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

Numerical modelling of the influence of the Westminster Station excavation and tunnelling on the Big Ben clock tower

K.G.Higgins & R.J.Mair
Geotechnical Consulting Group, London, UK

D.M.Potts
Imperial College of Science, Technology and Medicine, London, UK

ABSTRACT: This paper describes analyses of the effects of construction of the Jubilee Line Westminster Station on the adjacent "Big Ben" clock tower. Construction of the station involves an excavation to approximately 37m below ground level, 33m away from Big Ben. Between the excavation and Big Ben two tunnels are to be constructed. In order to estimate potential movements of Big Ben, a series of finite element analyses was undertaken, using an idealised construction sequence. Fully coupled consolidation and non-linear elastic constitutive perfectly plastic models were adopted for the soils. Predictions of the potential settlement and tilt of the structure are presented.

1. INTRODUCTION

The construction of an underground station at Westminster forms part of the Jubilee Line Extension Project (JLEP). To form the proposed station, an excavation is to be undertaken to the north of Bridge Street (Figure 1). Two 7.3m diameter tunnels are also to be constructed. Formation of the station box will involve excavation to approximately 37m below ground level. The station tunnels have the same horizontal alignment and are to be constructed to the south of the excavation, generally following the line of Bridge Street. The Palace of Westminster and the Big Ben clock tower are located to the south of Bridge Street. In order to assess potential ground movements associated with the station construction, a series of finite element analyses was undertaken. They were used, by London Underground Ltd's JLEP Team, to provide evidence for the House of Lords Select Committee prior to construction of the station.

There were two forms of analysis; one modelled the construction of the station box alone, and the second analysed construction of the station tunnels as well. The analyses described in this paper examined the sensitivity of Big Ben's movement to:

(i) Restraint of the diaphragm wall at base slab level before starting the excavation for the station box.
(ii) Partial drainage in the London Clay and Woolwich and Reading Bed (WRB) clay during construction.
(iii) The effect of tunnel construction.

2. BASIS OF THE ANALYSES

Figure 2 shows the cross-section (section A-A) analysed together with the assumed soil stratigraphy deduced from the investigations at the site. The same cross-section was used for all analyses. None of the analyses modelled the loading applied to the ground by Big Ben nor the rigidity of the structure. Big Ben is founded on a mass concrete raft at the top of the Thames Gravels. Application of an assumed load to plane strain analyses was considered to be unrealistic. Because the structure is of relatively short length compared to the excavation it could not reasonably be represented as an infinitely long element in the analyses.

During excavation for the station box, the diaphragm wall is to be supported in one of two ways, either by prestressed temporary supports which are eventually replaced by individual permanent struts (type A wall panels), or by continuous slabs which form the permanent works (type B wall panels). The "least stiff" type A panels were specified by the designers where escalators will pass down through the station and this support system was assumed for the analyses.

Table 1 summarizes the main features of the analyses undertaken. They all followed the same general construction procedure. After initial conditions had been established, the running tunnels (pilots) were constructed. Construction of the station box then followed. Temporary pre-stressed supports to the wall were introduced as excavation proceeded but once formation level had been reached, and the base slab constructed, the temporary propping system was replaced by the permanent supports. The running tunnels were then enlarged to form the station tunnels. In the analyses modelling tunnel construction, the "λ" factor approach (Panet and Guenot (1982)) was adopted. Volume losses in the range 2-2.5% were achieved corresponding to lining loads in the range 30-50% of overburden immediately upon construction (corresponding to "λ" values of 0.5-0.7). These are consistent with measurements associated with the construction of single tunnels in London Clay.

Runs 1B, 1C and 3B modelled construction of the station box alone, ignoring the effect of tunnel construction. These analyses were intended to examine the sensitivity of

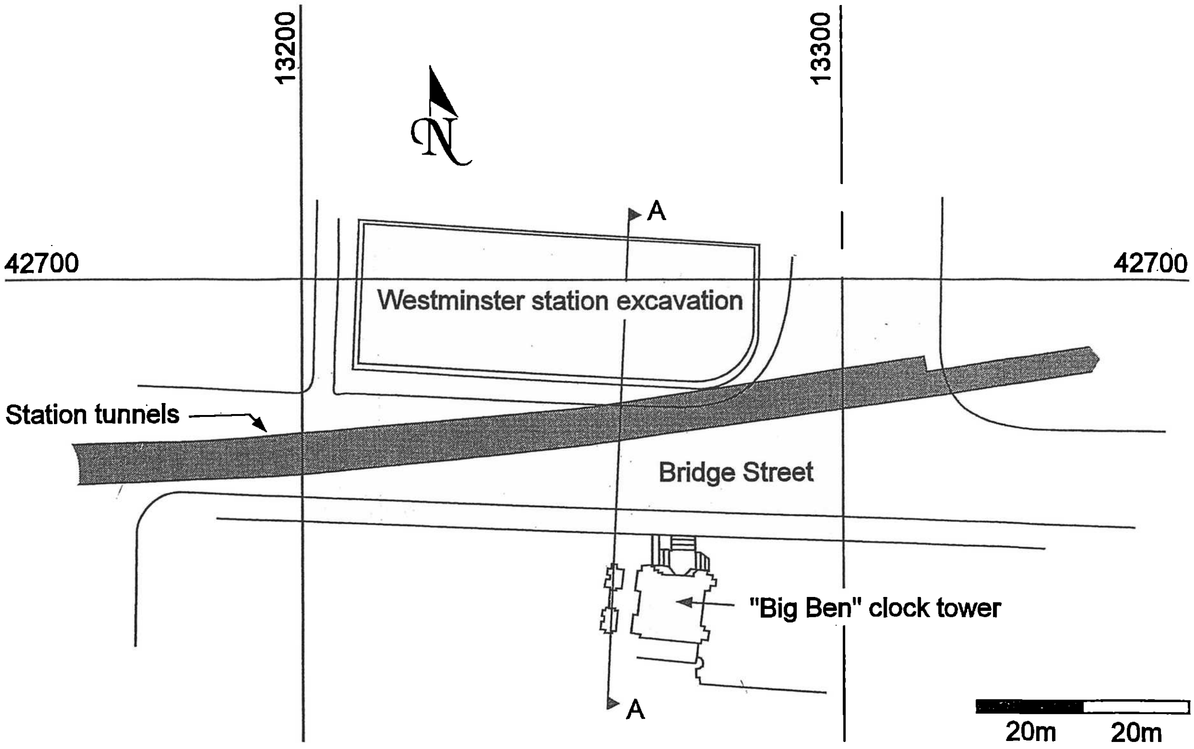

Figure 1: Plan of the site showing the cross section analysed

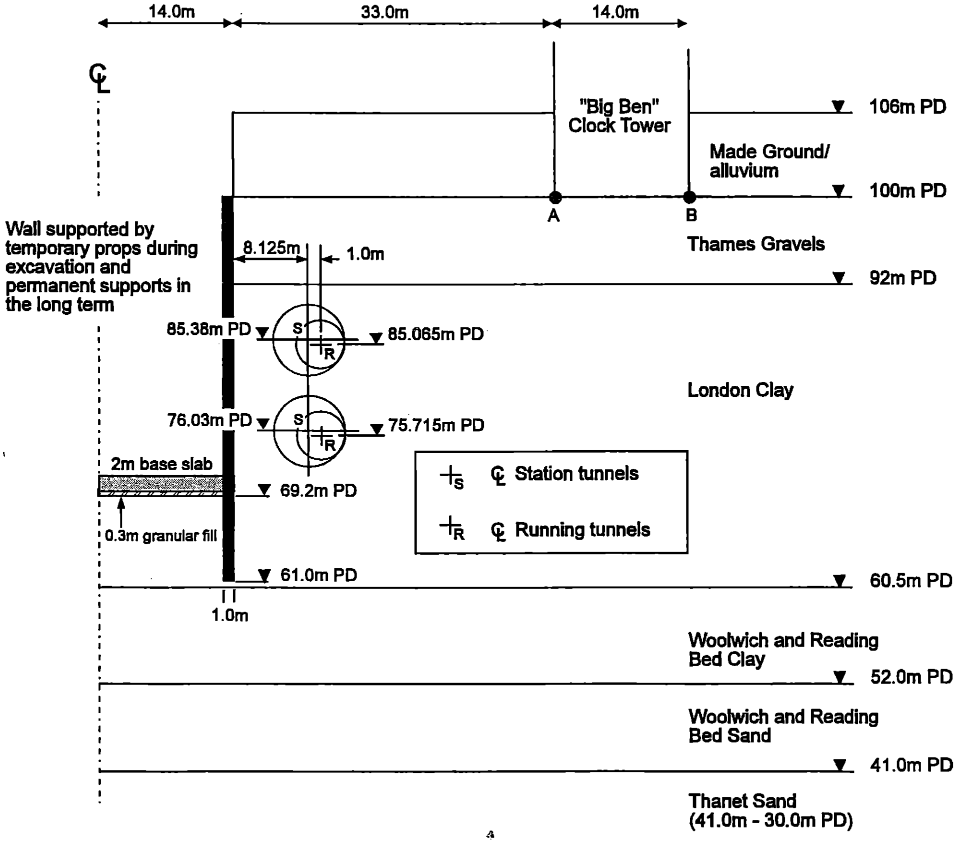

Figure 2: Cross section analysed (Section A-A, Figure 1)

Table 2 : Soil Properties

Strata	Density (kN/m³)	K_o	c' (kN/m²)	φ'	Angle of dilation		E' (MN/m²)	μ	Permeability (m/s)	
					Comp.	Extn.			Vert.	Horz.
GRANULAR FILL	20.0	0.5	0.0	35.0°	0.0°	0.0°	10.0	0.2	-	-
MADE GROUND & ALLUVIUM	19.0	0.5	0.0	25.0°	0.0°	0.0°	5.0	0.2	-	-
THAMES GRAVEL	20.0	0.5	0.0	35.0°	17.5°	0.0°	NON - LINEAR ELASTIC PARAMETERS, SEE TABLE 3		-	-
LONDON CLAY 92.0-83.0mOD	20.0	1.4	5.0	23.0°	12.5°	0.0°			$1.0x10^{-9}$	$0.5x10^{-9}$
LONDON CLAY 83.0-73.0mOD	20.0	1.4 to 1.1	5.0	23.0°	12.5°	0.0°			$1.0x10^{-8}$ to $1.0x10^{-10}$	$1.0x10^{-9}$ to $0.5x10^{-10}$
LONDON CLAY 73.0-83.0mOD	20.0	1.1	5.0	23.0°	12.5°	0.0°			$1.0x10^{-10}$	$0.5x10^{-10}$
WRB CLAY	20.0	1.1	250.0	27.0°	13.5°	0.0°			$2.0x10^{-11}$	$1.0x10^{-11}$
WRB SAND	20.0	1.0	0.0	34.0°	17.0°	0.0°			-	-
THANET SAND	20.0	1.0	0.0	40.0°	0.0°	0.0°			-	-

Table 3: Coefficients for non-linear soil stiffness expressions

STRATA		A	B	C(%)	δ	λ	R	S	T(%)	γ	Δ
Thames gravel	comp.	1104	1035	5×10^{-4}	0.974	0.940	275	225	2×10^{-4}	0.998	1.044
	extn.	1380	1248								
London clay 92.0m - 83.0m	comp.	1120	1016	1×10^{-4}	1.335	0.617	514	475	1×10^{-3}	2.069	0.420
	extn.	896	813				549	506			
London clay 83.0m - 60.5m	comp.	1400	1270	1×10^{-4}	1.335	0.617	686	633	1×10^{-3}	2.069	0.420
	extn.	1120	1016				549	506			
WRB Clay	comp.	1000	1045	5×10^{-4}	1.334	0.591	530	460	5×10^{-4}	1.492	0.678
	extn.										
WRB Sand	comp.	1300	1380	1×10^{-4}	1.220	0.649	275	235	5×10^{-4}	1.658	0.535
	extn.	1350	1330		1.075	0.715	495	400			
Thanet Beds	comp.	930	1120	2×10^{-4}	1.100	0.700	190	235	1×10^{-3}	0.975	1.010
	extn.	1000	700	1×10^{-4}	0.660	1.250	350	240	21×10^{-4}	1.160	1.020

Table 4: Summary of results

RUN	COMPLETION OF CONSTRUCTION			LONG TERM		
	ΔY-A (mm)	ΔY-B (mm)	TILT	ΔY - A (mm)	ΔY - B (mm)	TILT
1B	14	8	1:2500	17	10	1:2260
1C	9	5	1:5190	10	6	1:3890
3B	5	4	1:8750	8	5	1:6360
4B	40	21	1:750	43	23	1:680
4C	45	24	1:690	45	24	1:680

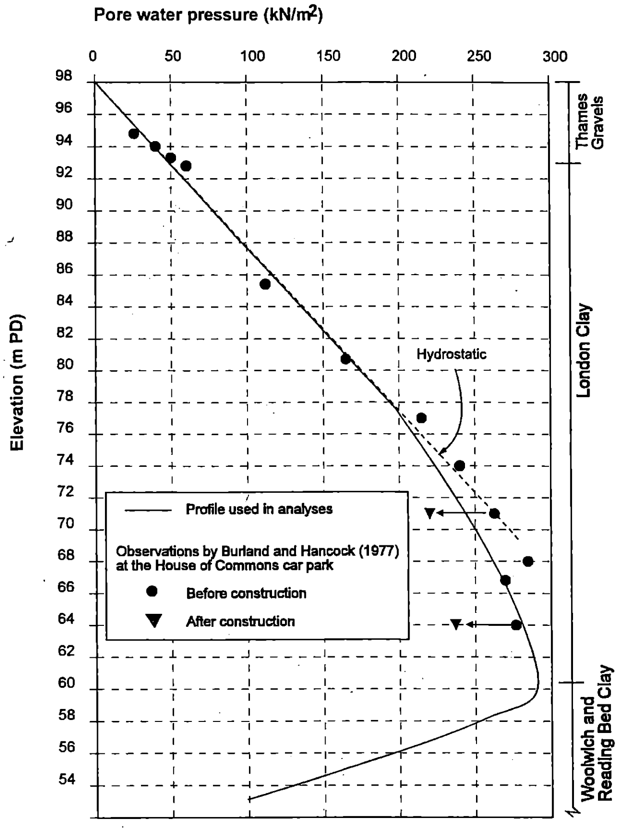

Figure 4: Pore water pressure distribution

clay were assumed to be undrained until construction had been completed in Runs 1B, 3B and 4B. Thereafter they were allowed to drain to a steady state condition. However, in Runs 1C and 4C the clays were allowed to continually drain.

In the analyses that modelled tunnel construction it was assumed that the tunnel linings were permeable. Therefore, immediately after a tunnel had been constructed it was assumed that the pore pressures around the lining would be zero unless the analysis indicated that a suction existed. At any point on the boundary where a suction existed the pore pressure was not specified until the suction reduced to zero. Thereafter the pore pressure was maintained at zero. Removal of the suction when the tunnel was completed by immediately setting the pore pressure to zero would have implied a supply of water from the tunnel to the soil. This was considered to be unrealistic.

4. RESULTS OF THE ANALYSES

Big Ben is founded directly on the surface of the Thames Gravels and is, at the closest point (Point A, see Figure 2), approximately 33m from the sides of the excavation for the station box. It is approximately 14m wide; the furthest point (Point B, see Figure 2) is therefore appoximately 47m from the excavation. Table 4 summarizes the results of the analyses giving the vertical displacements of points A and B upon completion of construction and in the long term. The simplified analyses (Runs 1B, 1C & 3B) were intended only to demonstrate the effects of various assumptions prior to undertaking the more detailed analyses combining tunnel and station box construction (Runs 4B & 4C).

Drainage in the clays during construction of the station box appeared to have a significant effect on the differential settlement of Big Ben. Although tunnel construction would be relatively rapid, at the time the analyses were undertaken it was estimated that excavation for the station box would take approximately 18 months. Run 1C, in which the clays were allowed to drain during construction, gave lower differential settlements of Big Ben than Run 1B; approximately 4mm was predicted as opposed to 6mm upon completion of construction. In the long term, when the clays had fully drained, approximately 4mm and 7mm respectively was predicted.

The effect of introducing the rigid restraint at base slab level (Run 3B) appeared to be even more significant. Differential settlements were reduced to 1mm in the short term and 3mm in the long term.

Given the apparent sensitivity of the predictions to the degree of drainage in the clays during construction, for the more detailed analyses (combining tunnel and station box construction) comparisons were made of the effects of allowing no drainage within these strata (Run 4B) during construction and allowing these soils to drain (Run 4C). Figure 5 shows the settlement profile of the top of the Thames Gravel, upon which Big Ben rests, predicted by Run 4C at the main stages in the construction sequence.

The effect of tunnel construction can be seen by comparing the results of Runs 1B and 4B: differential movements at the end of construction increased from approximately 6mm to 19mm and in the long term from 7mm to 20mm. With drainage in the clays allowed during construction, differential settlements were 4mm (Run 1C) and 21mm (Run 4C) both at the end of construction and in the long term.

Although in Runs 4B and 4C construction of the running tunnels prior to construction of the station box caused small movements of Big Ben (points A and B settled by 5mm and 2mm respectively in Run 4B and by 7mm and 3mm in Run 4C), construction of these tunnels apparently had a significant effect on the subsequent movements of Big Ben. Not only did Big Ben settle due to construction of the running tunnels but the magnitude of the differential settlement directly attributable to construction of the station box increased; it was 6mm in Run1B and 9mm in Run 4B, whereas in Run 1C 4mm was predicted as opposed to 12mm in Run 4C.

The results of the analyses modelling tunnel construction are likely to have been sensitive to assumptions concerning short term volume loss. The analyses conservatively modelled higher volume losses (2-2.5%) than it was thought would actually be achieved when enlarging the running tunnels to form the station tunnels. Mair (1993) presents data to suggest that the presence of the running tunnels acting as "pilots" is likely to reduce ground movements associated with the enlargements.

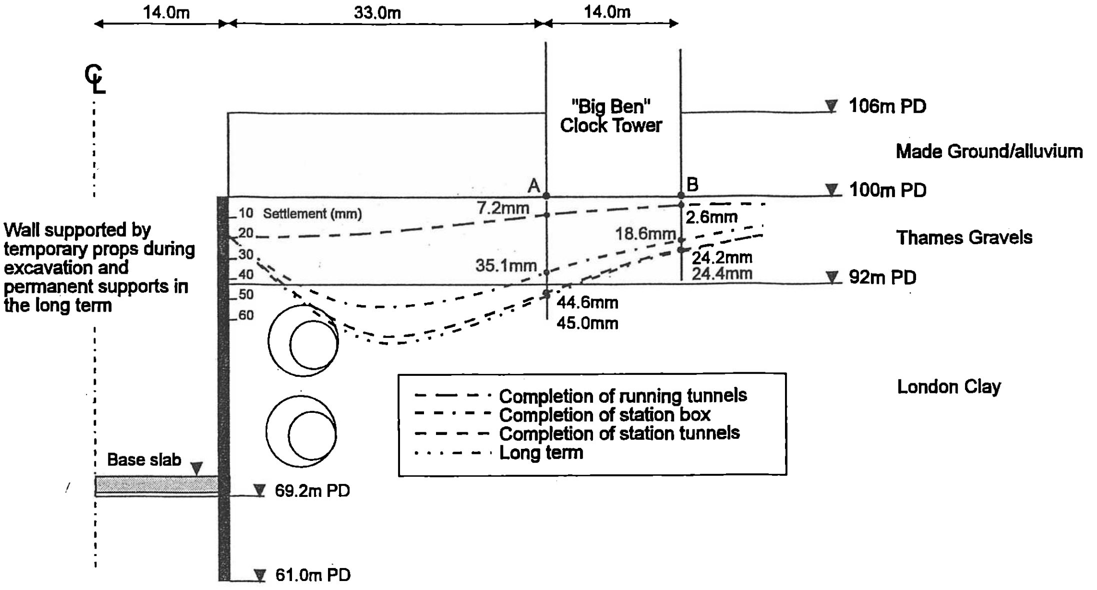

Figure 5: Run 4C settlement profiles for the surface of the Thames Gravel at stages in construction

5 CONCLUSIONS

The finite element analyses showed the beneficial effect of providing deep level horizontal restraint to the diaphragm wall prior to commencement of excavation. This feature was subsequently incorporated in the design.

The analyses indicated that the settlement of Big Ben directly due to construction of the running tunnels was small in comparison to the settlements attributable to other construction activities. However, the construction of these tunnels influenced subsequent movements of the structure. Station box and station tunnel construction were shown to potentially have a greater effect. However, the total settlements predicted are likely to be over-estimates because the analyses combining station box and tunnel construction did not model the deep level restraint to the diaphragm wall. Also the actual volume losses associated with tunnel enlargement are expected to be lower than those assumed for the analyses.

The two analyses modelling tunnel construction gave similar settlements of Big Ben in the short term and in the long term suggesting that the differential settlement is apparently insensitive to the assumptions made concerning drainage in the clay strata during construction.

References

Burland J.B. and Hancock R.J.R. (1977). Underground car park at the House of Commons: geotechnical aspects. The Structural Engineer, Vol 55, No. 2, pp87-100.

Jardine R.J., Potts D.M., Fourie A.B. and Burland J.B. (1986). Studies of the influence of non-linear stress-strain characteristics in soil-structure interaction. Geotechnique, 36, No. 3, pp377-396.

Mair R.J. (1993). Unwin Memorial Lecture 1992. Developments in geotechnical engineering research: application to tunnels and deep excavations. Proc. Instn. Civ. Engrs., Civ. Engng., 1993, 93, Feb., pp 27-41.

Panet M. and Guenot A. (1982). Analysis of convergence behind the face of a tunnel. Tunnelling '82, IMM, 197-204.

Simpson B., Blower T., Craig R.N. and Wilkinson W.B. (1989). The engineering implications of rising groundwater levels in the deep aquifer beneath London. CIRIA special publication 69.

Acknowledgements

The authors would like to acknowledge the assistance of Dr D.W. Hight of the Geotechnical Consulting Group and Dr R.J. Jardine of Imperial College. Details of the design and the anticipated construction programme upon which the analyses were based were provided by G Maunsell & Partners.