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Westminster Station – Deep foundations and top down construction in central London

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Abstract: Construction of the new Westminster Station as part of the Jubilee Line Extension Project is proceeding without detriment to surrounding structures and operations. To achieve this, temporary measures and monitoring procedures have been incorporated with construction of the permanent works - to limit movement and avoid potential collapse.

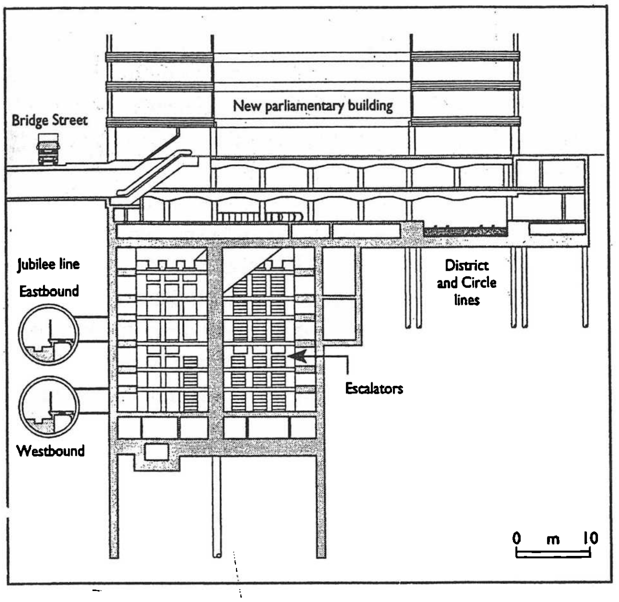

Fig. 1. Westminster Station: the District and Circle Line station extends obliquely across the new (deeper) JLE station.

1. INTRODUCTION

The new Westminster Station, currently under construction as part of the Jubilee Line Extension Project, is a deep reinforced concrete box structure - extending some 45metres below existing road level. It is being constructed around a fully operational, high-level, underground station. Building of the new structure utilises a modified "top-down" method of construction, not only to support the existing station and limit ground movements during construction, but also to allow early commencement of the new Parliamentary office building located above the station. The commencing level for installation of the permanent (diaphragm wall and piled) foundations for the new structure is some 4.5 to 7metres below existing road level. Temporary retaining structures are therefore required, and must be supported as work proceeds, in order to comply with the limiting values of allowable horizontal displacements. These are severely restricted due to the proximity and national importance of adjacent buildings.

In order to accomodate the unique combination of "bottom up" and "top down" techniques, a series of specific measures have been implemented; to provide the required support whilst allowing excavation to proceed with the minimum of interference.

2. "BOTTOM UP" TECHNIQUES

2.1 *(Temporary) Piled Retaining Walls*

The decision was made early within the contract to give as free an access as possible to subsequent diaphragm walling operations and therefore wherever possible, an unpropped cantilevered design solution was chosen. Variations on three main support methods were used - determined by subsequent construction immediately at the foot of the temporary retaining walls.

Sections adjacent to diaphragm wall construction were supported by king piles, with infill panels constructed during later excavation. As percussive piling techniques were not permitted under the contract, king piles were installed within augered holes drilled by a hydraulic piling rig. The majority of piles consisted of a 750mm diameter bore, up to 15m deep, with a typical stanchion being a 356 x 406 x 467 kg/m section installed full depth. The bore

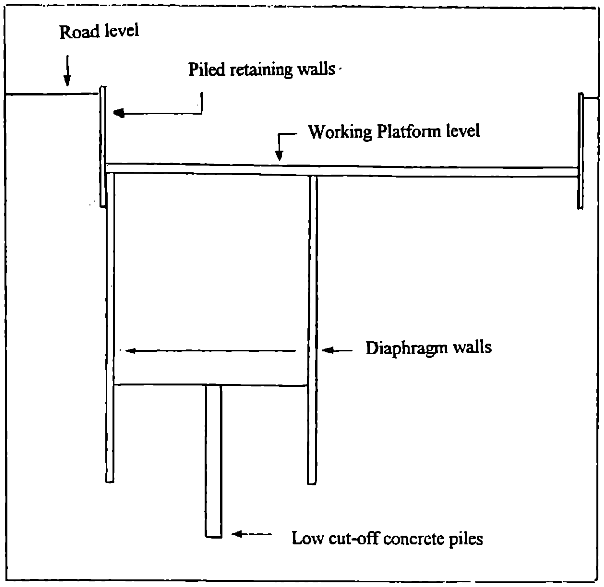

Fig.2. Westminster Station : working platform level and temporary piled retaining walls.

was then concreted up to the lower working platform level. Typical pile spacing was 1.75m.

Two methods of infill panel were employed;
a) in-situ concrete with reinforcing mesh, cast in 1.5m lift heights and b) full length trench sheets with 'H' section walings, installed using a 'dig and push' technique. Both were equally effective, but the concrete solution was generally favoured as the sheets tended to jam between the H piles unless there was a certain degree of over-dig.

Diaphragm walling construction involved the excavation of discrete panels, up to 6m in plan length; which had to be constructed without the loss of support to the (high-level) piled retaining walls. However, the excavation of the diaphragm wall trench automatically invoked a loss of earth support over the length of the trench - with up to four king piles being completely

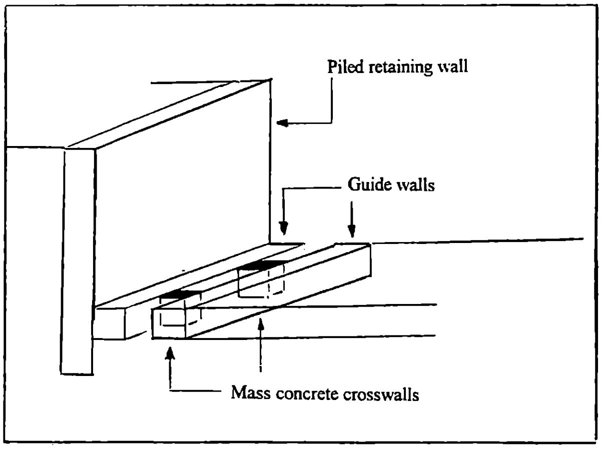

Fig.3. Diaphragm guide walls designed as structural beams.

undermined at any one time. Furthermore, the lateral forces generated by the piled retaining walls were not allowed to act on the side walls of the trench during excavation.

By designing the diaphragm guide walls as structural beams, it was possible to transmit the horizontal forces around the open diaphragm panel into the internal guide wall, which was also designed as a structural member. Both guide walls were concrete sections, 1m square, heavily reinforced with T32 high yield bars.

To transfer loads between inner and outer guide walls, discrete crosswalls of mass concrete were cast between guide walls at each end of the current panel, except in the case of infill panels, where previously cast panels provided the necessary connection. This involved the breaking-out and re-casting of space walls depending on the pour sequence adopted.

The passive forces mobilised by the inner guide wall alone over a depth of only one metre were insufficient to resist movement of the king piles and therefore secondary stutting of the guide walls was necessary. This was achieved in two ways:-

At the east side of the site, the mass of the over-site reinforced concrete slab when slightly thickened above that originally proposed and augmented by a R.C. toe beam along the free edge, was calculated to be capable of withstanding the forces generated.

At the west side of the site, the overall square metreage of slab was much lower and alternative means had to be found. Resistance was gained by constructing R.C. ground beams beneath the oversite slab, normal to the guide wall, which took load back to the existing District and Circle Line station walls. These walls were of substantial construction and consisted of brickwork up to 2.5m thick.

To ensure full support to the full length of the king panel wall, the material between guide wall and retaining wall was excavated and replaced with mass concrete.

During later excavation phases, the robustness of the outer guide wall construction proved to be invaluable in locations where final cut-off of the diaphragm wall was below the design range of the king-pile wall. By using the guide wall as a waling member, one large prop could support several king posts, once again eliminating the requirement for intensive propping.

The action of the toe of the piled retaining walls requires further consideration. In order for the design of the piled retaining walls to work during excavation of the diaphragm wall; firstly, the prop at working platform level must be infinitely stiff. Secondly, the embedded length was deliberately curtailed, to guarantee that the retaining wall tended to move outwards (away from the d. wall) below prop level - avoiding any tendency to move into the trench during excavation.

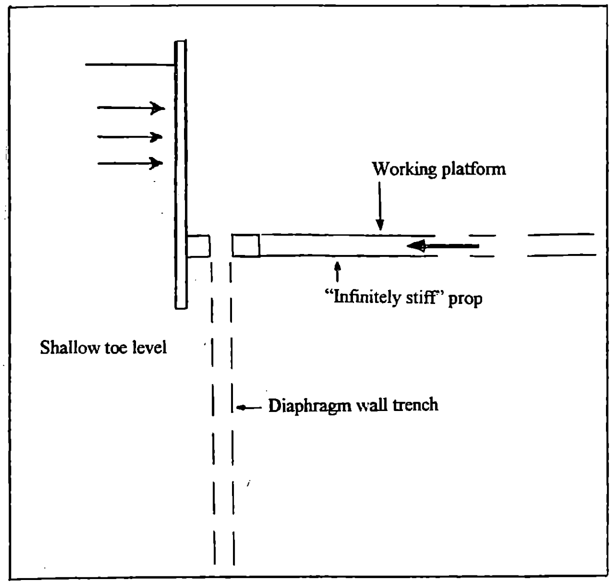

Fig. 4. Piled retaining wall propped at toe.

Beneath the existing District and Circle Line station - where the diaphragm wall must be constructed in low-headroom conditions - the kingpile wall is replaced by an anchored mini-pile wall, propped top (by the station underpinning beam) and bottom. The retained ground is Thames Ballast (injected with silicate grout) overlying London Clay.

Areas of the site outside the footprint of the diaphragm wall box are generally excavated to a depth 4m lower than platform level. In sections where immediate access down to platform level was required, contiguous bored piles were utilised. These comprised 850mm diameter reinforced concrete piles installed to a depth of 20m. The bored piles were capable of providing support by cantilever action alone to platform level; but before excavation could proceed to the lower level, a secondary means of support was necessary - grouted ground anchors installed in a single row at 4m above platform level.

2.2 *Battered Slope*

The third solution applied to an area where it was acceptable to leave a battered face at the side of the excavation in the short term. At the top of the batter, a line of Larssen 20w sheet piles were driven to a depth of 10.5m using a silent piling rig.. A second row of heavy duty trench sheets was then formed approximately 6m behind the row of sheet piles. A coffer-dam was sunk using hydraulic pump-out struts, lowering the trench sheets as the dig progressed.

On achieving formation level, a section of the permanent works base slab was constructed. This section of base tied into permanent works bored piles, previously installed from the higher level. Raking steel props were then positioned from the base up to the sheet pile wall, enabling material behind the trench sheets to be excavated and the trench sheets to be removed.

3. "TOP DOWN" TECHNIQUES

3.1 *Pile and Diaphragm Wall Support*

Whilst the previous techniques support the "bottom up" operations, "top down" techniques are required not only to speed construction of the station box , but also (more critically) to support the existing District and Circle line station during bulk excavation.

One of the practical requirements of the construction process is to ensure uninterrupted operation of both the District and Circle line and also the existing Westminster Station - which runs across the middle of the new station box, at high level.

The original station was constructed during the 1890's supported on an inverted brick arch footing, founded at high level in the Thames Ballast. The new station extends some 35m below this level . One of the requirements of the project is to replace the exisiting structure with a reinforced concrete composite beam - constructed using underpinning techniques - bridging the new station box.

The "top down" measures supporting the high level station are twofold:-

4No. diaphragm walling panels constructed to within 2metres of the station platform (separated from passengers only by a one-hour fire barrier). The diaphragm walling rig had to be located obliquely to access the panel locations; specific safety barriers were installed to ensure that there was no danger to the public.

4No. low cut-off (30m below working platform) large diameter piles (2No. at 3.0m diameter and 2No. at 1.8m diameter) were bored and cast in situ - incorporating composite steel columns to support the station loadings during construction. In three of the piles, the steel columns were suspended from the surface, and cast in the pile during concreting.

The piles were bored to full depth (circa 53m) using a rotary auger and the bore flooded with bentonite mud. A steel guide frame specially designed to suit the composite column was accurately located in the bore, using a downward-looking laser. The weight of the columns (up to 55 tonnes) necessitated construction of a ring beam / jacking system around the temporary pile casing at ground level - to avoid buckling the casing and to avoid settlement during installation.

Once the guide frame was positioned and fixed, the 30m composite beam (in 3 sections) was lowered into the bore a section at a time, and bolted together. The top level of the column was then accurately fixed; with the toe of the column extending the required depth below concrete trim level (ie 3 - 5metres). Concrete placement was by tremie, ensuring effective embedment of the column at the toe.

The technique ensures a minimum accuracy of +/- 25mm at the top of the column and a minimum verticality of 1:200. It avoids the requirement for man access down the bore to trim level to prepare the pile cap.

The positioning of the column for the 4th pile required an accuracy of +/- 10mm top and bottom - dictating that man access to the bore would be necessary. In order to achieve this the pile was bored as previously, but incorporated a grouted 10mm steel lining extending below the pile trim level. The pile was cast with the concrete low, providing access in the dry and allowing the column to be fixed later.

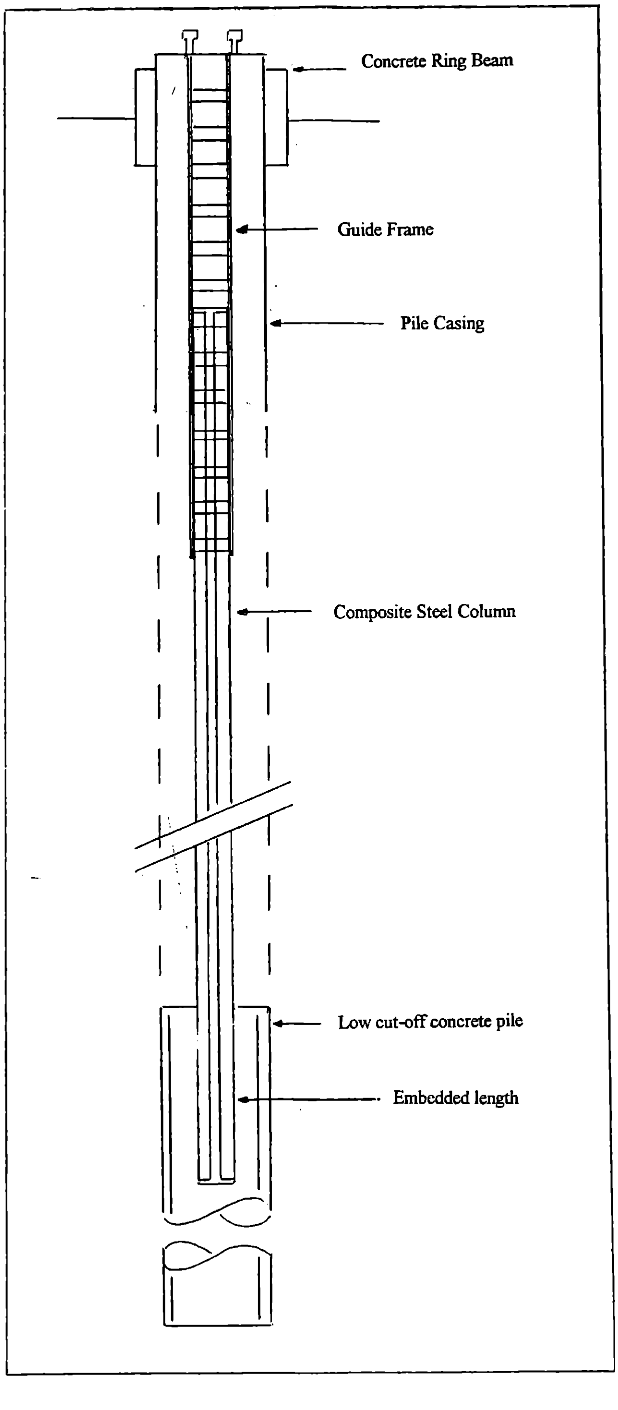

Fig. 5. Cast in Composite Steel Column.

Following completion of the underpinning beam, and with the station supported by the 4No diaphragm wall panels and the 4No. piles, bulk excavation of the station box could proceed beneath the District and Circle line station; thereby allowing access for construction of the low-headroom diaphragm walling.

A further 3No. low cut-off piles and the balance of the diaphragm walling is utilised to support the new parliamentary building during "top-down" construction.

3.2 *Low Level Strutting*

During the escalator box design stages, it was identified that a 33% reduction in predicted ground movement could be achieved by addition of low level strutting - with provision for pre-loading - between the diaphragm walls, beneath base slab level. These struts were to be constructed before bulk excavation commenced. Originally designed as tunnelled struts, they had been changed to low level diaphragm cross walls at award because of safety concerns.

Due to doubts regarding the ability to achieve full contact between perimeter wall and cross strut and also problems associated with installing substantial jacking rigs under a 40m head of bentonite, the diaphragm cross wall was not considered to be the optimum solution. Furthermore, 30 % of the cross walls would require installation in low headroom conditions.

With these considerations, the decision was taken to revert back to the original tunnelled strut solution - with the struts redesigned using conventional pre-cast concrete tunnel segments. On completion of tunnelling, the struts would be concreted and the jacks installed.

The eventual scheme consisted of three 1770mm diameter hand excavated tunnels with continuous walings against the diaphragm walls 1800 deep x 1200mm wide. At the south end of each strut, a 2440mm diameter jacking chamber houses 5 pairs of flat jacks each with a capacity of 7640kN. Total jacking capability is up to a maximum of 50mm in each strut.

Access to the tunnel system was via the steel-lined bore of one of the 3m diameter piles. A temporary platform was located within the lining at strut invert level, breaking out into an access tunnel. Installation of the steel column within the pile (for "top-down" support) was delayed until completion of all tunnel struts.

Before excavation progresses beyond 11metres below working platform, each strut will be pre-loaded to 5000kN. Subsequent requirements for further jacking will be determined on the basis of the measured deflections of the diaphragm wall.

The safeguard afforded by these tunnelled struts was one of the key factors that influenced the decision to permit construction of such a radical structure directly opposite one of the nation's major landmarks.

4. MONITORING

4.1 *Movement Criteria*

Although the contract is specific regarding acceptable deflections of the diaphragm walls, no limits have been set for movements associated with temporary works. However, clearly there is an obligation to carry out all works using techniques which will minimise settlement to the surrounding area.

It was always a key aim to minimise propping to both temporary and permanent works and by diligent monitoring of the king pile walls, sufficient confidence was gained in the behaviour of the retained material to adopt an observational approach for the upper levels of the diaphragm wall. By using this technique, although contingency props were available, pre-determined 'trigger' values for deflection were never reached and the requirement for installation of 'mandatory' propping to the top of the diaphragm wall was eliminated.

4.2 *Monitoring Systems*

Across the Jubilee Line Extension Project as a whole, a high degree of monitoring is specified and Westminster Station is no exception. Monitoring is carried out at Westminster for three main reasons:

to control settlement of adjacent buildings.

to ensure the track of the District & Circle Line railway remains within operational tolerances.

to control deflections of the diaphragm wall during escalator box construction.

The system used for monitoring is a combination of electronic and precision surveying techniques. Throughout the Westminster area, several hundred precise levelling points have been established. Buildings that are considered to be at risk have been fitted with a series of electrolevels mounted on alloy beams. The precision of the equipment is such that measurement of vertical and horizontal surface settlement is better than +0.5mm.

The primary function of the surface monitoring in the areas adjacent to Westminster Station is to record settlement resulting from Jubilee Line tunnel excavation. When pre-determined 'trigger' values have been reached, compensation grouting is initiated. However, construction techniques employed on the station site also contribute to overall settlement, particularly if excessive deflections to the perimeter retaining structures occur during excavation. To monitor wall deflections, reflecting prisms have been attached to all king piles and contiguous bored piles and twice daily records of king pile locations were taken during peak excavations activity. Monitoring frequency was reduced when confidence was gained that no significant movement was apparent. Overall, maximum movement recorded at the king pile walls was less than 30% of the predicted values.

As previously highlighted, one of the unusual features of construction at Westminster is the presence of a live underground station in the centre of an extremely congested site. With the track being in such close proximity to groundworks installation, settlement of the rails could be a major potential problem - especially as operating limits impose strict tolerances on twist and cant, as well as vertical displacement. Between last train each night and first train each morning (engineering hours) a team of Surveyors carries out a precise levelling survey of all running rails at 2m intervals. Data collected is entered into a computer and analysed against previous readings. In high risk periods, teams of railway engineers were on constant stand-by to re-level the track if displacement occurred beyond acceptable tolerances.

It was found that the greatest settlement of the rail tracks was as a result of vibrating the 3.2m diameter pile casings immediately adjacent to the station, through the Thames Gravels into the clay beneath. Cumulative settlement at some points was in the order of 100mm.

Extensive instrumentation has been installed to monitor deflections of the diaphragm wall, as excavation of the escalator box proceeds to depth. Much of this instrumentation was installed actually within the diaphragm wall panels. To measure total pressures at the interface between the diaphragm walls and the ground on both faces, 48No. jack-out Earth Pressure Cells have been installed, each with an integral piezometer. Six inclinometers have also been installed, each pentrating 10m below the base of the diaphragm wall.

Augmenting the electronic instrumentation, extensive use of reflective prisms is to be adopted at the internal face of the diaphragm wall, fitted as excavation proceeds. Once again the survey team will record convergence of the diaphragm walls on a daily basis. On completion of escalator box excavation, long term monitoring equipment will be installed beneath the base slab in the form of piezometers, magnet extensometres and deep settlement points to record the behaviour of the structure with time.

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