of TAMs required to achieve this requirement was agreed on site on the basis of further settlement assessments and amounts to 24,000m^2. Separate arrays were required to cater for the movements created by tunnels at varying elevations. This paper considers only the lower level tunnels. 313 TAMs have been installed requiring a total drilled length of 10.6km. Ports are generally at metre centres along the tubes and a total of 9,000 separate injection points are available. The layout of the TAMs is shown in Figure 2. All of the low level compensation grouting arrays have been installed from shafts. 8 shafts have been utilised of which 6 have been constructed especially for this purpose; the other two shafts are part of the permanent works.

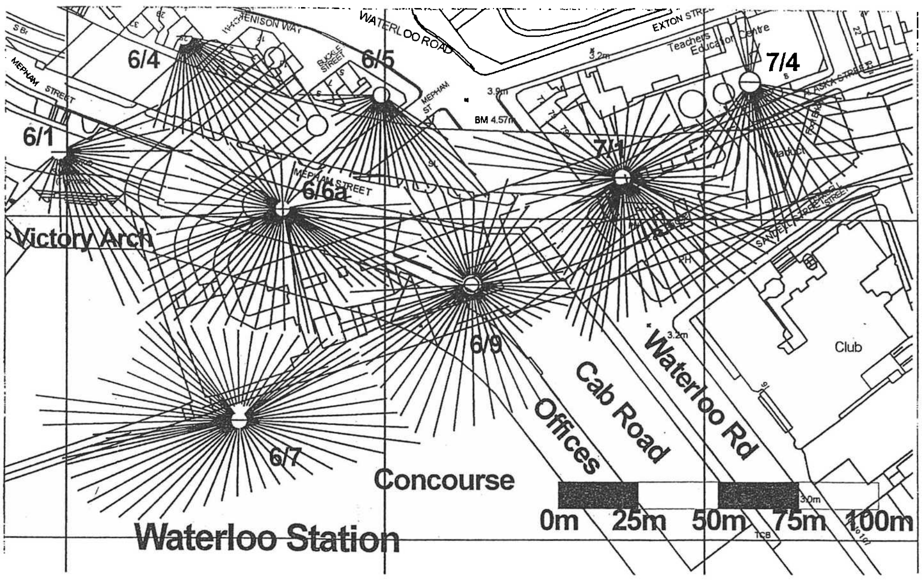

Figure 2 Layout of compensation grouting TAMs

Two basic grout types have been utilised which have been termed 'fluid' and 'paste' (or 'mortar'). The mixes comprise (by weight):

Fluid:	Water: OPC = 4:1
	Bentonite = 6%
Paste or mortar:	Water: OPC = 10:1
	PFA: OPC = 20:1
	Bentonite = 6%

Different pumps are required to inject the grout: conventional grouting pumps are used for the fluid but concrete pumps are required to overcome the higher resistance to flow of the paste. This novel mix has required the development of new, larger grouting equipment. 42mm i.d. pipework is used and TAMs of 70mm i.d. and 3mm wall thickness have been used to accommodate the larger packer required.

The concept behind the development of the paste system by the grouting sub-contractor, Amec Geocisa JV (AG), was to limit the extent of grout flow in the ground thereby producing thicker lenses giving more control on the grouting operations and allowing larger volumes to be used for individual injections. Samples recovered from the ground indicate that the fluid grout produces extensive layers 1-2mm thick; this is in line with expectations from previous experience. In contrast the paste grout produces lenses of more limited extent with thicknesses of about 10mm.

Grout injections can be categorised into three phases:

i) Pre-treatment is grout injected in advance of tunnelling; this is intended to prove the system by producing controlled nominal heaves. Grout is injected at a uniform intensity over the prescribed area in a number of passes until discernible heave is observed on the overlying structures.

ii) Concurrent grouting is carried out during the tunnelling and the grout injections are directly linked to the advance of the tunnel. The grout injections are in a pre-determined pattern relative to the tunnel heading. Longitudinally five blocks, nominally 2m wide, are selected each of which has 20% of the total grout volume; the position of these blocks relative to the tunnel is illustrated in Figure 3(a). Each block comprises 8 injections; the volumes of which are determined to approximately reflect the empirically determined Gaussian distribution of ground movement as shown in Figure 3(b). Thus 40 injections are made for each 2m advance of tunnel; the total volume of grout injection is modified observationally on the basis of recorded surface and structure settlements.

iii) Further consolidation settlements inevitably occur subsequent to tunnel construction and its associated concurrent grouting. Periodically further grouting passes may be necessary, particularly if future tunnelling activities will produce further settlements in the same area. These further passes have been termed Observational grouting with the extent and intensity related to observed settlements.

The construction programme on JLE C102 requires up to 12 tunnel faces to be advanced

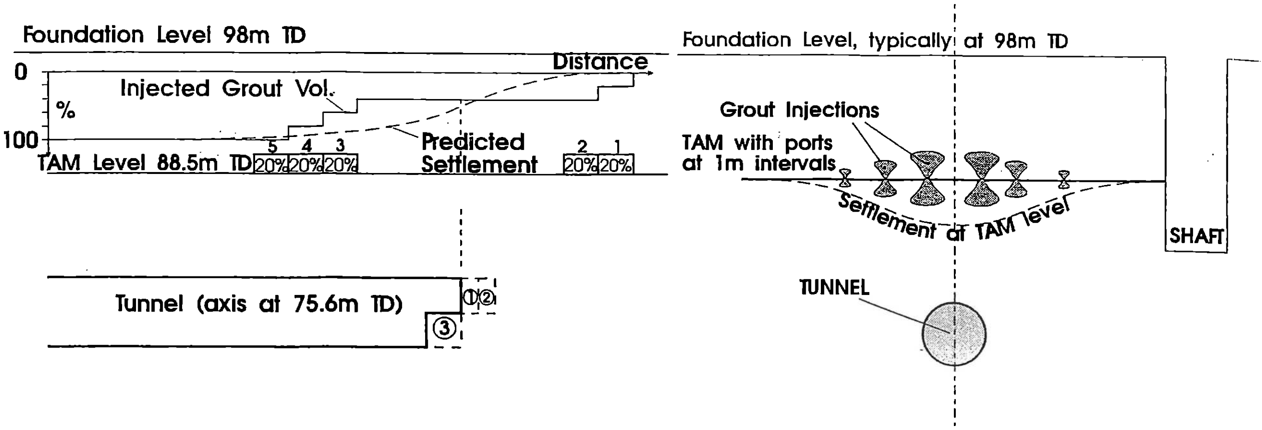

Figure 3: (a) Longsection showing location of grout blocks **(b)** cross section of grout block

simultaneously. Compensation grouting is required in most of these locations and consequently control and supervision of grouting operations is a major task. All injections carried out are detailed in grouting proposals in terms of Shaft, TAM, and port number and the volume to be injected. Restrictions on grouting in close proximity to excavations are detailed by exclusion zones and time periods. The grouting proposals are, as far as practicable, based on standard methodology to allow rapid modifications to be made should these be required. Concurrent grouting requires that close communication between grouters and tunnellers is maintained to ensure that the two activities remain synchronised. This is achieved by both tunnellers and grouters reporting completion of each advance or grouting pass to the monitoring department which also has data from surveying and electronic instrumentation and therefore has access to all of the relevant information. The monitoring office gives the instruction to proceed with the next operation and thereby co-ordinates activity on an hour by hour basis.

The longer term performance of all grouting proposals is monitored at daily meetings (and more frequently if necessary) by representatives of BBA, AG and JLE. Tunnelling and grouting progress since the previous meeting are presented together with reports on the monitoring data, both from within the NATM tunnels and from surface structures. Any trends in the movement monitoring data are identified

4 PERFORMANCE TO DATE

The tunnels constructed to date are described in Section 2 and illustrated in Figure 1. The predicted greenfield site settlement associated with these tunnels has been calculated on the basis of a Gaussian distribution with a volume loss of 2% and a trough width factor (k) of 0.5. The resulting contours of settlement are shown on Figure 4(a). A maximum settlement of over 60mm is predicted with a large area having settlement of 35 to 45mm. The distribution of the grout volume injected to compensate for these potential settlements is shown in Figure 4(b) as a contour plot. This is generated by summing all injections within each square of a 5m grid over the whole area. Comparison of Figure 4(b) with Figure 1(a) shows the general association of the grout volumes with the location of the constructed tunnels. It is of note that the peak grout intensity of 160 l/m^2 is not in the area of maximum predicted settlement but over an enlarged section of running tunnel where two openings for passageways have been formed. The residual settlements not mitigated by the grouting are shown in Figure 4(c). The settlements are generally less than 10mm with local maxima of up to 12mm.

It would appear from the three parts of Figure 4 that the volumes of grout injected are well in excess of the volume loss based on 2% of the excavated volume. This is confirmed in Figure 5 where the cumulative total volume of grout injected is plotted as a percentage of the volume of excavation against the cumulative volume of excavation. This shows that the percentage of grout rose to 4% in the first $5000m^3$ of excavation and has subsequently remained reasonably constant but with a steady rise evident over the most recent $10000m^3$ of excavation. The volume currently being injected is 5.1% of the excavated volume.

The efficacy of the grouting in maintaining the level of structures during tunnel construction is illustrated

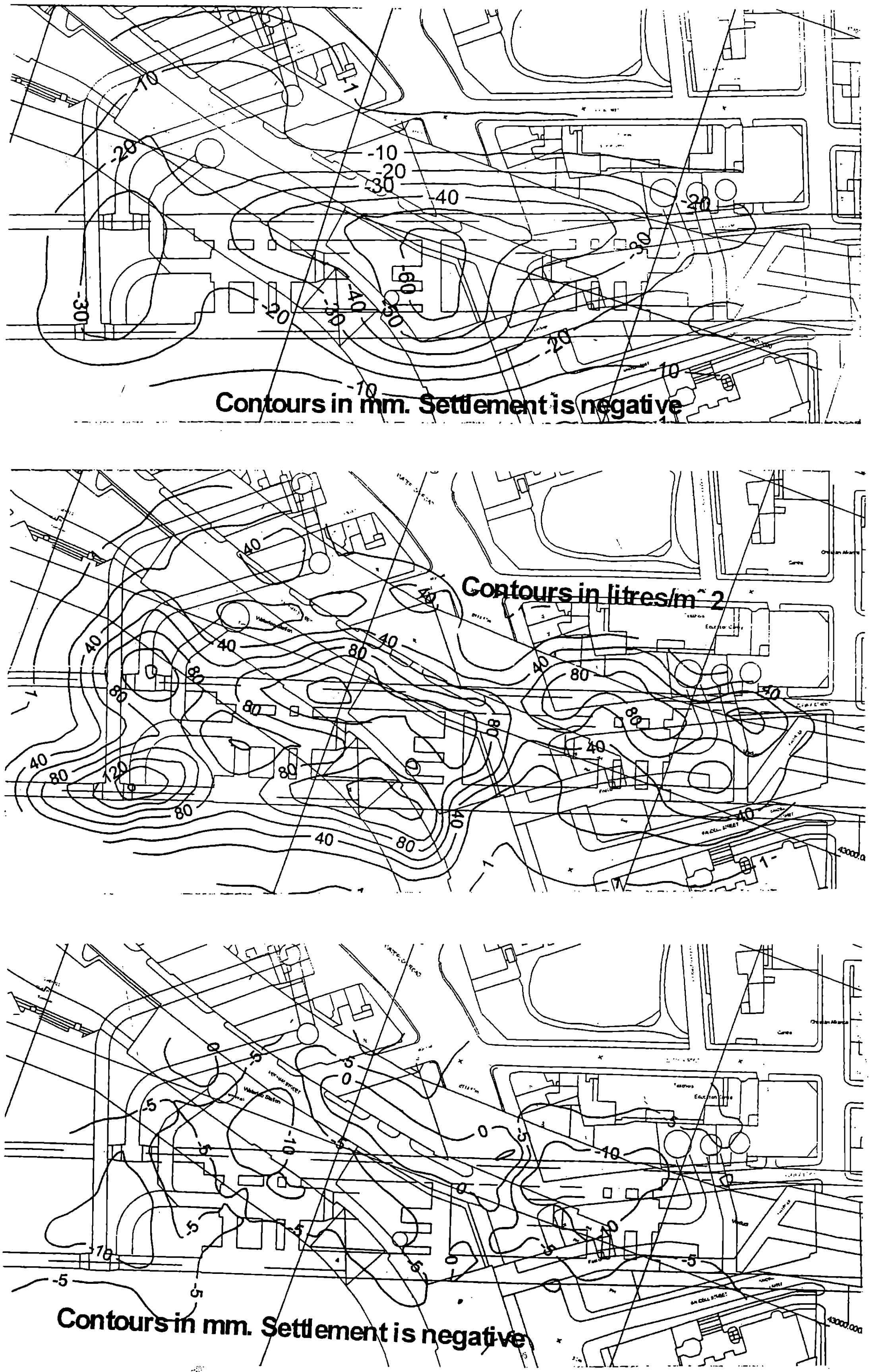

Figure 4 Contours at 23/12/95: **(a)** Predicted settlement **(b)** Grout intensity **(c)** Actual settlement

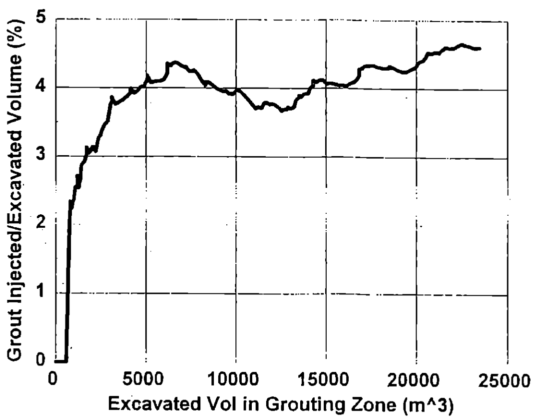

Figure 5 Grout volume as % of excavated volume

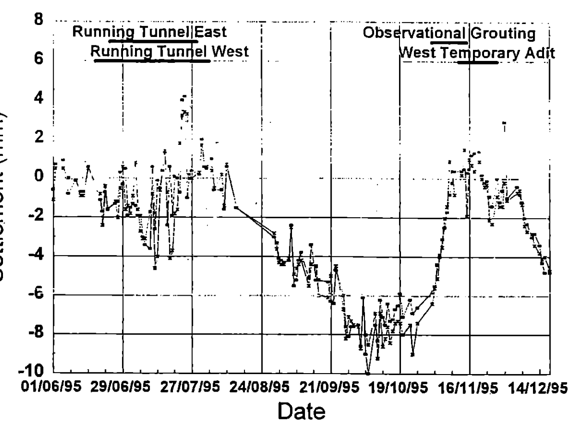

Figure 6 Settlement time plot of overlying structure

in Figure 6. This shows that a variation in level of approximately +/- 3mm is achieved during construction but that significant time dependent settlements develop thereafter. An episode of observational grouting is then implemented which recovers about 8mm of settlement before the cycle is repeated as further tunnels are constructed.

5 CONCLUSION

A significant proportion of the low level tunnels for the Waterloo Station of the JLE has been successfully constructed with temporary shotcrete linings. Compensation grouting has been implemented to protect the overlying main line railway station. Settlements have been successfully restricted to a small proportion of their potential magnitudes. The importance of time related movements within the construction period of a major station tunnel complex has been highlighted.

6 REFERENCES

Harris, D.I., Mair, R.J., Love, J.P., Taylor, R.N. and Henderson, T.O. (1994). Observations of ground and structure movementsfor compensation grouting during tunnel construction at Waterloo Station. Geotechnique, Vol. 44, No. 4, 691-713

Mair, R.J., Harris, D.I, Blakey, D and Kettle, C. (1994). Compensation grouting to limit settlements during tunnelling at Waterloo Station. Tunnelling '94. Institution of Mining and Metallurgy, Chapman & Hall, 279-300.

Mair, R.J. and Hight, D.W. (1994). Compensation grouting. World Tunnelling, November 1994, 361-367.