

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

<https://www.issmge.org/publications/online-library>

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

Compensation grouting to control tilt of Big Ben Clock Tower

D.I.Harris & R.J.Mair

Geotechnical Consulting Group, London, UK

J.B.Burland & J.R.Standing

Imperial College of Science, Technology and Medicine, London, UK

ABSTRACT: Big Ben Clock Tower is the most famous of many historic and important structures affected by ground movements associated with construction of the Jubilee Line Extension Project in London. The construction works for the new Westminster Station are outlined. Compensation grouting undertaken to control the tilt of the Tower is described, drawing particular attention to the instrumentation used to monitor tilt and the precision to which the tilt could be controlled.

1 INTRODUCTION

The construction of Westminster Station on London Underground Limited's (LUL's) new Jubilee Line Extension (JLE) project in London was predicted to produce significant movements of The Big Ben Clock Tower and the adjoining Palace of Westminster (Fig. 1) as a result of excavation of two 7.4m OD (outer diameter) tunnels and the 39m deep station escalator box. These activities produce two components of movement; an initial, immediate movement directly associated with the progress of excavation and a time related component due to drainage and consolidation of the London Clay. Protective measures, primarily in the form of compensation grouting below the Clock Tower, have been implemented during the construction period to control settlement and tilt of the structure.

This Paper describes the compensation grouting and monitoring procedures undertaken over a 21 month period to control the tilt of the Clock Tower during construction of the tunnels and the deep excavation for the station box.

2 JLE WESTMINSTER STATION

The layout of the new Westminster Station on the JLE is shown in plan on Figure 2 and in section on Figure 3. The station comprises bored 7.4m OD platform tunnels in a vertically stacked arrangement below Bridge Street with a 39m deep diaphragm wall box to the north. Access to the platforms is provided by four adits between the tunnels and the box at both tunnel levels. Escalators to the ticket hall and Bridge Street

with interchange facilities to the new District and Circle station are provided within the station box. Design of the station is described by Carter et al. (1996).

Prior to any substantial excavation within the station escalator box, the running tunnels were driven from east to west as pilot tunnels. The lower, westbound (WB) tunnel was constructed in March 1995 and the upper, eastbound (EB) tunnel in October 1995 at depths of 30m and 21m below ground level respectively. The running tunnels are 4.85m OD and were built in expanded concrete segmental linings, each of which was 1.0m in length. A Howden open face shield with a backactor was used for both drives.

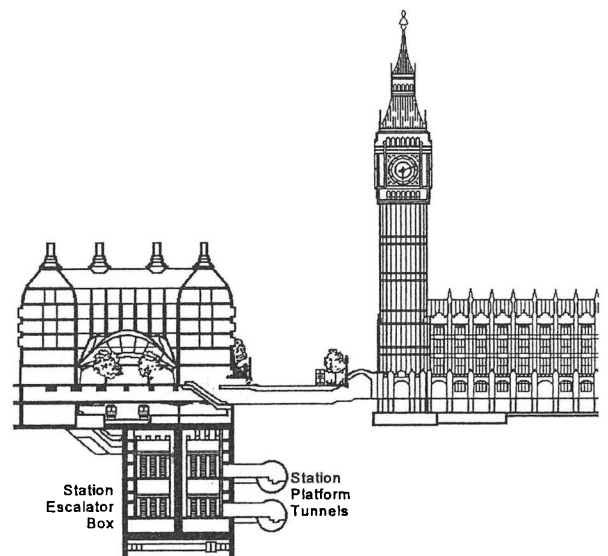


Figure 1. Big Ben and the Palace of Westminster.

The 9.4m OD shield chambers for the platform tunnels were at the west end of the tunnels (see Fig.2). The platform tunnels were driven from the shieldchambers in the opposite direction to their pilots, necessitating mucking to be carried out through the

face. An open face shield with a backactor was also used for the enlargement to form the platform tunnels. The tunnels are 160m long and are lined with bolted segmental SGI (Spheroidal Graphite Iron) rings each of 1m width. The WB platform tunnel was constructed

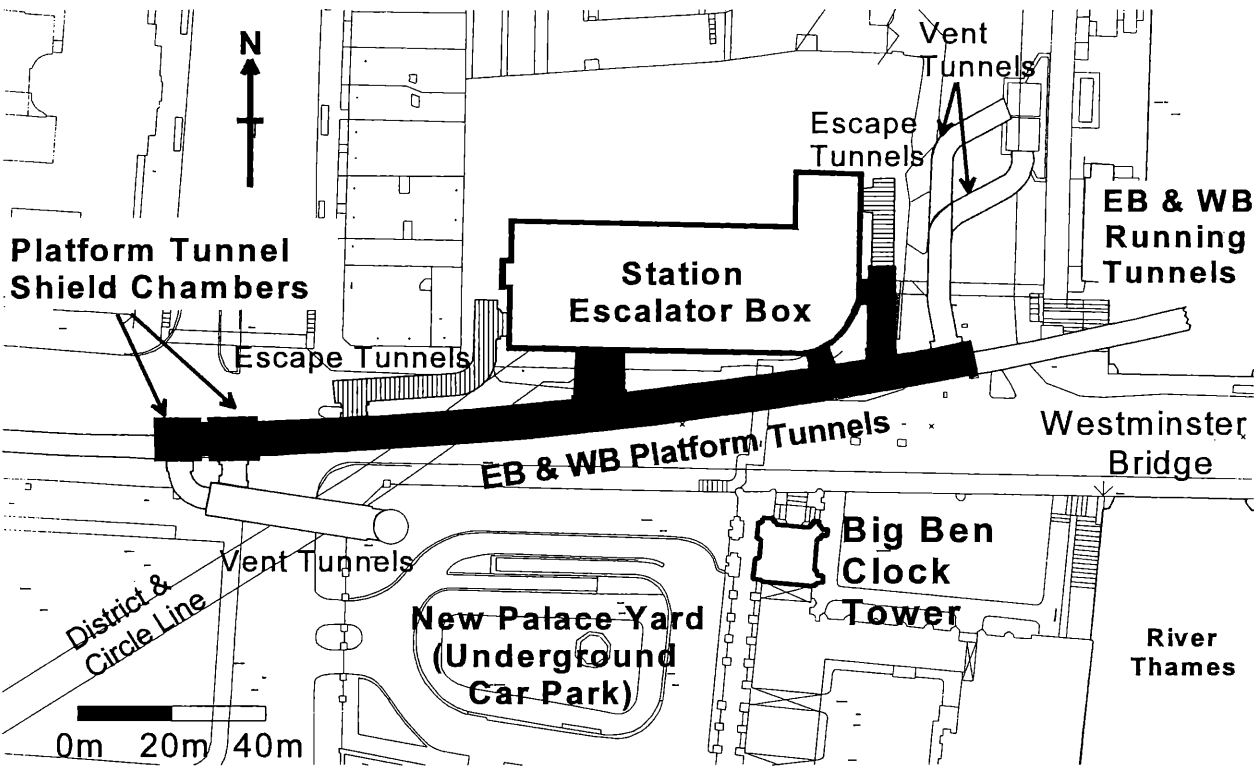


Figure 2. Plan of JLE Westminster Station.

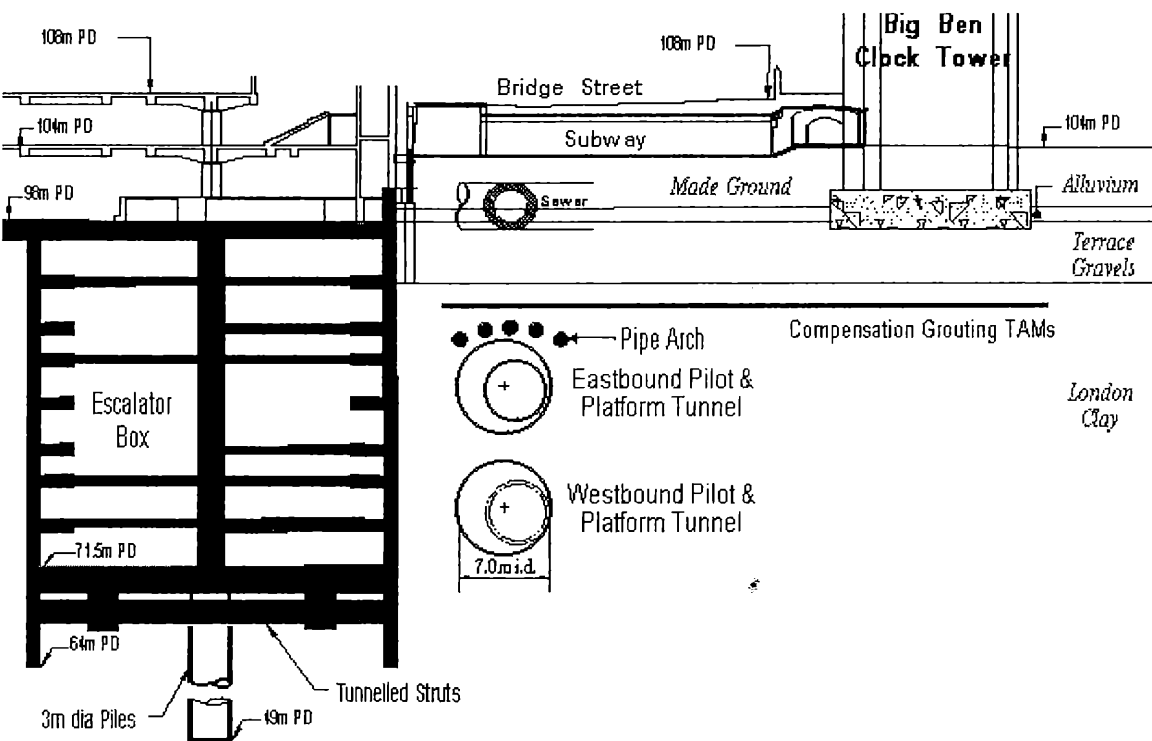


Figure 3. Section through JLE Westminster Station.

in February 1996 and the EB in November 1996. The ventilation and escape tunnels (Fig. 2) were hand mined and lined with bolted segmental linings of concrete and SGI. These tunnels had negligible effect on the Clock Tower.

The station escalator box excavation was supported by a king post retaining wall to a level of 100m PD up to 8m below adjacent street level. Diaphragm walls were constructed from this level to a maximum depth of 40m. The diaphragm wall box is 74m by 28m in plan and, with excavation up to 39m below street level, is substantially the deepest basement ever to have been constructed in London. The structure was built using a 'top down' technique but with low level tunnelled struts installed close to the base of the diaphragm wall prior to excavation below the main roof slab at 98m PD (Crawley and Stones, 1996). The location of the tunnelled struts is shown in elevation on Figure 3 and in plan on Figure 4. Excavation to 100m PD level was completed by December 1994 with the excavation with the diaphragm walls undertaken between September 1995 and September 1997.

3 COMPENSATION GROUTING FACILITIES

The Big Ben Clock Tower was constructed in 1858, and consists of load bearing brickwork with a stone cladding to a height of 61m, supporting a cast iron framed spire to the total height of 92m. The Tower is founded on a mass concrete raft 15m square and 3m thick. The raft is founded within the Terrace Gravels about 7m below the adjacent ground level. The Tower is estimated to have a mass of 85.4MN giving an average bearing pressure of about 400kPa.

The north edge of the Tower is 31m from the diaphragm walls of the 39m deep escalator box. Construction of the 18m deep New Palace Yard car park (see Fig. 2), which is 16m to the west of the Clock Tower, caused the Tower to tilt towards the car park by about 1:4000 (Burland & Hancock, 1977). Analysis indicated that the Clock Tower was likely to tilt towards the new station by a significantly greater amount unless protective measures were implemented. In addition to the low level tunnelled struts described above, compensation grouting was introduced as a contingency protective measure.

The plan area over which grouting arrays were required was determined from settlement assessments carried out by the contractor, Balfour Beatty - Amec Joint Venture (BBA). These resulted in a proposal to install grouting arrays over all of the tunnels in the Westminster Station complex to protect a number of structures and services within the zone of influence including Big Ben Clock Tower. The extent of the arrays was in general defined by extending in elevation a 45° line from the centre of the tunnels to the grouting horizon. A notable exception to this rule was made in the case of the Clock Tower where the arrays were

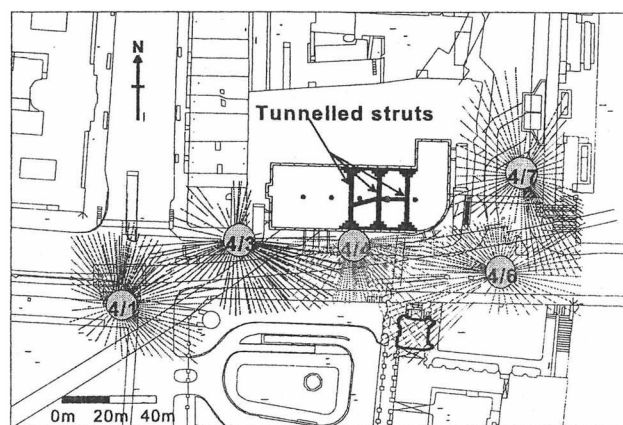


Figure 4. Compensation grouting arrays and tunnelled struts.

extended below the full footprint of the Tower's foundations. The extent of the arrays installed which required 10.5 km of drilling, is shown on Figure 4.

The settlement assessments carried out using empirical methods prior to the commencement of excavation works indicated that an increase in tilt of approximately 1:2000 could be anticipated based on a combination of predicted short term movements determined separately for the tunnels and for the deep box excavation. LUL had previously, during the Parliamentary proceedings, commissioned Geotechnical Consulting Group (GCG) to carry out sophisticated finite element analyses (FEA) to assess the validity of superposition of movements from the two sources and the potential for long term consolidation settlements. The results of these analyses demonstrated that movements could be substantially increased by interaction effects and that long term settlements could be expected following tunnelling, but these would be offset to some extent by swelling associated with the large unloading of the ground during the box excavation (Higgins et al., 1996). Thus, prior to construction, it was anticipated that a substantial proportion of the construction works could be completed without the change in tilt of the Clock Tower exceeding 1:2000.

The provision of grouting arrays below one of London's busiest areas was not a simple matter. The only practical option was to install horizontal arrays of Tubes à Manchettes (TAMs) by drilling from vertical shafts. Identification, negotiation and procurement of the necessary sites was problematic; eventually five locations were obtained (see Fig. 4) which allowed the desired area to be covered with a maximum drilling length of 60m. The elevation of the TAMs was constrained to be between the upper platform tunnel and the London Clay / Terrace Gravel interface (see Fig. 3). In order to minimise the potential effect of grouting on the tunnel, the maximum clearance should be maintained between the tunnel and the grouting horizon. At the same time, drilling in London Clay

without provision for dealing with large quantities of ground water necessitates that an adequate cover is maintained to the overlying permeable stratum. The clay cover to the tunnel was about 5m and consequently the selected grouting horizon was 3m above the crown of the upper station tunnel, as shown on Figure 3.

The main contractor, BBA, employed a joint venture, AMEC-Geocisa, as a sub-contractor to undertake all grouting works. They were responsible for proposing the layout of TAMs. Initially six TAMs were installed from Shaft 4/4 below the Tower with a maximum spacing of 5m. Subsequently, due to changes in other construction activities, these arrays had to be replaced; a total of 16 TAMs were then installed from Shaft 4/6 with the maximum spacing reduced to 2.5m (see Fig. 4).

4 STRATEGY FOR IMPLEMENTATION OF COMPENSATION GROUTING

No grouting below the Tower was carried out during the first of the 4 main tunnel drives (the WB running tunnel). Limited grouting was undertaken from the arrays within the 45° splay trough but this proved ineffective in fully mitigating settlements above the tunnel and in preventing tilting of the Clock Tower. The tilt continued to increase significantly following the tunnel drive and it was evident that a re-appraisal of the potential movements was necessary and a strategy for implementation of compensation grouting to control tilt of the Clock Tower was required.

A back analysis of the recorded settlements associated with the WB running tunnel drive was carried out which indicated that volume losses in this area were about 3%, significantly greater than had been allowed for in the settlement assessments (2%). A revised assessment indicated that the predicted change in the tilt of the Tower increased by 50%. The observed increase in tilt after the WB tunnel drive confirmed that substantial time dependent movements should also be expected both during the construction period and subsequently.

Thus it was clear at this early stage of construction, with three further tunnel drives and virtually the full depth of the escalator box still to be excavated, that protective measures to control the tilt of the Tower would be essential. The following actions, inter alia, were taken:

- co-ordination of tunnel advance with the implementation of grouting to allow settlement to be fully compensated,
- an absolute limit on the permissible increase in the northward tilt of the Clock Tower of 1:2000 was set,
- a trigger level on the tilt of the Tower was set at which grouting would be instigated,
- a trial grouting episode below the Tower to

demonstrate that control could be exercised,

- a review panel, comprising Prof John Burland, Dr. Robert Mair and Dr. John King was established to advise on geotechnical and construction issues relating to the Clock Tower,
- close liaison with Parliamentary Works Directorate would be maintained through their geotechnical advisors, Ove Arup & Partners,
- GCG were commissioned to update the FEA undertaken earlier during the Parliamentary proceedings to take account of revised construction methods and sequences. The analysis was calibrated against observed settlements to give the best possible prediction of future movements. The results of the FEA assisted in identifying potential mechanisms of movement of the Clock Tower and the adjoining Palace of Westminster and allowed variations in the excavation and construction procedure of the station box to be investigated.
- further independent measurements of horizontal and vertical movements of the Palace of Westminster were arranged through the LINK research project into the response of buildings to tunnelling-induced ground movement being undertaken by Imperial College (IC) on the JLE (Burland et al., 1996).

The grouting management system developed was that all grouting had to be defined in terms of grouting proposals with injection locations prescribed in terms of shaft, TAM and sleeve number. The volume of each injection was also pre-determined and sequences of injections were also specified if deemed necessary. The grouting was controlled through a monitoring control office which was also in direct communication with the tunnellers and surveyors, and had access to the real time monitoring. Each grouting proposal incorporated communication procedures which required a positive confirmation to be received from the monitoring control office after completion of a specified part of the proposal before work could proceed. For example with an advancing tunnel, a pattern of injections relative to the face was defined (Harris et al., 1996). Injection could only commence once a given stage of the tunnelling cycle had been completed. The injections would then be undertaken and would have to be completed before tunnelling could proceed beyond a specific point.

In order to maintain the required flexibility to modify grouting proposals in response to observed behaviour, frequent meetings were held to review construction progress, grouting records and monitoring results. Minor modifications were made by omitting injections or changing grout volumes. If more significant changes were necessary a revised proposal would be produced. The short timescales for production, discussion, amendment and consenting to grouting proposals, required a co-operative approach from all parties to avoid delays to the works.

5 INSTRUMENTATION

Reliable and accurate monitoring, its rapid processing and dissemination and informed interpretation in conjunction with records of construction activities are the keys to successful implementation of the compensation grouting technique. The following instrumentation was installed on Big Ben Clock Tower and the adjacent Palace of Westminster.

5.1 Tilt monitoring

Tilt of the Clock Tower was identified as the most important parameter to monitor and consequently a range of independent systems were used.

An optical plumb had been used to monitor the tilt of the Clock Tower during construction of the New Palace Yard underground car park in the early 1970s (Burland & Hancock, 1977) and had been read intermittently over the intervening period. The original target which was removable was still available and it was decided that the JLE surveyors should monitor this. A Wild ZL optical plumb was used. A new datum was established which was related to the original datum giving a self-consistent data set extending over a period of nearly 30 years. A re-designed target was procured to improve the repeatability of the readings. Observations are taken on each of four faces in the north-south and east-west directions and then averaged to give a reading. The observations are recorded to an accuracy of 0.1mm and the 4 independent observations generally lie within a range of 0.5mm. The resolution and precision over the 55.4m gauge length are equivalent to tilts of about 1 in 550,000 and 1 in 110,000 respectively. Background diurnal movements described in Section 6 make it difficult to determine the accuracy of the measurements but it is considered to be about 1mm (c. 1 in 50,000).

Retro prism targets attached to the north, east and west clock faces were surveyed to give displacements in three dimensions using a Leica TC1610 Total Station. The observation of each target required a separate set-up location and hence the three measurements were entirely independent. Readings were taken to a resolution of 0.1mm for distance and 1" of arc on horizontal and vertical angles. The repeatability of readings was $\pm 2\text{mm}$ or 1 in 13,000.

In order to avoid the need for excessive surveying resources during grouting episodes, a real-time monitoring system was necessary. Eight electrolevels were installed on 1 metre long beams, six of which were mounted horizontally and the other two vertically. Four were oriented to measure north-south tilt and the other four east-west tilt. In the event, these instruments were not used to control the works due to the success of an alternative real time system developed by the contractor, an electronically monitored plumb line.

The electronically read (or digitised) plumb line was developed by the BBA surveying department and was named the "Gedometer" after its primary creator Gerald "Ged" Selwood. The instrument comprised a steel (latterly invar) strip suspended from a grillage in the belfry over a ventilation shaft which extends over the full height of the Tower in its northeast corner. A temporary decking was installed in this shaft 5m above ground level (which gave an almost identical gauge length to the optical plumb) on which a digitising tablet was installed. A puck was suspended from the end of the plumb line and the tablet programmed to automatically record the location of the puck at 1 second intervals. Individual observations were averaged to produce a reading at specified intervals; generally 30 minutes was found to be adequate. The instrument has performed reliably for a period of 4.5 years with only occasional adjustment and maintenance. In these instances adjustments to the recorded movements have been necessary. The readings are reported to 0.001mm and the accuracy is arguably as good as 0.1mm or 1 in 550,000 over the period of individual compensation grouting episodes.

A system of precise levelling primarily to monitor settlement is described below, however the four points on the corners of the Tower have been used to calculate a tilt of the Tower. The accuracy of the levelling for the four corner points generally lie within about $\pm 0.3\text{mm}$. The points are approximately 12m apart and hence the accuracy of the tilt calculated from the results over the 55m gauge length is at best 2.8mm or 1 in 20,000.

5.2 Settlement monitoring

Settlement has been monitored using a single system: precise levelling but with readings taken by three independent teams of surveyors (BBA, JLEP and IC). BRE sockets which had been installed to monitor movements during construction of the underground car park were augmented by additional points to provide a comprehensive system of 42 points on the Tower and the adjoining Palace of Westminster. Points were also installed in the subway below Bridge St to give a continuous profile over a distance of up to 90m from the escalator box diaphragm walls on a north - south section. The location of datums used by the three teams of surveyors differed but if the results are compared on a consistent basis discrepancies rarely exceeded 0.5mm.

5.3 Horizontal displacement

The potential for concentration of horizontal strain on pre-existing lines of weakness within the structure was of particular concern. Two systems of monitoring horizontal displacements were established. A string of retro targets for total station monitoring was used by

BBA and tape extensometer measurements were taken between the precise levelling BRE sockets by the Imperial College team.

5.4 Crack widths

A number of pre-existing cracks identified in the pre-construction defect survey were instrumented. Demec studs in pairs, and sets of three were installed and monitored by BBA using a digital vernier and by Imperial College using an original Demec gauge.

5.5 Temperature

Four temperature sensors were installed in the Tower.

5.6 Appraisal of tilt monitoring

The five methods used to measure the tilt of the Tower have been described. Of these four, excluding the electrolevels, gave stable and reliable readings. The Gedometer is the only system for which a reading is available for virtually every day. The mean daily tilt calculated from the Gedometer results has therefore been used as the basis against which measurements from the other systems have been compared. Figure 5 shows the difference between the tilt measured by the optical plumb, two sets of precise levelling and the retro prisms over a period of 4 years.

The results of all five sets of independent measurements can be seen to agree to within 1 in 20,000, or 3mm over the 55.4m normalised gauge length, for the vast majority of the readings. There are very few readings outside a tolerance of 1:10000. It cannot be assumed that the Gedometer result is the correct value and there is some indication that prior to March 1996 that there is a systematic variation in the differences between the Gedometer and the other three monitoring systems; this perhaps suggests that the

Gedometer was slightly less accurate over this period. The retro prisms appeared to give the largest discrepancies and also took the longest to monitor. Readings from this system were discontinued in September 1996 since a high degree of confidence had been gained in the accuracy and reliability of the other systems. It should be noted that the Tower itself moves due to environmental factors such as temperature, sunlight and tide. The maximum magnitude of these background movements in the north south direction is about 3mm.

6 OBSERVED TILT OF THE TOWER

The measured tilts of the Tower from the optical plumb throughout the construction period and for six months thereafter are shown on Figure 6. The timings of the main construction activities are indicated on the figure: the passage of the four tunnel drives are shown across the top of the figure and the dates of installation of the props at various levels within the escalator box excavation are shown at the bottom. The thick vertical line at December 1995 indicates the commencement of grouting to directly control the tilt of the Tower and the episodes of grouting undertaken up to September 1997 are indicated.

Northward tilt commenced in March 1995 as the westbound running tunnel was driven; an immediate movement of about 4mm was recorded. The tilt then increased at an approximately constant rate of 1.1mm/month until October 1995. For the eastbound running tunnel grouting within the settlement trough was undertaken with the progress of the tunnel controlled such that settlements were limited to a few mm by the compensation grouting. The Tower is outside the zone of influence of the shallower eastbound running tunnel, and the tunnel produced no noticeable effect on the tilt of the Tower. Shortly

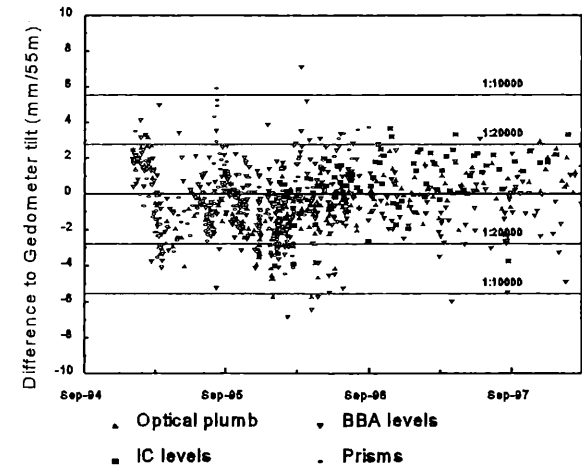


Figure 5. Comparison of tilt monitoring results.

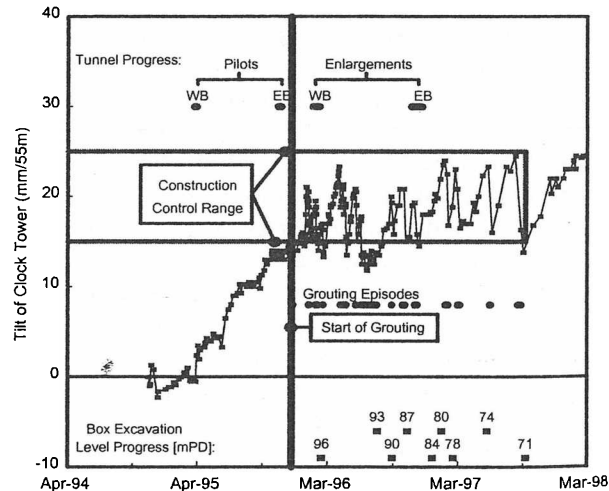


Figure 6. Optical plumb results for North-South tilt.

afterwards a trial episode of grouting was undertaken in December 1995. This was inconclusive and a further trial was delayed until February 1996 by the need to replace the TAMs below the Tower as described in Section 3. The tilt to the north was successfully reduced by 5mm over the 55m gauge length (c. 1:11,000) in this second trial confirming both the suitability of the method and that a good degree of control could be exercised.

The next episode of grouting was associated with the enlargement of the WB platform tunnel. Grout quantities were estimated from experience on the EB running tunnel and the first episode of grouting below the Tower such that full compensation for the tunnelling induced movements and a small reduction in the tilt would be produced; this was successfully achieved with the tilt reduced by 5mm. Thereafter, during the box excavation from 96m PD to 71m PD and the enlargement for the EB platform tunnel, grouting was undertaken in response to the observed tilts of the Tower rather than being directly related to construction activities.

The absolute maximum permissible limit on tilt had been determined as 1:2000 which is equivalent to about 27.5mm over the 55m gauge length used to compare the various instrumentation results. A trigger for initiation of grouting was also agreed at 1:2500 (c.22mm). In practice a construction control range of between 15mm and 25mm increase in tilt was adopted. Figure 6 shows that the upper limit of this control range was not exceeded throughout the construction period. A total of 24 episodes of grouting were undertaken between January 1996 and September 1997 in which a total volume of 122m³ of grout was injected.

As confidence was gained in the predictability of the response of the Tower to grouting, the area over which grouting was undertaken and the volume of grout injected in each episode was progressively adjusted to produce optimal results. The pattern of injections used most frequently is illustrated on Figure 7 which is for Episode 8. The plan location of the ports are indicated by the symbols and the volume injected in litres for each particular port is given alongside. The pattern is based on a 3m square grid with a port selected as representative of each square - with radial arrays from a shaft completely uniform rectangular grid cannot be achieved. The notional plan area covered by the grid is 30m x 21m giving a theoretical maximum of 70 injections. Episode 8 comprised 64 individual injection undertaken in two half passes. The circles and squares on Figure 7 are the first half pass and the triangles the second half pass. The pre-determined volume per injection was 72l; all but 2 injections were (to within practical tolerances) equal to the pre-determined value.

The cumulative volume of grout injected during Episode 8 is plotted on the right hand vertical axis of

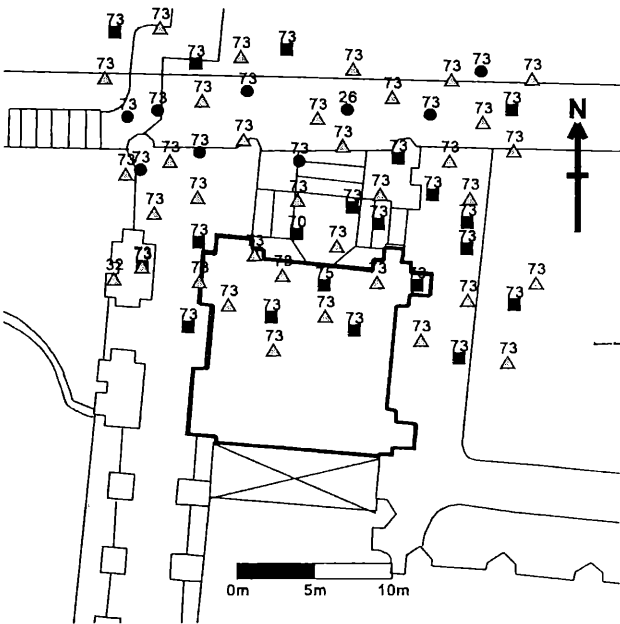


Figure 7. Grout injection pattern for the Clock Tower.

Figure 8 against time. Three periods of virtually continuous grouting are indicated which correspond to the three sets of injections shown on Figure 7 with a total volume of 4600l or 4.6m³. Also shown on Figure 8 is the change in tilt of the Tower (left hand vertical axis) recorded by the Gedometer. The northward tilt reduced by 5.6mm with a very close correlation with the volume of grout injected; thus 1m³ of grout reduced the tilt by 1.25mm. A slight tendency for the tilt to increase in the periods between and after grouting can be seen on the figure. A review of the data was carried out on the morning of 27/06/96 before the second half of the injections commenced.

The east west component of tilt shows a positive (westward) tilt of the Tower developed prior to the commencement of grouting. This is an example of the diurnal variations in the tilt measurements of the Clock Tower which have been shown to have a definite and predictable relationship with direct sunlight (or thermal radiation). Differential temperature between opposing faces of the structure caused by direct

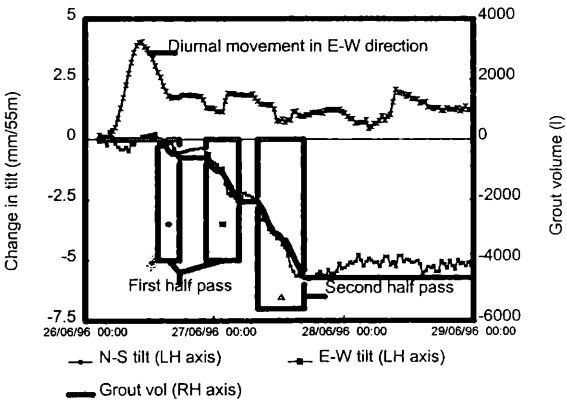


Figure 8. Episode 8: Change in tilt and grout volumes.

sunlight on one face produces bending of the Tower which is recorded as a change in tilt, although it is not a rigid body rotation. A maximum recorded daily range of tilt of 6.2mm has been recorded in the East-West direction compared to a cycle of about 2.5mm in the north-south axis. The magnitude of the thermal bending is related to the number of hours sunshine during the day and is consequently at its greatest in the summer months. Thus, in the summer months, the top of the Tower traces an approximately elliptical path with its major axis in the east-west direction (Fig. 9).

Immediately following grouting Episode 8, which is described above, it was decided to undertake further grouting episodes on a weekly basis to gain further insight into the response of the Tower. This was continued for a period of 6 weeks (Episodes 9 to 14). The volume of grout injected in these Episodes varied between 1.1 and 4.6m³. During this period the tilt was controlled within a range of about 2mm as illustrated on Figure 10. Thus compensation grouting is capable of controlling the tilt or slope to within a tolerance of less than 1:25000.

The total volume of grout injected below the Clock Tower in the 24 episodes of grouting was 122m³ which produced a cumulative reduction in the observed tilt of almost 100mm.

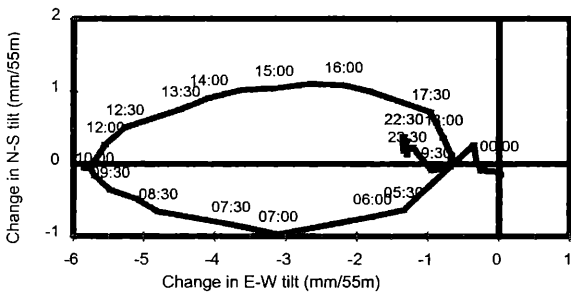


Figure 9. Diurnal variation in tilt of Clock Tower.

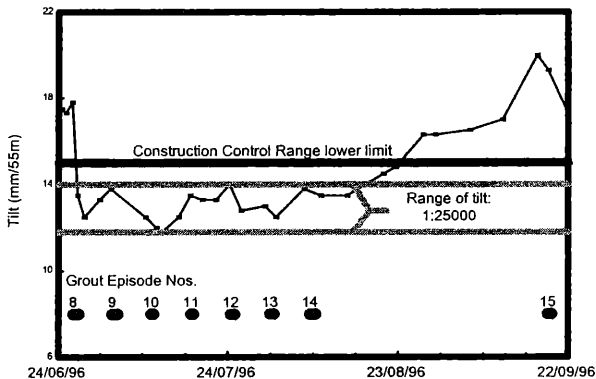


Figure 10. Tilt control during period of weekly grouting.

7 CONCLUSION

Compensation grouting has been used to control the tilt of the Big Ben Clock Tower during the construction of the new JLE Westminster Station. A number of very accurate systems of monitoring tilt have been used to record changes in tilt of the Tower. The implementation of compensation grouting has been extremely successful and it has been shown that control can be maintained within very fine tolerances using this technique.

REFERENCES

- Burland, J.B. & R.J.R. Hancock, 1977. Underground car park at the House of Commons, London: geotechnical aspects. *The Structural Engineer*. 55 (2), 87-100.
- Burland, J.B. et al., 1996. A collaborative research programme on subsidence damage to buildings: prediction, protection and repair. In R.J.Mair & R.N.Taylor (eds.), *Geotech. Aspects of Underground Construction in Soft Ground*: 773-778. Rotterdam: Balkema.
- Carter, M.D. et al. 1996. Jubilee Line Extension, Westminster Station design. In R.J.Mair & R.N.Taylor (eds.), *Geotech. Aspects of Underground Construction in Soft Ground*: 81-86. Rotterdam: Balkema.
- Crawley, J.D. & C.S.Stones, 1996. Westminster Station -deep foundations and top down construction in Central London. In R.J.Mair & R.N.Taylor (eds.), *Geotech. Aspects of Underground Construction in Soft Ground*: 93-98. Rotterdam: Balkema.
- Harris, D.I. et al. 1996. Construction of low-level tunnels below Waterloo Station with compensation grouting for the Jubilee Line. In R.J.Mair & R.N.Taylor (eds.), *Geotech. Aspects of Underground Construction in Soft Ground*: 361-366. Rotterdam: Balkema.
- Higgins, K.G., et al., 1996. Numerical modelling of the influence of the Westminster Station excavation and tunnelling on the Big Ben Clock Tower. In R.J.Mair & R.N.Taylor (eds.), *Geotech. Aspects of Underground Construction in Soft Ground*: 525-530. Rotterdam: Balkema.