Geotechnical Aspects of Underground Construction in Soft Ground, Kusakabe, Fujita & Miyazaki (eds)
 ISBN 90 5809 1 066

Compensation grouting at the Docklands Light Railway Lewisham Extension project

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ABSTRACT: As part of the Docklands Light Railway Lewisham Extension project, the construction of nearly 1.1 km of twin 5.85m diameter running tunnels, passing under the River Thames, was undertaken. The slurry shield method combined with compensation grouting was employed in order to limit surface settlements and to control settlement of the overlying structures. Ground and building movements were carefully monitored and as a result, the compensation grouting technique was successfully implemented. This paper briefly describes the tunnel construction, including the compensation grouting, and the results of the ground movement monitoring.

1 INTRODUCTION

In order to improve access to the south east area of the Docklands in London, a 4.2 km extension to the Docklands Light Railway running from Mudchute Station on the Isle of Dogs to Lewisham Station has been constructed. This project included the construction of around 1.1 km of twin 5.85m diameter running tunnels, passing under the River Thames, and running from Island Gardens to Greenwich (see Figure 1).

Figure 2 shows a cross section through the tunnels, together with the ground stratigraphy. In this project the slurry shield method, together with the compensation grouting technique during tunnelling, was employed. Ground movements have been carefully monitored. The twin tunnel construction was successfully conducted and the costs of the soil improvement (including compensation grouting) were reduced by 20 percent compared with those expected.

This paper briefly describes the shield tunnel construction and the results of the ground movement monitoring. The implementation of compensation grouting during tunnel construction is also reported.

The contractor for the main works was a joint venture of three companies, Nishimatsu Construction and Mitsui Products of Japan and John Mowlem Construction of the UK. Compensation grouting was undertaken by a specialist subcontractor, Keller.

2 GROUND CONDITIONS

The ground conditions are summarized in Figure 2. The geotechnical strata from surface level along the route of the bored tunnels comprise varying thicknesses of Made Ground, Terrace Gravel, the Woolwich and Reading Beds (WRB)– now known as the Lambeth Group – and Thanet Sand. The tunnels were mostly driven below the water table through Terrace Gravel, the WRB and

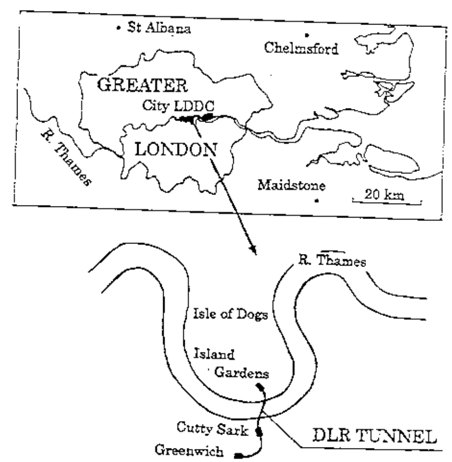


Figure 1. Route of DLR-LWE tunnel.

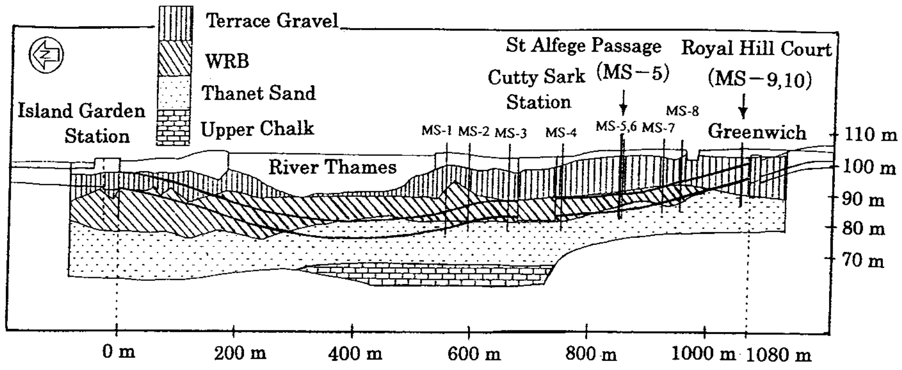


Figure 2. Schematic geological section along DLR- LWE route.

Thanet Sand. Terrace Gravel is a fluvial gravel bed and is typically well-graded, varying from silty fine sand to coarse gravel.

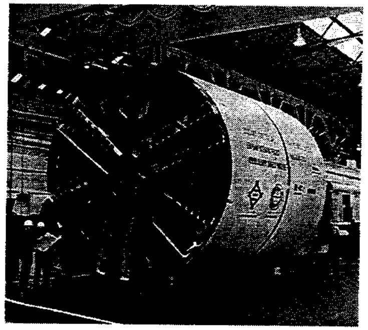
The WRB, consisting of various kinds of soils from very stiff to hard clays to dense sands and gravels, is a very complex formation. Stiff to hard clays were the principal strata encountered by the tunnels in the WRB formation. Thanet Sand consists of silty fine very dense sand.

3 TUNNEL CONSTRUCTION

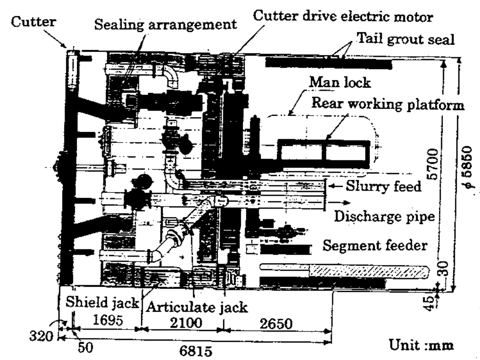
Since very mixed face ground conditions were anticipated and there were some important overlying and underground structures that would be potential affected, the slurry shield method was employed to maintain face stability and minimize ground movements. The slurry shield method is a closed-face type shield tunnelling technique and has been considerably developed in Japan in recent years (Fujita, 1994).

Figure 3 shows a general view and section of the shield machine for this project. A slurry shield machine with an outer diameter (D) of 5.85 m and a length (L) of 6.82 m was employed to excavate the two parallel single tunnels. Of the two tunnels, the south bound route was constructed first, followed by the north bound route. The length of each tunnel was about 1.1 km and the cover-to-diameter ratio (C/D, C being the depth to tunnel crown) ranged from1.6 to 2.5. An advance rate of the tunnelling machine in the WRB averaged 11 m/day.

Ground surface movements during shield tunnel construction were carefully measured, particularly at various transverse cross-sections.



(a) Slurry shield machine (ϕ =5.85 m)



(b) Section of the machine

Figure 3. General view of the slurry shield machine for this construction work.

4 SETTLEMENT PREDICTIONS

Prediction of ground settlement due to tunnelling was made using the method described by O'Reilly and New (1982) and Selby (1988). Assessments of the likely effects of settlement on all structures lying within the settlement trough were also made.

The settlement criteria for the main structures are summarized in Table 1. In making the prior assessment of settlement, it is necessary to estimate a value of 'volume loss', which may be defined as the amount of ground lost in the region close to the tunnel. The volume loss is generally expressed in terms of the volume of the surface settlement trough, expressed as a percentage fraction of the excavated area of the tunnel.

Based on the authors' recent experience of shields in similar ground conditions, a volume loss of 1.0 % and a maximum settlement of 15 mm were generally adopted as the project design criteria prior to tunnel construction. This value of volume loss was consistent with those given in the recent report by Mair (1996).

In addition, a maximum angular distortion (see Table 1) of 1 in 1000 was set to minimize the risk of building damage and disruption to sensitive operational equipment. Based on this assumption the settlement at the centre of the trough was estimated to be approximately 30 mm at the location of the Royal Hill Court structure for which data is being presented in this paper. Therefore, the compensation grouting technique was chosen in order to acceptably control settlements, as briefly described below.

5 COMPENSATION GROUTING

The main objective of compensation grouting is to limit the movements of overlying structures within a specified level during tunnel construction. Compensation grouting has tunnel construction with closed-face type recently been introduced to the UK on tunnel construction beneath Waterloo Station and subsequently for the Jubilee Line Extension (Harris et al, 1994; Harris et al, 1996); the principles and applications of compensation grouting are presented by Mair and Hight (1994).

All compensation grouting has been carried out through tubes a manchettes (TAMs). The layout of the TAMs is shown in Figure 4. The compensation arrays have been installed from shafts in the case of the Royal Hill Court building or from the ground surface in the case of North River Wall. Compensation grouting was roughly divided into two main stages:

(1) Conditioning grout
Conditioning grouting was injected into the ground below the structures prior to advance of tunnelling. The aim was to stiffen the ground locally so that the subsequent compensation grouting could be effectively conducted.

(2) Compensation grouting
Compensation grouting was carried out to compensate for ground loss and stress relief by tunnel excavation, when it was needed, based on the monitoring results. Controlled quantities of grout were injected to compensate for the volume losses along the route. The compensation grout was mostly injected in the Terrace Gravel at locations where the tunnel was in the Terrace Gravel and likely to adversely affect certain structures.

The compensation grout comprised a bentonite cement mix with various additions such as Pulverised Fuel Ash (PFA) and Silica gel. Generally 30 litres per sleeve were injected at pressures ranging from 5 bar to 7 bar, depending on the TAM positions. Volumes equivalent to

Table 1. Design criteria for overlying structures.

Structures	Soil cover depth (m)	Angular Distortion	Settlement (mm)
Manchester Road		1:1000	15
Sewer	5.0	1:1000	15
Gas Main (12 inch)		1:1500	10
Community Centre	14.8	1:1000	15
British Railroad	6.5	1:1000	15
Royal Hill Court	6.6	1:1000	15

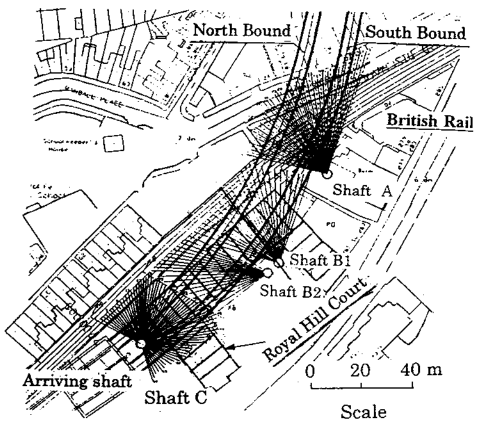


Figure 4. Grouting array – plan (Royal Hill Court).

approximately five times the actual volume losses were injected at any one location.

6. SUMMARY OF MONITORING RESULTS

6.1 Non compensation grouting areas

The surface settlements above the tunnel centre line (S_{max}) are summarized in Table 2. It can be seen that all values of S_{max} for south bound are less than 15mm and the volume losses were satisfactorily controlled to a mean value of 0.7 %, and were smaller than 1.0 % (the predicted value) at all locations. The sophisticated tunnel excavation control system contributed significantly to achieving these results.

Figure 5 shows a typical example of monitoring results of longitudinal settlement for a non compensation grouting area. Very small settlement above the tunnel face was observed, mainly because the face pressure was carefully and well controlled. The settlement due to the tail void was only about 1.5 mm, which was about 50 % of the settlement that occurred during passage of the shield. One of the reasons for this is believed to be the immediate grouting to fill the tail void, which is an effective means of minimizing ground movements.

Figure 6 shows the normalized transverse surface settlement troughs (S/S_{max}) associated with shield construction at the monitoring section MS-5 (St Alfege Passage, southbound tunnel). This slightly large K value may be influenced by the stiffness of the houses.

All points D, E and F are consistent with those in Figure 5. The best fit Gaussian distribution curve (Peck,1969) estimated from the monitoring results is also shown in Fig. 6, and this corresponds to a value of K=0.6 (K being the trough width parameter, Mair and Taylor,1998). These monitoring points were on a row of two storey mansonry houses within basements. The transverse settlement trough based on the monitoring results is reasonably represented by the Gaussian distribution curve. The more detailed discussion on the ground movements in the non compensation grouting areas is described by Sugiyama et al.(1999).

6.2 Compensation grouting areas

Figure 7 shows the development of surface settlement above the centreline of the tunnel during the passage of the tunnel machine through the compensation grouting areas beneath the Royal Hill Court. The tunnel was mostly in

Table 2. Monitoring results (South Bound).

Monitoring Point	Ground Conditon	Compensation Grouting	Smax (mm)	Volume Loss (%)
MS-1	WRB	Non	5.4	0.85
MS-2	WRB	Non	—	—
MS-3	WRB	Non	5.4	0.97
MS-4	WRB	Non	6.7	—
MS-5	WRB	Non	5.5	0.45
MS-6	WRB	Non	5.5	0.46
MS-7	WRB	Non	6.4	0.54
MS-8	WRB	Non	10.6	0.78
MS-9	Terrace Gravel	Done	6.3(12.3)	0.34
MS-10	Terrace Gravel	Done	0.0(3.0)	0.02

*1) MS-5:St Alfege Passage, MS-9,10:Royal Hill Court
*2) ( ): Maxmimum Settlement immediately before Compensation Grouting

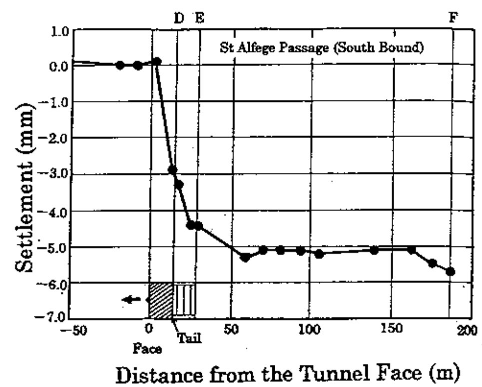


Figure 5. Longitudinal surface settlement troughs (Non compensation grouting area).

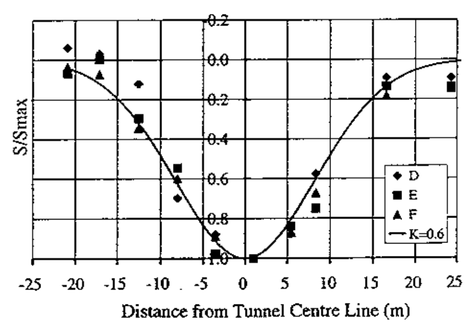


Figure 6. Normalized transverse settlement troughs (Non compensation grouting area).

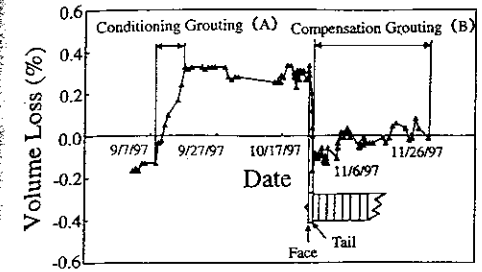


Figure 7. Change of volume loss during development of longitudinal settlement troughs (Compensation grouting area).

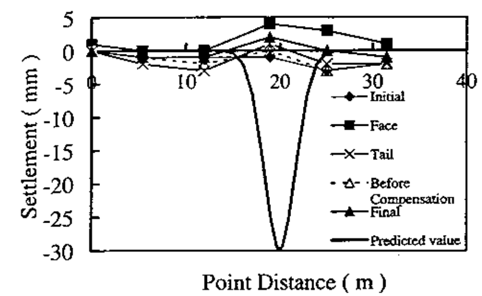


Figure 8. Transverse settlement troughs (Compensation grouting area).

the Terrace Gravel. The Royal Hill Court structure is a 2 storey reinforced concrete frame building founded on shallow foundations in the Terrace Gravel. The conditioning grouting was carried out during Period A ahead of the tunnel face. Some heave occurred during this period. Immediately after the tunnel face passed, compensation grouting was undertaken(Period B). It can be seen that the implementation of the grouting at this stage effectively reversed the heave, resulting in very small net movements.

The change of the transverse settlement at the ground nearby the Royal Hill Court is shown on Figure 8. Although a little heave occurred due to the grouting, indicating the form of the grouted "slab" between the ground surface and the tunnel, it can be seen that the maximum surface settlement could be minimized by compensation grouting, showing a much smaller value compared with that predicted.

In order to investigate the effects of the compensation grouting on the tunnel lining, internal displacements of the tunnel were measured by using a theodolite and a tape extensometer. There were no significant displacements associated with the grouting (being generally less than 2.0 mm), nor were there any cracks in the lining. As a result, the effects on the tunnel lining of the compensation grouting were found to be very small. Numerical approaches to this problem have been carried out by Kovacevic et al.(1996) and Lee et al.(1999).

The soil improvement costs (including compensation grouting) for the whole project were reduced by 20 percent compared with the expected costs.

7 CONCLUDING REMARKS

It has been observed that the volume loss associated with slurry shield tunnelling in the mixed face ground condition, including Terrace Gravel and WRB, could be successfully controlled, being less than 1.0 %. The technique of compensation grouting has been proved to be effective in protecting the overlying sensitive structures and in controlling settlements.

The key element of the success in the tunnel construction was the careful control of compensation grouting in response to the detailed observations of the strucure movements. In addition, a good synchronized harmony between sophisticated slurry shield operations developed in Japan and the compensation grouting technique developed in the UK contributed to the success of this project.

REFERENCES

Fujita, K. 1994. Soft ground tunnelling and buried structures, State-of-the-Art Report, *Proc. 13th, Int. Conf. on Soil Mechanics and Foundation Engineering*, New Delhi, Vol.5, :89-108.

Harris, D. I., R. J. Mair, J. P. Love, R. N. Taylor, & T. O. Henderson, 1994. Observations of ground and structure movements for compensation grouting during tunnel construction at Waterloo Station, *Geotechnique*, 44(4): 691-713.

Harris, D. I., C. O. Menkiti, A. J. Pooley, J. A. Stephenson, 1996. Construction of low-level tunnels below Woterloo Station with compensation grouting for the Jubilee Line Extension, *Proc. of Geotehcnical Aspects of Underground Construction in Soft Ground*, Mair & Taylor(eds):361-366.

Kovacevic, N., H E. Edmonds, R.J. Mair, K. G. Higgins, D. M. Potts, 1996. Numerical modelling of the NATM and compensation grouting trials at Redcross Way, *Proc. of Geotechnical Aspects of Underground Construction in Soft Ground*, Mair & Taylor (eds):553-559.

Lee, S. W., G. R. Dasari, R. J. Mair, M. D. Bolton, K. Soga, T. Sugiyama, Y. Ano, T. Hagiwara, & M. Nomoto, 1999. The effects of compensation grouting around segmental tunnel linings, *Proc. of Geotechnical Aspects of Underground Construction in Soft Ground* (IS-Tokyo '99), Tokyo.

Mair, R.J. 1996. Settlement effects of bored tunnels, Session Report, *Proc. of Geotechnical Aspects of Underground Construction in Soft Ground*, Mair & Taylor(eds):43-53.

Mair, R .J. & D. W. Hight, 1994. Compensation grouting, *World Tunnlling*, November:361-367.

Mair, R. J. & R. N. Taylor, 1997. Bored tunnelling in the urban environment, Theme Lecture, Plenary Session 4, *Proc. 14th, Int. Conf. on Soil Mechanics and Foundation Engineering*, Hamburg, Vol.4:2353-2385.

O'Reilly, M. P. & B.M. New, 1982. Settlement above tunnels in the United Kingdom - their magnitude and prediction, *Tunnelling 82*, London, IMM:173-181.

Peck, R. B. 1969. Deep excavations and tunneling in soft ground, *Proceedings of the 7th ICSMFE* (Mexico), State of the Art Volume:225-290.

Selby, A. R. 1988. Surface movements caused by tunnelling in two−layer soil, *Engineering Geology of Underground Movements*, Bell, F. G. et al(eds), Geological Society Engineering Geology Special Publication, No.5:71-77.

Sugiyama, T., T. Hagiwara, T. Nomoto, M. Nomoto, Y. Ano, R. J. Mair, M. D. Bolton & K. Soga, 1999. Observations of ground movements during tunnel construction by slurry shield method at the Docklands Railway Lewisham Extension- east London, *Soils and Foundations*, 39(3):99-112.