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Jubilee Line extension, Westminster Station design

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ABSTRACT: The new Westminster Station involves construction of a 40m deep box structure and twin platform tunnels at locations where consequent ground movements were predicted to affect the clock tower containing Big Ben. The lateral supports within and below the box are of unusual form and were designed to minimise deflections. Support of the temporary loads developed from above and within the box relies on very large capacity piles.

1 INTRODUCTION

As part of the Jubilee Line extension project a new station is being constructed at Westminster incorporating interchange facilities with the existing District and Circle Line. The dominant feature of the new station is a rectangular box, 80m long, 26m wide, and extending 40m below street level, within which banks of escalators provide vertical circulation. The Jubilee Line platform tunnels are arranged one above the other to the side of this box. The proximity to buildings of priceless historical and national significance, including Westminster Tower which contains Big Ben, meant that control of ground movements has been a major design consideration for these structures.

The station also functions as the substructure for the prestigious New Parliamentary Building. The need to allow for full flexibility in the construction of this complicated the design. Additionally architectural aspects were given a high degree of influence over structural form and layout within the station.

The existing District and Circle Line station lies diagonally across the site just below ground level. The requirement to keep this operational as much as possible was a major restriction on the design and construction in a congested urban site. A cross-section and plan of the station is shown in Figures 1 and 2.

2 SOIL SAMPLING AND TESTING

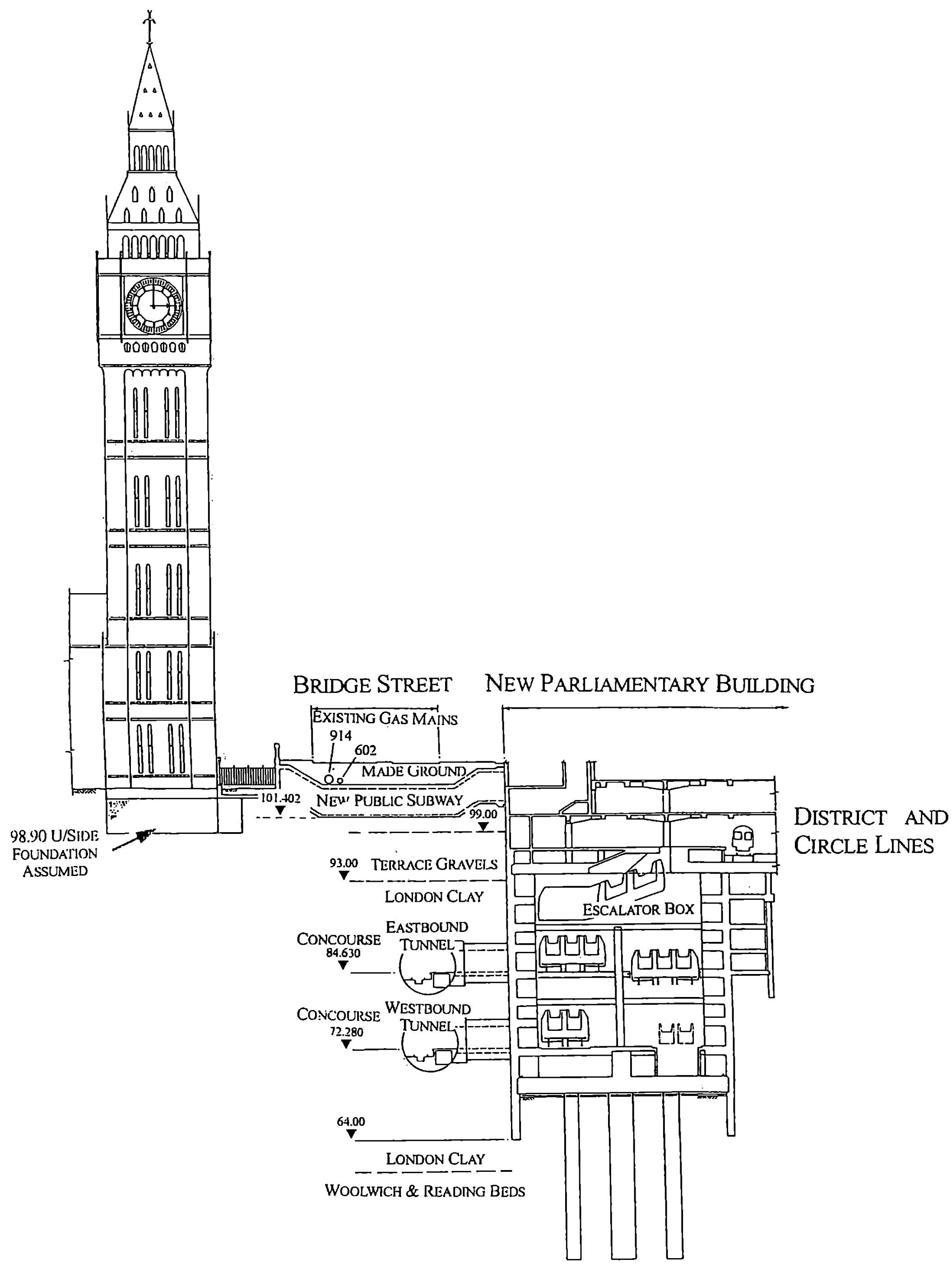
Prior to the commencement of the station design phase, a site investigation had been carried out for the new line as a whole and is described further in a paper on Site Investigation for the JLE which is being presented in this Symposium (Linney and Page 1996). The boreholes and testing at the Westminster site had been commissioned on the basis of a conceptual design which had the new station tunnels alongside one another, accessed via inclined shafts and a tunnelled concourse. The original investigation was mainly confined to the London Clay and simply proved the top of the Woolwich and Reading Beds. The re-design required high capacity piles penetrating into the Woolwich and Reading Beds or possibly the Thanet Beds, and an estimation of heave loads on the basement slab.

The development of the design into the form finally adopted required a supplementary investigation. Two rotary cored boreholes were carried out to depths of 80m and 70m to prove the thickness of the Thanet Beds and Woolwich and Reading Beds. Soil samples were tested to assess soil strengths, stiffnesses and swelling pressures. In addition vibrating wire piezometers were installed at various depths in the boreholes to determine the pore pressure profile from the London Clay to the Chalk.

3 ESCALATOR BOX DESIGN

The escalator box is sufficiently wide to allow triple escalators to pass either side of a central row of 2m diameter columns. Over the 35m length and 20m height taken by the escalators, the box is entirely without either slab or walls, thereby creating a large open space through which the escalators pass on discrete steel supporting structures (see Figure 3). It was hoped this would provide as open an environment as possible and a change from the traditional "rabbit warren" of London's older underground stations.

The permanent propping of the walls within this region was required to be as compact and inconspicuous as possible. This objective was achieved by using solid 660mm diameter forged steel struts. The pattern



NOTE: All levels referred to in this paper relate to Project Datum (PD) PD is equivalent to OD + 100m

HORIZONTAL SCALE

5 0 10

1:200 metric

Figure 1: Westminster Station

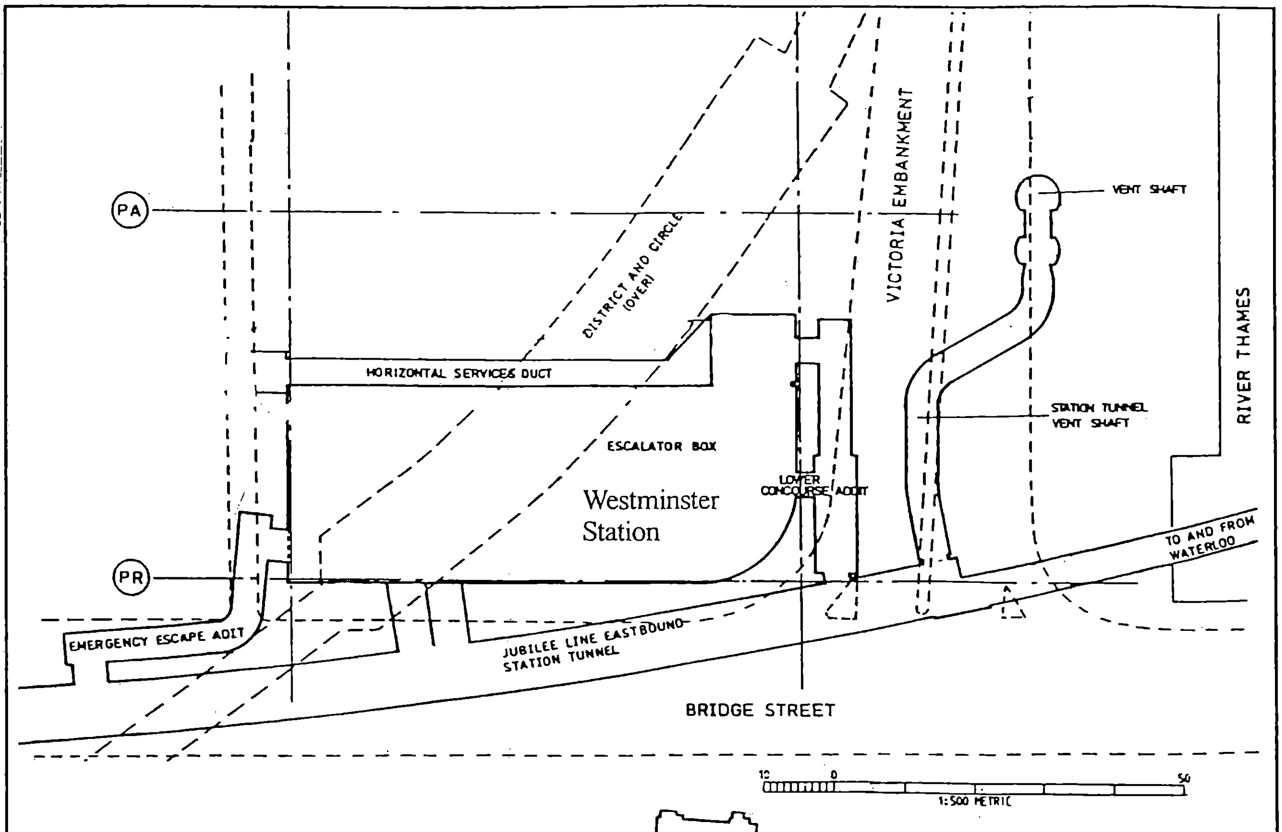


Figure 2: Layout of Westminster Station

and separation of these struts was such that no conventional walling system would have been able to span between them. A 2.5m wide grillage of reinforced concrete buttresses and walings was therefore introduced to span between the props and bring the wall spans down to manageable proportions.

The form of wall chosen nevertheless had to be able to sustain substantial load effects, and the construction method had to minimise movements, bearing in mind the historical significance of Big Ben . It needed to be capable of installation with minimum ground disturbance and to be as stiff as possible. The interior wall surface would be exposed beside the escalators and therefore needed to be architecturally presentable and to minimise water ingress. These factors led to the adoption of diaphragm walls, with the grillage being constructed progressively as bulk excavation was carried out.

Soil pressures on the diaphragm wall and load effects in it were evaluated for both the short and long term using soil structure interaction programmes. Undrained soil parameters were used for short term conditions during construction. Drained parameters were used for the long term design case. The original site investigation had determined values of K_0 existing at the site, and these were related to the data obtained during the construction of the House of Commons Car Park (Burland and Hancock 1977). The data from the House of Commons Car Park meant that the soil conditions with respect to the diaphragm wall were relatively well known and could be back analysed.

Installation of diaphragm walls causes significant relaxation of horizontal effective stresses, which cannot be fully restored on dissipation of the corresponding porewater pressure changes. The design of the walls was based on an initial $K_0 = 1.5$ and not re-established at the end of construction. The maximum credible load was the long-term condition with K_0 re-established to 1.5, which was used for design against progressive collapse of the structure following the loss of a permanent strut. Factors of safety of 1.0 were used for this load case, and plastic yielding of the reinforced concrete was allowed.

The support stiffness provided to the wall by the grillage varied from place to place. The nature of the grillage meant that the supports to the diaphragm wall were inter-dependent. A load on a supporting waler at one level will cause other levels of walers to deflect. Furthermore, as the grillage was to be built progressively as excavation permitted, the support stiffness at any point would vary during construction. The stiffness of the grillage members also depended on the degree to which the concrete cracked, the influence of their rather small span-to-depth ratios, and the extent to which they acted compositely with the diaphragm wall.

These complications and uncertainties were allowed for by designing for a wide range of support stiffnesses. The support reactions produced by the wall analysis

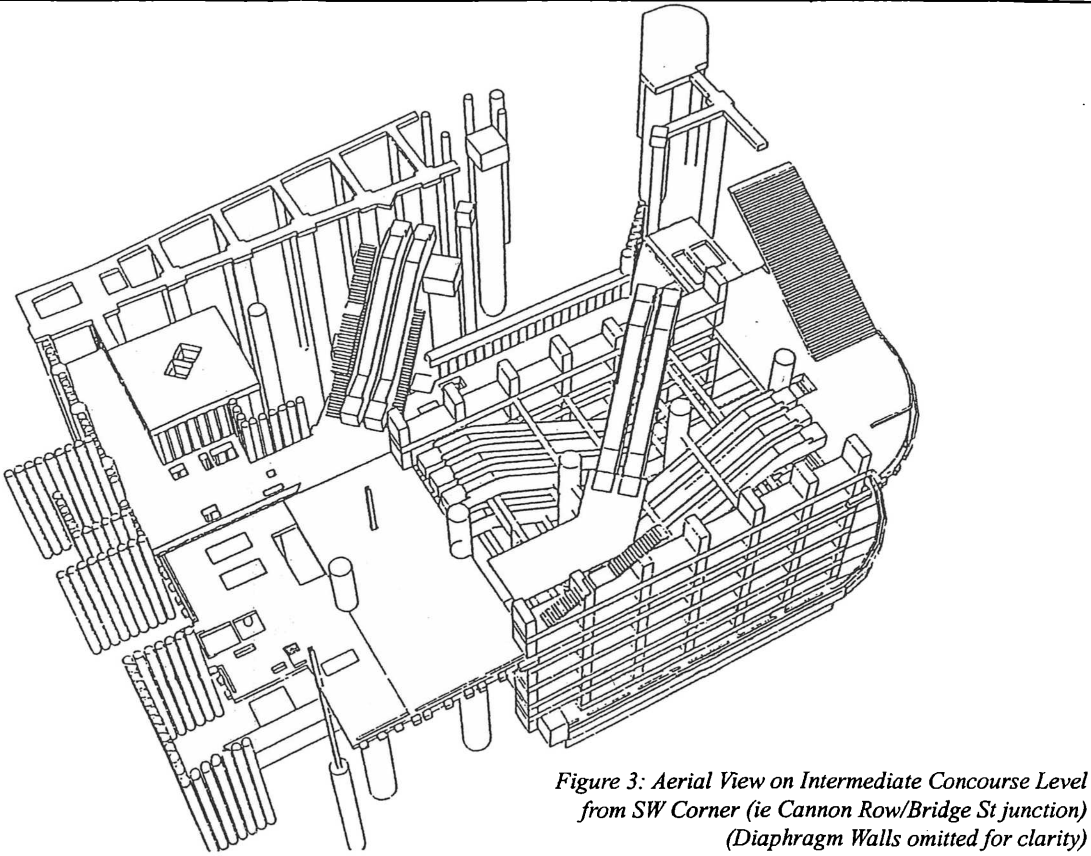


Figure 3: Aerial View on Intermediate Concourse Level from SW Corner (ie Cannon Row/Bridge St junction) (Diaphragm Walls omitted for clarity)

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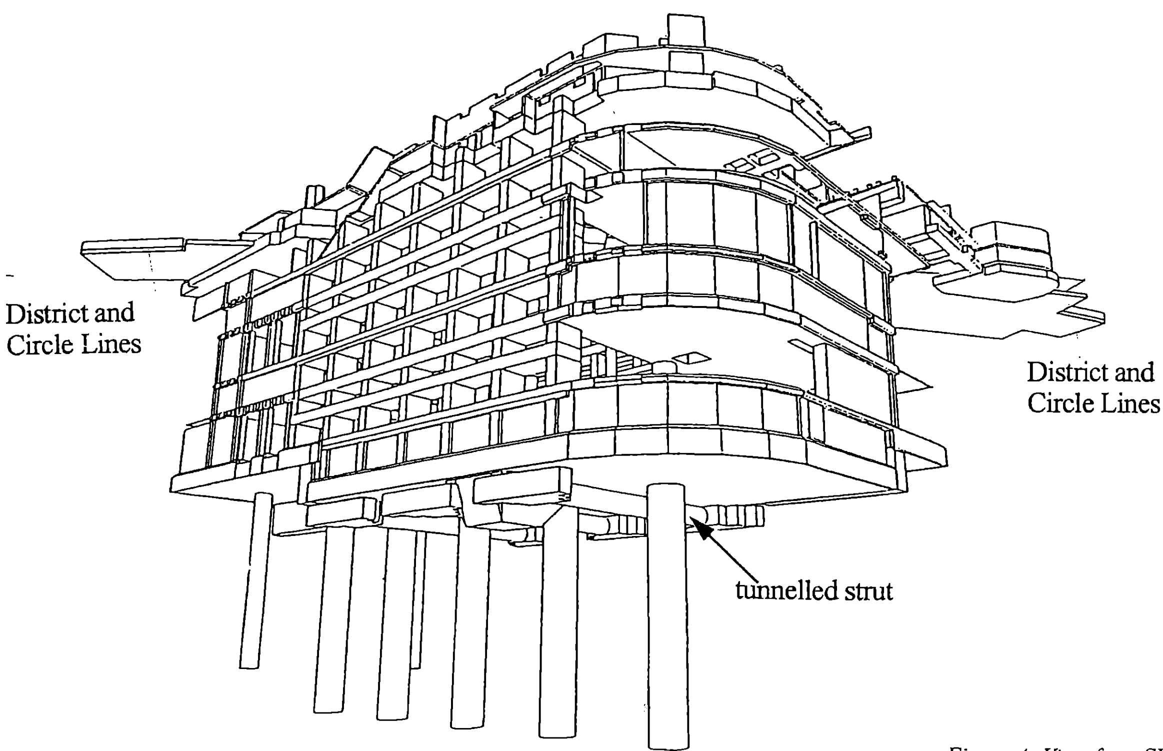

Figure 4: View from SE Corner (ie at junction of Bridge St and Victoria Embankment) (Diaphragm Walls omitted for clarity)

were fed back into the grillage as loads, producing the design load effects in the grillage. The deflections of the grillage under these loads were compared with the stiffnesses used in the diaphragm wall analyses. The use of a wide range of stiffinesses to cater for the uncertainty in parameters avoided the need for iteration. The deflection at each level of the wall was required to be kept within prescribed limits, and was defined on the drawings which served as a constraint on altemative construction sequence proposals.

Two separate soil structure interaction programmes were used and their output was compared. The first "Diana" is an elasto plastic beam and spring model developed in-house by Maunsell, and allowed rapid evaluation of varying soil and support scenarios prior to detailed design. The second was the finite element program CRISP which was calibrated initially using the data from the site investigation and the instrumentation installed at the House of Commons Car Park excavation (Burland and Hancock 1977), and then applied as a check to the design solution adopted.

Two main sequences of construction were compared during design. In both cases the central very high capacity piles were constructed before any excavation in order to provide support to slabs and struts installed as the excavation progressed. Due to uncertainty in the timing of the New Parliamentary Building loads from this construction (and more particularly the possible settlements) were also taken into consideration. The first sequence involved building the buttresses, walers and permanent struts level by level as the excavation proceeded downwards. The second involved building walers on the way down, together with an arrangement of temporary propping, and constructing the buttresses and permanent props from the bottom up after the completion of excavation. The first option seemed likely to be cheaper and quicker. The second was preferred because:

1. Constructing the buttresses top down would make it very hard to achieve the required quality of finish -

2. The use of temporary propping would provide more opportunity for contingency measures in the event that wall deflections tended to exceed the permissible.

3. Installing the permanent struts after the base slab was constructed minimised the differential deflection (between diaphragm walls and central piles) which would create bending stresses in the struts.

However the Contractor has chosen the top down method of construction.

Big Ben is at a distance from the excavation approximately equal to the excavation depth (see Figure 1). Initial calculations for the scheme showed the deflections of the lower regions of the diaphragm wall combined with the possible effects of tunnelling gave excessive ground movements and settlements of Big Ben. Schemes were therefore developed to reduce this settlement.

No sensible alteration to the wall design or the construction sequence would produce a reduction in low-level deflections of the order required. The solution therefore was to introduce substantial props below the level of the base slab, before excavation had progressed far. Two methods were considered for this:

1. Hand dug tunnels of approximately 2m diameter filled with structural concrete.

2. Low height diaphragm walls, constructed between and at right angles to the main walls, below base slab level with mass concrete infill above this level.

The tunnelled struts were likely to be the cheaper option. However the diaphragm cross-walls were preferred because:

1. They would provide additional support at higher levels during the excavation process;

2. They would reduce heave of the base of the excavation and thus be more effective in reducing settlements of adjacent structures.

As a further contingency measure against unexpectedly large wall deflections, a system of jacking was included in the low level props (see Figure 4). Such a system had been used successfully during construction of the Barbican Arts Centre in London. (Stevens et al 1977).

The contractor subsequently offered the tunnelled strut solution with a system of jacks, which was adopted with the post contract development that contingency compensation grouting could be carried out beneath Big Ben to assist in minimising settlement.

Finite element and empirical methods of analysis were carried out to assess the effect of both the tunnelling and station excavation. Analyses of the excavation with the tunnelled struts indicated that differential settlements of the clock tower base would be of the order of 6mm, whilst the tunnelling might add a further 6mm.

Figures 2 and 4 show the District and Circle Lines station crossing the excalator box. The diaphragm walls could not be constructed across the existing station from track level without disrupting railway operations unacceptably. An underpinning slab was therefore designed to span underneath the tracks and transfer the weight to the diaphragm wall and central piles. The ground under the supporting slab is then excavated to sufficient depth to allow a low headroom rig to complete the diaphragm wall under the District and Circle Lines.

4 LARGE DIAMETER PILE DESIGN

On the centreline of the escalator box a row of 2m diameter columns at 11.8m centres supports the permanent struts and slabs within the box, as well as the station and the New Parliamentary Building above (see Figures 1 & 3). Within the open section of the box there are secondary columns of 1m diameter, halfway between adjacent large columns, which support permanent struts only.

The 2m diameter columns are supported on 3m diameter piles. The piles are excavated from +101m level and extend to approximately +49m level 20.6m below the bottom of the escalator box. Fabricated steel column cores are then lowered into the piles, and the piles are concreted up to the level of the bottom of the base-slab. The column cores extend to +98m and carry all the load during construction of the box. The 2m diameter encasement is constructed from the bottom up and helps to carry all subsequently applied vertical load.

The 20.6m of pile below the base slab carries all the load from the columns prior to the base slab being constructed. Once it is in place the base slab is capable of carrying all the structural load.

The base slab design is governed by heave pressures and in this condition the piles act in tension assisting to resist upward movement.

The base slab is designed to take the full change in effective stress or a heave pressure of approximately 300 kPa. To prevent water pressures developing under the base slab a gravel and geotextile drainage layer is introduced which is drained into the station. Without this drainage layer the base slab would have been designed for a heave pressure equivalent to the change in total overburden pressure of 600 kPa.

The presence of the cross wall struts and large diameter piles is expected to restrict the upward movement of the soil and therefore provide a minimal reduction in the heave pressure. Without the piles or cross-struts the soil would swell and some reduction in the heave pressure may have been allowed for.

The 3m diameter piles were designed using the effective stress method due to the lack of sufficient reliable testing at depth. The piles are some of the largest piles constructed in London and were proportioned to carry all the working load in skin friction, (maximum working load 36MN). The pile end bearing was designed to give the additional factor of safety and for this the strongest layer of Woolwich and Reading Beds was chosen. The piles are to bear on the cementitious calcareous layers of the Woolwich and Reading Beds or the Lower Mottled Clay (Linney and Page 1996). Due to the uncertainty over the construction programme for the New Parliamentary Building the potential for differential movements to sensitive structures has led to the design of a jacking facility on the pile columns.

Many of the structural elements supported on both these piles and the diaphragm wall are sensitive to differential settlements between the piles and the wall. The diaphragm wall is not expected to move appreciably, and the piles are not expected to move downwards appreciably after construction of the base slab. The settlement of the piles and compression of the column cores under the temporary condition before construction of the base slab was a limiting factor. Upward movement of the piles due to heave pressure was not expected to exceed the earlier downward movement. Design of the piles for the condition was therefore limited by strength considerations.

One of the large 3m diameter piles is located under the District and Circle Line and height restrictions have led to the use of hand dug pile construction. The pile was redesigned as a shorter belled-out pile.

5 INSTRUMENTATION

Extensive instrumentation is being installed under the construction contract. This has three purposes:

1. To check that the soil and structures are behaving as foreseen in design.
2. To monitor movements of the ground and adjacent structures
3. To provide information of use on future projects.

The instrumentation installed includes, in the diaphragm wall panels, electrolevel inclinometers, earth presure cells with integral piezometers and beneath the basement slab rod extensometers and piezometers. In addition one of the large diameter piles is extensively instrumented.

Recent excavation of the west bound running tunnel has caused 4 to 5mm of settlement and the east bound tunnel 1 to 2mm, at the Clock Tower.

6 ACKNOWLEDGEMENTS

i Project Director, Jubilee Line Extensions Project
ii Prof J B Burland, Imperial College of Science & Technology
iii Balfour Beatty Amec Joint Venture.

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