CHALLENGES FACED IN THE CONSTRUCTION OF 60M DEEP DIAPHRAGM WALLS, WITH HYDRAULIC GRABS IN CENTRAL LONDON, ENGLAND

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ABSTRACT

This paper will discuss how utilising standard hydraulic grab technology, the Northern Line Extension (NLE) Project Team tackled the geotechnical challenges of constructing 1.2m thick, 60m deep diaphragm walls through highly variable London strata and overcame the significant impact that the ground conditions had on grab productivity, excavation rates, wear and tear of the equipment and delivered a high quality diaphragm wall, with zero lost time accidents, on programme and on budget. In addition to overcoming the difficult ground conditions, one third of the Station Box was constructed from within a three sided, 3m deep sheet piled cofferdam. The paper will present how the Project Team overcame the difficulties this presented to the management of the works together with the procedures and innovations developed to successfully install structural steel plunge columns into diaphragm wall panels with cut off levels up to 10m below the working platform.

Keywords: Northern Line Extension, Diaphragm Walls, London Clay, Harwich Beds, Lambeth Group, Thanet Sands, excavation rates, damage to grabs, BIM, plunge columns

INTRODUCTION

The Northern Line Extension (NLE) connects the Northern Underground Line from the existing “Kennington Loop” to the Battersea Power Station redevelopment. Although relatively short at 3.2km, the route includes the construction of two new in-line stations, one at Nine Elms and one at Battersea Power Station (refer to Figure 01). When completed the extended underground line will bring much needed public transport infrastructure into the wider Nine Elms and Battersea redevelopment areas of the Borough of Wandsworth. This paper focuses on the Battersea station development.

Figure 01: Overview of the Northern Line Extension route from the existing Kennington Loop to Battersea Station and a computer generated photograph and the Battersea and Nine Elms Developments.
The Battersea Station Box was divided into two discreet sections, the Crossover Box and the Station Box. The diaphragm walls for the Crossover Box, also the launch chamber for the Tunnel Boring Machine (TBM), were constructed first and from within a 3m deep, three sided sheet pile cofferdam. The Station Box diaphragm walls were constructed second. The Station Box will form the main public areas of the Station and are designed to provide step free access to the ticket halls, platforms and retail outlets.

Construction of the diaphragm walls commenced in November 2015 and was completed in March 2017.

![Figure 02: Photographs showing panel excavation in the Crossover Box from within the 3m deep cofferdam.](image)

**GROUND CONDITIONS AND DIAPHRAGM WALL PANEL LAYOUT**

The London Clay formation, prevalent within the London basin, provides ideal conditions for the construction of diaphragm walls. It is uncommon however, for walls to extend beyond this strata, through the hard and variable Harwich Beds and Lambeth Group to found in the dense Thanet Sands some 60m plus below ground level (refer to Table 1).

<table>
<thead>
<tr>
<th>Soil strata</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Made Ground &amp; River Terrace Deposits</td>
<td>0m - 5m</td>
</tr>
<tr>
<td>London Clay</td>
<td>5m – 38m</td>
</tr>
<tr>
<td>Harwich Beds (London Clay Formation)</td>
<td>38m – 42m</td>
</tr>
<tr>
<td>Lambeth Group</td>
<td>42 m – 54m</td>
</tr>
<tr>
<td>Thanet Sand</td>
<td>54m – 60m ++</td>
</tr>
</tbody>
</table>

The diaphragm walls were designed for two conditions. In the first instance, to provide lateral stability of the station box structure itself and to satisfy this design requirement, the depth of the walls extended approx. 27m from existing ground level, with each panel founding within the London Clay.
Secondly, the diaphragm walls were designed to accommodate the loads imposed by the future Battersea Power Station Phase 3 (BPS Ph3) development. This design requirement necessitated that alternate diaphragm wall panels be extended to a depth of 60m below existing ground level. To achieve this depth, excavation through Harwich Beds and Lambeth Group was required before founding each panel into the dense Thanet Sands (refer to Figure 03).

Figure 03: (i) Typical diaphragm wall elevation showing the alternate deep (green) and shallow (orange) diaphragm wall panels. The horizontal length of the deep panels was determined by the load draw down and bearing capacity required by the proposed BPS Ph 3 structure (ii) The actual plan view of the Crossover Box diaphragm wall panel layout.

PANEL EXCAVATION

Panel lengths varied between single bite, 2.8m long panels; ~1.5 bite, 5.6m long panels and multi bite, 7m long panels. Target excavation rates varied through each of the strata encountered but as an average, each 2.8m long, 60m deep panel was scheduled to take approx. 3 days to excavate. However, actual excavation rates achieved on the first two panels were approximately 50% slower than the target excavation rates.

Excavation through the uniform London Clay proceeded as expected, excavation through the Harwich Beds and Lambeth Group was significantly more difficult but also considerably variable. Excavation rates into the Thanet Sands to form the panel toe, were largely as expected. With 50% of the panels extending through the Harwich and Lambeth formations to the Thanet Sand, subsequently panel sequencing was extremely difficult. With individual panel concrete volumes ranging between ~90m³ and ~500m³, planning for the large concrete pours was also extremely difficult because very little sequencing could be determined with any degree of confidence until productivity had settled.

In order to understand the problems faced it was important to determine the variability of the ground conditions and relate this back to the changes in strata levels. By logging the excavated spoil as accurately as possible and utilising basic “time and motion” techniques combined with an analysis of the on board grab instrumentation (refer to Figure 04), an as-built geotechnical long section (refer to Figure 05) through the site was developed to determine the worst case, baseline scenario. In the first instance, this enabled “time windows” to be set for delivery of the reinforcement cages and target dates for concreting to be organised with the ready mix concrete supplier, bringing back some degree of normality to the planning and sequencing of the works.

Secondly, this enabled the success of each small change to the excavation strategy to be measured against the baseline. After trialling a number of modifications to the grab teeth with mixed success, a strategy for pre-drilling of each of the 60m deep panels over their full depth was developed.
Figure 04: Typical time verses excavated depth plots taken from the on board Jean Lutz rig instrumentation. When overlaid with the strata profiles, the plots were used to determine excavation rates (m²/hr) through the different soil layers.

A number of different pre-drilled configurations were considered before opting for a single pre-drill in the geometrical centre of each panel (refer to Figure 06). The Project Specification allowed for a maximum verticality of 1:200 over the exposed face of the diaphragm wall and so there was a risk that any pilot hole, pre-drilled with a verticality less than 1:200, may cause problems with grab verticality during subsequent diaphragm wall excavation.

Figure 05: Extract from the “as-excavated geotechnical long section”
It was decided that an 880mm temporary cased, 800mm diameter pilot hole, drilled centrally within the 1200mm thick diaphragm wall would offer sufficient improvement to grab excavation rates and with a [target] tolerance of 1:125, provided sufficient mitigation to the risk that the pilot hole would not adversely impact the verticality of the later diaphragm wall excavation.

The Geotechnical Baseline Report for the site, stated that the Harwich Beds contained bands (up to 100mm) of hard strata with a maximum unconfined compressive strength of 100MPa. Our construction records showed that grab excavation rates reduced to as little as 0.3m²/hr and that the band ranged in thickness from 0.6m to 3.5m. In its in-situ state the grabs simply could not penetrate the strata. However, experience of piling through the same strata presented no significant difficulty to conventional piling techniques. It was therefore considered that a central pre-drill through this hard band would create a weak spot that would assist the grabs in breaking up the material.

A similar theory was developed for the Lambeth Group. Excavation rates through this strata varied from between 1.9m²/hr and 3.0m²/hr. The strata consists of an unpredictable make up of hard clays, silty clays and sands. In its confined in-situ state, a 27 tonne grab could at best only scrape across the excavation face and in turn achieve very little penetration. However, traditional piling techniques had again no significant difficulty excavating through the same strata. It was considered that the single central pre-drill would put the strata into an “unconfined” state and provide a pathway into which the material could fail into with each bite of the grab. Refer to Figure 06.

![Figure 06: Schematic showing the location of the centrally drilled pre-drill in each of the 60m deep panels.](image)

The success of the pre-drilling was immediate and is presented in Figure 07. Excavation rates through the Harwich Beds increased to an average of 2.9m²/hr and through the Lambeth Group, increased to an average of 5.1m²/hr.
Figure 07: Typical plot of grab excavation rates against depth versus time against strata

**DAMAGE TO THE GRABS**

The hard excavation through the Harwich and Lambeth formations had a significant impact on wear and tear of the grabs. After completion of the Crossover Box, where the grabs had been working continuously for 20 weeks, both grabs required significant repair not only to the jaws and other typical wear parts of the grab but also to the main structural body (refer Figure 08).

All repairs to the grabs was carried by our own Specialist Plant Department in Doncaster, England.

Figure 08: Clockwise (i) Replacement of spring bushes (ii) In line boring of grab jaw (iii) Replacement pivot bosses (iv) Structural cracking to grab body (v) Structural cracking to the jaws of the grab (vi) Structural cracking to the jaw pivot, repaired by speacialist welding techniques.
The occurrence of major breakdowns was of significant concern and detailed record keeping of productive versus non-productive time identified that there was a re-occurring pattern to the major breakdowns. From the graph presented in Figure 09, it can be seen that cumulatively and approximately every 10 to 11 weeks, the grabs experienced some kind of significant breakdown. A programme of preventative maintenance, over and above what would normally be considered as routine preventative maintenance was introduced. This included the strip down and structural checking and testing of all major welds on the body of each grab.

The maintenance programme proved successful in limiting the amount of non-productive time as can be seen from Figure 09, where during the last 18 weeks of the Project grab productivity reached its highest levels and grab break down time was minimised.

![Figure 09: Graphical representation of the 10-11 week cycle of major grab breakdown (Note: the impact of each breakdown can be seen in the corresponding reduction in excavated m²).](image)

**CONCRETE DISCHARGE CHUTES**

Constructing the Crossover Box diaphragm walls from within a three sided sheet piled cofferdam presented a number of logistical and health & safety challenges. Access for excavated spoil, reinforcement cages and concrete into the box was restricted to a single entry and exit ramp. In real terms a standard 60m deep x 2.8m long panel produced ~200m³ of excavated spoil, required 5 reinforcement cages sections and ~200m³ of concrete to complete the panel. The excavation sequence and programme necessitated concurrent excavation and concrete operations and truck logistics therefore required careful planning and coordination not only to ensure that activities did not grind to a halt, but also to ensure the safety of operatives working within the box.

A number of options were considered to try and negate the need for any trucks to enter into the Crossover Box. The use of concrete pumps from the high level was considered as an expensive but viable option. With planned production requiring an average of three panels per week to be concreted, the use of pumps would eliminate approximately 80 concrete truck deliveries from the site logistics plan (~160 truck movements when considering entry and exit from the box).

However, the use of concrete boom pumps was an expensive solution. Following the principle idea of delivering and discharging concrete from the higher level to the lower level, the Project designed and fabricated a simple but effective concrete discharge chute. A fully articulated lower chute section provided flexibility in the system to allow for variances in site constraints and panel lengths and enabled a “one type fits all” chute to be developed (refer to Figure 10).
Designed and fabricated by Cementation Skanska and costing a fraction of the equivalent concrete boom pump costs, the system was extremely successful and was a key factor in maintaining the high levels of health & safety management required on the Project and was a significant factor that contributed to final zero lost time accident statistics achieved by the Team.

**DIAPHRAGM WALL PLUNGE COLUMNS**

The construction of plunge columns, installed to structural steelwork tolerances in rotary bored piles using long plunging frames to facilitate top down construction techniques, is common practice and the methodology is well defined. However, the construction of plunge columns in low cut off diaphragm wall panels where the ability of a plunging frame to obtain reaction from a pile casing to accurately move and position the plunge column does not exist, had not been done before as far as the author is aware.

The Station Box design called for the installation of 12 plunge columns within the low cut off, internal diaphragm wall running longitudinally along the length of the box. In order to construct these columns, a bespoke frame for placing and positioning the columns was designed and fabricated by Cementation Skanska (refer to Figure 11).

In their final working condition, each plunge column section was designed to be encased in concrete. However in the short term, each column was designed to carry the temporary construction loads
imposed as the ground within the station box was excavated and the roof support structure was constructed. Therefore, in both conditions, installation tolerances were critical, 1:300 verticality, +/-10mm in plan and +/-5mm in level.

The installation frame was based on the same principles as a typical plunging frame (but inverted) and needed to be sufficiently robust to (i) carry the self-weight of each column (ii) be sufficiently stable and rigid so as to provide adequate reaction to move and position each column into its final design position and (iii) to be able to have a mechanism suitable to make fine adjustments to the column position.

The successful installation of each plunge column relied upon a number of elements of the panel construction being within acceptable limits of deviation, most importantly the final position of the reinforcement cage, through which each column need to be placed. During the construction of Panel 8.20, verticality of the panel excavation, the final position of the reinforcement cage and the position of the internal shear links within the reinforcement cage were all at the limit of their tolerances and the combined effect resulted in the reinforcement cage clashing with the position of the plunge column (refer Figure 12(i)).

Consequently, the plunge column was installed with a verticality tolerance 1:104. Unfortunately, this column was designed as the main support for a temporary bridge over the Station Box and back analysis of the design demonstrated that the column now failed in the temporary condition. Due to the accuracy of the construction records, the as-built details were fed into the Project’s BIM model and remedial works to strengthen the column were designed and fabricated in advance of bulk excavation by the main contractor. This is a good example of pro-active use of the BIM model to assist in the timely resolution of a construction issue that resulted in minimal cost and programme impact to the follow on works (refer Figure 12(ii)).

CONCLUSION

The difficulties encountered during the excavation of 60m deep diaphragm wall panels through what is generally considered to be well known, well understood and typical of the strata of the London Basin, demonstrated that the relationship and understanding between ground conditions and excavation technique can never be taken to be mutually exclusive. This diaphragm wall is the deepest ever
constructed by Cementation Skanska and one of the deepest constructed in the UK with hydraulic grab technology.

In addition to resolving the unforeseen difficulties presented by the ground conditions, the Project Team also demonstrated the positive impact that BIM and 3D modelling can have on a projects costs and programme by informing and changing construction strategies as the project works continue.

Many of the successes of the Project were made possible by the accuracy of the as-built records collected by the Project Engineers out in the field who were managing and supervising the construction activities. Although the benefit of this level of data collection is often questioned, the data collected and the often real-time data analysis undertaken on this Project demonstrated that with the right focused approach, data can be a powerful tool.

The design and fabrication of the bespoke and innovative Concrete Discharge Chutes not only mitigated hundreds of concrete delivery truck journeys into a restricted work area, reducing congestion and improving productivity but more importantly set the tone for the Project that Safety was important, a message and theme that continued throughout the Project and was rewarded with a zero lost time accident achievement record for the Project Team.

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