PILING ADJACENT TO RAIL TUNNELS AT KING'S CROSS CENTRAL

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ABSTRACT

This paper addresses the experience designing and installing bored piles for the King's Cross area. This includes continuous flight auger and rotary bored piles, with a range of diameters between 600 mm and 1200 mm, reaching a maximum depth of 56 m below ground level. Existing Network Rail Thameslink twin bored running tunnels are located directly beneath the subject plots. These tunnels have an external diameter of 6.6 m and the crowns of the tunnels are very shallow, in some cases just 10 m below the existing ground level. Some plots needed piles to be installed in close proximity to the tunnels, which required additional control measures and contingency plans. Pile verticality was monitored as the tip of each pile advanced and in-tunnel monitoring readings were verified and are presented. Lessons learned from designing, installing and testing the piles and monitoring the tunnels are addressed in this paper.

Keywords: King's Cross, bored piles, tunnels, monitoring, London Clay

INTRODUCTION

King's Cross Central Development is one of the largest redevelopment areas in London, located to the north of King's Cross Station in the London Borough of Camden. New buildings, streets and public areas have been constructed over the last decade in this area, where a significant number of piles have been installed to form the foundations of those structures.

Ramboll and Bachy Soletanche Ltd (BSL) have been involved on the study of several buildings' foundations, some of them installed very close to existing live rail tunnels, as it is the case of plots S1 and S3 (Fig. 1). S1 and S3 are 12 and 11 storey office blocks with the most of the buildings' footprint situated over a pair of Network Rail Thameslink Canal Tunnels which run directly beneath the site. Ramboll was the Structural and Geotechnical Engineer for both the projects, responsible for the design of the superstructures and substructures together with the foundation and retaining wall concept. Ramboll also successfully led the ground movement interface with the third-party stakeholder, Network Rail. BSL was the Piling Contractor for both the projects, responsible for the design and installation of the bearing piles and contiguous pile walls. BAM was the principal contractor for S1 and S3 projects.

The structure for building S1 comprises a transfer structure bridging over the tunnels and supported by three lines of contiguous piles either side of and in-between the two tunnels, all these piles were constructed within the tunnel exclusion zones. The piles are located not closer to 1.5 m clear distance between the edges of the bore and the extradoses of the tunnels (accounting for construction and surveying tolerances). The structure of building S3 bridges over Thameslink Tunnels and sits on a line of piles between them, with the remaining piles located away from the tunnels on each side. The building grid and orientation have enabled it to simply bridge the pair of tunnels below, without requiring a major transfer structure as S1. For S3 the central line of piles is located within the exclusion zones of the live tunnels, with a minimum situation of 1.35 m distance from the tunnel extrados.

The Thameslink Tunnels have an internal diameter of 6 m and were built between 2004 and 2006. The crown of the tunnels lies at a depth of approximately 12 m to 13 m below ground level beneath Plot S1 and between 12 m and 6.3 m beneath Plot S3. The tunnels were built using a tunnel bore machine and constructed with a lining of 300 mm thick precast concrete segments reinforced with steel fibers. The tunnels have a designated land ownership zone around them which forms a 3 m collar of soil measured from the extrados of the lining. The presence of this retained subsoil places a legal condition on developments above and within this zone which required Argent to demonstrate to Network Rail that any works would neither compromise the integrity of the structural lining of the tunnels, nor effect the continued safe operation of the railway line. Ramboll were employed by Argent to fulfil this service.

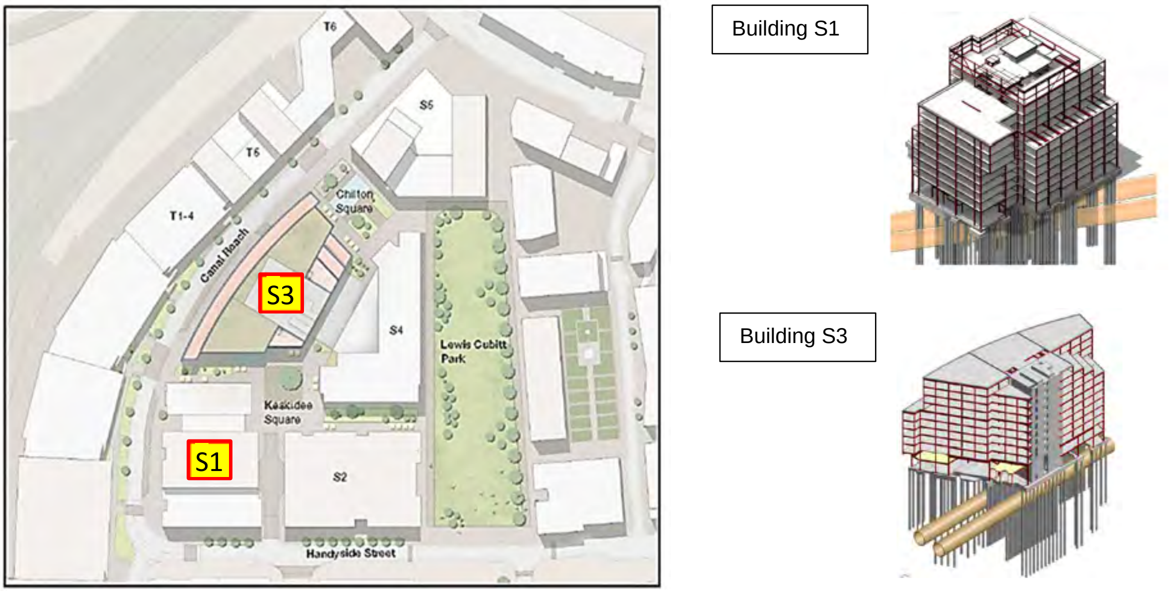

Fig. 1. Position of plots S1 and S3 in King's Cross central area and buildings' views

Tunnel and rail movement monitoring was undertaken during construction and tight controls on pile installation were instigated beyond normal practice. The use of PRAD sensors on the auger allowed the vertical and horizontal deviation of the piles to be measured, providing confidence to the Client that there was no risk to adjacent assets, and that the project specification had been met.

GEOTECHNICAL CONDITIONS

Specific ground investigation works have been carried out for every plot, typically consisting of trial pits, cable percussive and rotary boreholes, with in situ SPT tests at regular intervals. Geotechnical laboratory testing were carried out, namely moisture content, Atterberg limits, particle size distribution and undrained shear strength in triaxial compression. For the purpose of this analysis, results from in situ and laboratory tests have been analyzed in the context of the area, including results from neighboring plots around S1 and S3.

The ground conditions in the area consist generically of a sequence of Made Ground, overlying London Clay, above the Lambeth Group. The Made Ground was encountered across all the S plots area, with a maximum thickness of approximately 5 m and comprising a mix of clay, sand and gravel, with brick cobble content and concrete fragments. At the base of the Made Ground, a thin layer of reworked alluvium was detected in some of the boreholes.

The London Clay shows a weathered upper part, approximately 7 m thick, described as firm to stiff brown to orangish brown mottled bluish grey slightly silty CLAY with occasional pockets of orangish brown fine sandy silt, closely fissured. Below, the un-weathered London Clay, with thickness of around 28 m, is described as stiff to very stiff, extremely closely to very closely fissured brown gravelly slightly micaceous sandy CLAY. The weathered part of the London Clay exhibits a slightly higher Liquid Limit (w_L), Plasticity Index (IP) and moisture content (w), when compared with the un-weathered part, as can be seen in Fig. 2 where results for sites S1, S3 and other neighboring plots have been plotted. The values of bulk unit weight for the weathered London Clay are less scattered and with a lower average than the ones for the more competent London Clay. Results from Fig. 2 suggests a clay material of high to very high plasticity, with an average PI above 40%.

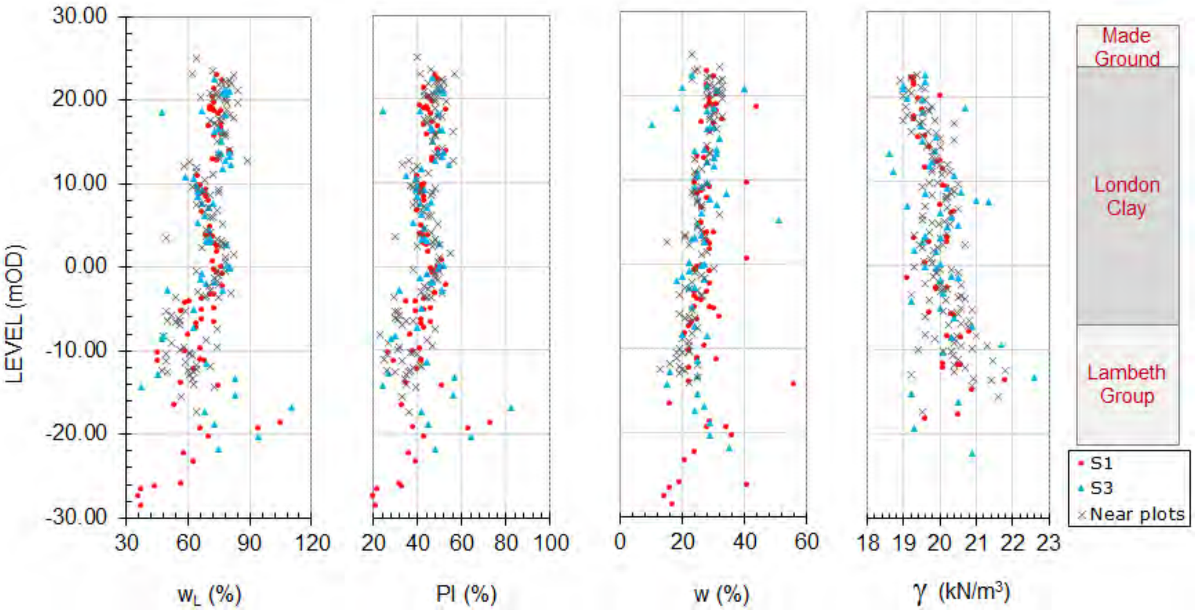

Fig. 2. Variation in level of liquid limit, Plasticity Index, moisture content and bulk unit weight

The Lambeth Group Formation was encountered on the deepest boreholes carried out in the area and it is described as very stiff, dark brown mottled bluish grey CLAY becoming very stiff, multi-coloured silty CLAY grey mottled yellowish brown. This formation presents a more scattered range of index properties and the results suggest that the soil is generally a clay material of low to very high plasticity.

Although in this area the top of the Lambeth Group is in general predominantly a clayey material, one of the boreholes carried out in plot S3 encountered sandy soils with high water pressure at shallower depths when compared with adjacent plots, which would result in some of the piles to be installed using support fluid. Options to reduce the risk to the tunnels by removing the need for support fluid required input from the entire project team of Ramboll, BAM, BSL and Argent. Those investigations included revisiting the underlying design, the potential for lowering the working platform level, and the best balance of diameter against achievable depth with the CFA (Continuous Flight Auger) rigs. Iterative design comparisons showed that the installation and testing of a preliminary load test would allow the optimisation of pile diameters as well as reduced load factors, and result in the pile toe levels being lifted above the problematic soil layer.

Non corrected results from SPT tests are plotted in Fig.3, side by side with undrained shear strength from unconsolidated undrained triaxial tests, both for S1 and S3 sites and neighboring plots. Results for plots S1 and S3 are within the average results for the overall area. The undrained shear strength has also been inferred from SPT ‘N’ values using Stroud (1989) proposed relationship $c_u=f_1xN$, with $f_1=4.5$, typical for soils with a medium to high plasticity. Graph on right hand side on Fig. 3 presents c_u design line for plots S1 and S3 based on results from triaxial and SPT tests.

PILE DESIGN

Pile design was carried out to BS EN 1997-1 and UK National Annex (NA). As stated in the UK-NA, Design Approach 1 (DA1) is to be used for the ultimate limit state (ULS) design calculations. DA1 requires separate checks to be performed for failure in the soil and in the structure, using two combination: Combination 1 (DA1-1) and Combination 2 (DA1-2). A serviceability limit state (SLS) calculation has been performed to estimate pile settlements.

It was considered for pile design purpose both the London Clay and the Lambeth Group as fine grained materials, with total stress response. The design was based on achieving the settlement criteria of 1% of shaft diameter at the SLS representative load for a single pile.

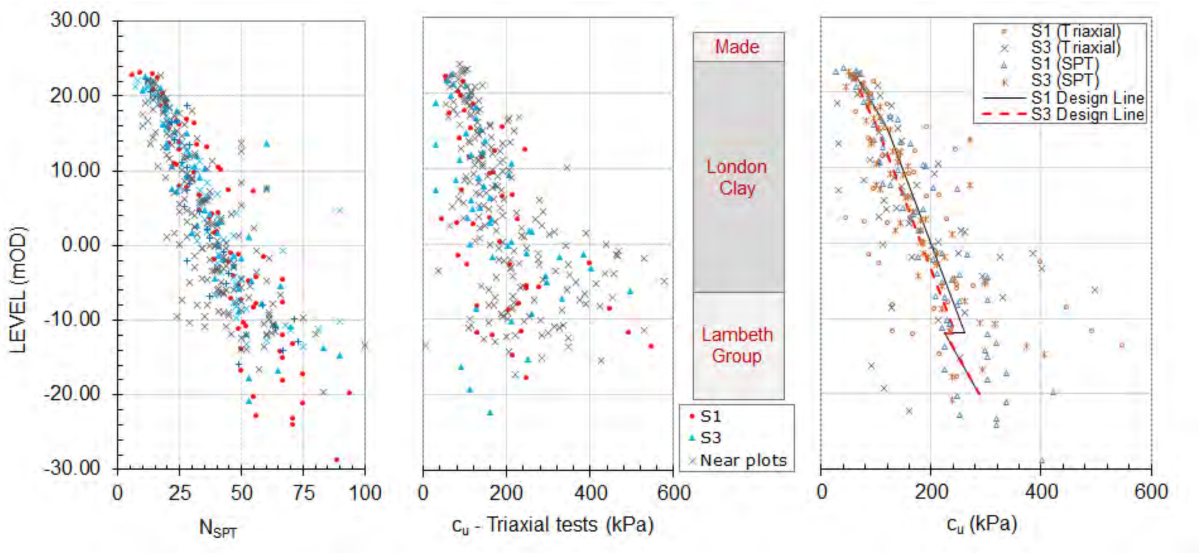

Fig. 3. Variation with depth of SPT ‘N’ and undrained shear strength

The characteristic shaft resistance was assessed based the characteristic value of shaft friction in each soil layer, which for cohesive soils is given by:

$$q_{sik}=\alpha\times c_{u} \qquad [1]$$

where α is the adhesion factor and c_u is the undrained shear strength.

For the London Clay the α value was assumed as 0.5, as per LDSA (2017) guidance and for the Lambeth Group, taking into account the range of c_u values and soil index properties, an α of 0.45 has been used (CIRIA C583, 2004). Design lines in terms of c_u for plots S1 and S3 were as per Fig. 3.

Characteristic base resistance was taken as:

$$q_{bk}=N_{c}\times c_{u} \qquad [2]$$

where N_c is a bearing capacity factor, assumed as 9.0 for the bearing piles and 7.5 for contiguous piles.

PILING LAYOUT

Ramboll developed the initial pile layout for both buildings S1 and S3, which BSL then reviewed against interpretation of the geotechnical performance achievable for each pile diameter. Figure 4 presents the piling general arrangement for both buildings with a schematic representation of the cross section through piles adjacent to Thameslink Tunnels, with key dimensions and levels for each building as per Table 1. For building S1, 94 number of piles out of 188 were constructed within Network Rail’s retained subsoil (Table 2). The piles were located between the existing canal tunnels and to the west of them. Ramboll initially allowed for a continuous row of piles founding within the Lambeth Group, which would have led to the requirement for rotary bored piles (LDA - Large Diameter Auger piles) with support fluid throughout. After several iterations of the design working collaboratively with Ramboll, BSL was able to find the optimum balance for the piles between CFA piles and rotary (wet and dry) bored piles. BSL decreased the number of piles, reduced the size of piles resulting in certain contiguous piles became discrete lengths. The length of certain piles was able to be reduced above the anticipated zone of water-bearing Lambeth Group, enabling them to be constructed as rotary, dry bored. Only eight of the piles were designed as rotary, wet bored with the use of polymer support fluid, due to the magnitude of applied loads on these piles and the proximity of the existing tunnels which constrained any modification to the pile diameter.

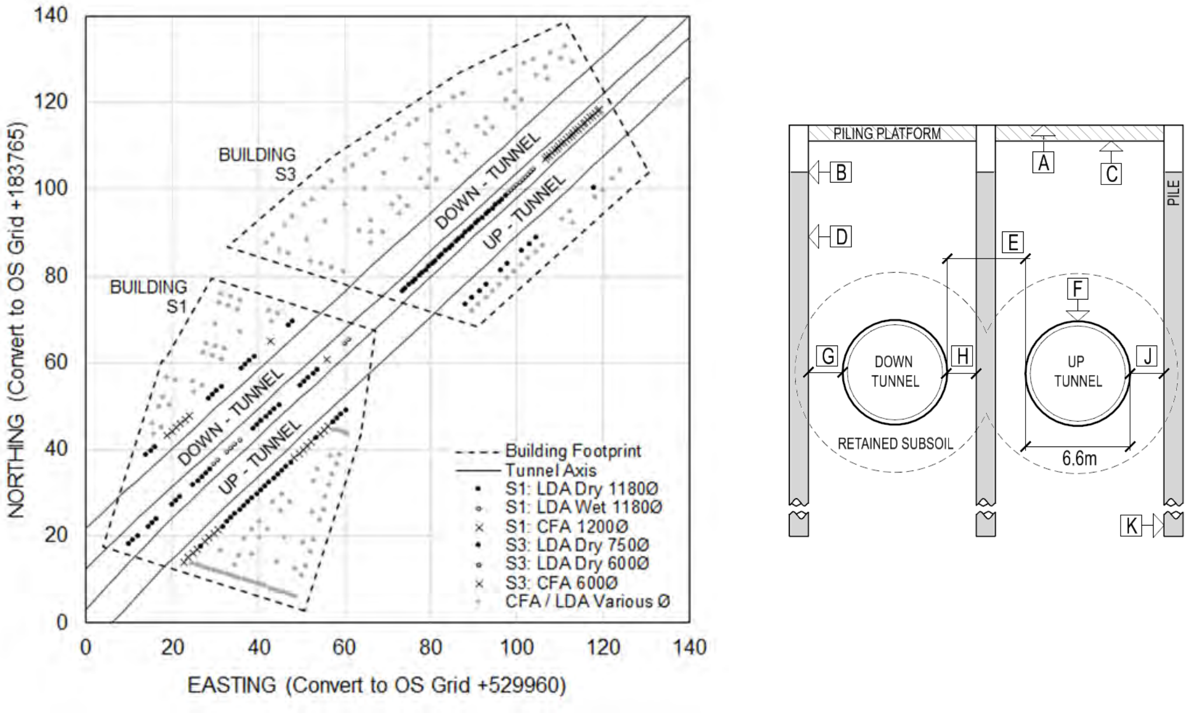

Fig. 4. Piling general arrangement relative to alignment of Thameslink Tunnels

Table 1. Notes on Fig.8 including key dimensions for each building

ID	Description	Building S1	Building S3
A	Pile Platform Level	+25.8mOD	+26.5mOD
B	Pile Cut Off Level	+23.9mOD	+22.8 to +23.9mOD
C	Platform Formation Level	+25.0mOD	+25.7mOD
D	Pile Diameter & Construction	See Fig.4	See Fig.4
E	Distance Between Tunnels	5.8 to 4.6m	4.5 to 3.9m
F	Crown Level of Tunnels	+13.6 to +15.4mOD	+15.8 to +17.8mOD
G	Pile Clearance to Down-Tunnel	1.5m	>3m
H	Central Pile Clearance to Tunnels	1.5m	1.35m to 1.5m
J	Pile Clearance to Up-Tunnel	1.5m	2.3m to >3m
K	Pile Toe Level	5.8mOD to -27.7mOD	-1.5 to -12mOD

Table 2. Bearing piles and contiguous piles for building S1

Element Type	No. of Piles	Pile Type	Drilling Method	Diameter (mm)	Maximum Bored Length (m)	Temporary Casing Length: min / max (m)
Contiguous Piles	8	CFA	Dry	1200	23.5	n/a
	23	LDA	Dry	1180	43.0	22.0 / 26.5
	5	CFA	Dry	750	18.0	n/a
	25	CFA	Dry	900	21.0	n/a
Bearing Piles	16	CFA	Dry	1200	25.0	n/a
	39	LDA	Dry	1180	46.5	22.0 / 26.5
	8	LDA	Wet	1180	56.0	22.0 / 26.5
	22	CFA	Dry	750	26.5	n/a
	19	LDA	Dry	750	37.0	5.5
	23	LDA	Dry	900	40.5	5.5

For building S3, a total of 172 number of piles where installed, of which 76 were constructed within Network Rail's retained subsoil (Table 3). For Plot S3 BSL took lessons learnt from the initial design of building S1, to eliminate some iterations of the pile layout, and also applied the experience acquired from the construction stages of the previous phase of works, to eliminate the need for rotary, wet bored piles between the existing tunnels. Where practicable, for the piles between the tunnels, the construction method was modified from rotary bored to CFA, which de-risked the construction process and reduce the number of piles requiring the use of temporary support casings between the tunnels.

The option for building S3, of carrying out a preliminary pile test in a sacrificial pile in advance to working piles installation, permitted the reduction to the design model factor from 1.4 to 1.2. This led to shorter piles, allowing the toe level to be above the potentially problematic sandy layer and avoiding the need of support fluid for the deepest LDA piles between the tunnels.

Table 3. Bearing piles and contiguous piles for building S3

Element Type	No. of Piles	Pile Type	Drilling Method	Diameter (mm)	Maximum Bored Length (m)	Temporary Casing Length: min / max (m)
Contiguous Piles	24	CFA	Dry	600	27.7	n/a
	42	LDA	Dry	880	38.2	15.5 / 16.50
Bearing Piles	6	CFA	Dry	600	23.2	n/a
	44	LDA	Dry	750	37.7	6.0
	5	LDA	Dry	750	31.7	6.0
	51	LDA	Dry	900	39.7	6.0

PILE LOAD TEST

For building S3, a pile load test was carried out on a sacrificial pile in order to prove the geotechnical design, validate achievable performance criteria and prove suitability of construction method. The test pile was a 750 mm diameter pile, constructed by the rotary bored piling method, without support fluid. Over the upper portion a 880 mm diameter and 16.5 m temporary casing was used to replicate the same construction conditions as the piles to be installed between the tunnels. The observed settlement at design verification load (DVL=3750 kN) was 3.52 mm and at DVL + $0.5F_{rep}$ = 5378 kN (where F_{rep} is the representative action) was 5.37 mm, versus the predicted pile settlements of 6.8 mm and 11.7 mm, respectively.

GROUND MOVEMENT ASSESSMENT

During piling, tunnel displacements can occur in response to an alteration to the stress state of the region of soil that exists between the tunnel and the pile. The displacement response of the Thameslink Tunnels to the installation of the piles at buildings S1 and S3 was expected to be a function of:

- the quantity, size and proximity of the piles from the tunnels;
- the methodology and sequencing of the piling works;
- the ground and groundwater conditions;
- and to a lesser extent, the condition and stiffness of the tunnel lining.

An assessment of the likely magnitude of tunnel displacements was carried out by considering the items listed above and undertaking a review of relevant case studies (Do et al. 2013; Chadorowski and Hope 2008; Chapman et al. 2001 and Schroeder 2002), including monitoring data from piling works previously completed by BSL in close proximity to tunnels. The magnitude of tunnel displacement was expected to accumulate in response to the sequential construction of multiple contiguous piles, with predicted peak values presented within Table 4. The displacement profiles of the tunnels were anticipated to be back-to-back ‘S’ curves peaking at the center of each building footprint and reducing to zero at, or close to, the boundary of each plot.

Table 4: Predicted tunnel displacements

Direction of Displacement	Plot S1	Plot S3
Vertical (positive is settlement)	3 mm	2 mm
Transverse (positive is towards the piles)	1 mm	1 mm

CONSTRUCTION

Figure 5 shows the typical arrangement of LDA and CFA piles between Thameslink Tunnels. For the rotary bored piles, the segmental temporary casing up to 1180 mm external diameter was specified to extend to at least the invert level of the tunnels, circa 18 m depth for piles to building S1, slightly lesser depth for piles to building S3. In cases where the in-tunnel instrumentation and monitoring system indicated that adverse movement of the tunnel lining had occurred, and where there was a need to further control ground displacements, the rotary bored pile temporary casing would need to be extended. This extension was taken to a minimum of one full diameter of the tunnel, below the invert level of the tunnel, circa 25 m depth for piles to S1 and a slightly lesser depth for S3.

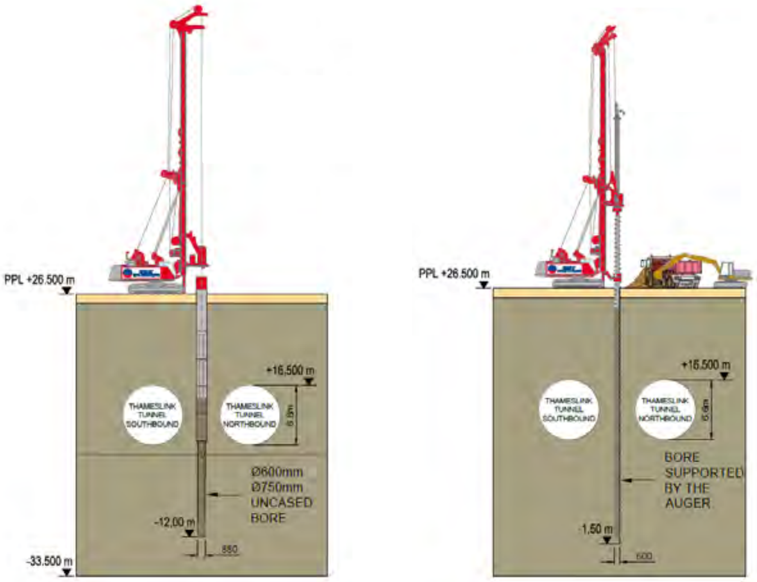

Fig. 5. Installation of LDA and CFA piles between the tunnels

For sequencing of the temporary segmental casing installation, it was permitted to install the temporary casing to a depth which was no greater than the crown levels of the tunnels, the day before that pile being due to commence, so long as extracting the casing could still be guaranteed at the end of the pile construction on the following day. For the eight rotary bored piles constructed to up to 57 m depth requiring polymer support fluid at building S1, construction sequencing allowed for the piles to be bored dry to a depth of 0.5 m above the depth to which ground water was expected to be encountered. Then at that stage, the bores were filled with polymer support fluid, so that the length of bore within water-bearing Lambeth Group were drilled under support fluid. The use of a cleaning bucket to dig and clean the pile toe was then initiated from the point where support fluid was added.

The piles were installed in a hit-and-miss approach, with a minimum of 5 m (i.e. greater than 3 times the pile diameter) left between consecutively constructed piles. Also, the installation was alternate between the sides of the tunnels to reduce the risk of the installation effects being concentrated and/or being developed unevenly. In order to achieve a setting out accuracy of +/-25mm at each contiguous pile location which was adjacent to, or between the existing tunnels, this accuracy was achieved by the use of a guide-wall.

As has previously been noted, verticality of the piles constructed on the projects was recorded using the PRAD system [by Jean Lutz SA; www.jeanlutzsa.fr]. This system uses an inclinometer sensor, which is rigidly mounted to either the lowest portion of the hollow stem of a CFA auger, or to the kelly bar connection point on a rotary auger tool. Drilling verticality data are then recorded by the sensor on the way into and then out of the pile bore, and that data is transferred by bluetooth connection back to a data logger within the piling rig cab, once the pile has been completed. The system therefore gives a post-construction record, but the piling operator still must rely upon the normal best practice for setting up the temporary casings, for setting up on the pile positions and for assessing rig and tool verticality prior to construction of the pile. During the course of the works to building S1, there were two occasions where the uncased pile bores were found to have deviated slightly outside of the specified verticality tolerances (1:100), at more than 5 m below the invert of the tunnels, but not sufficiently enough to have any impact on the tunnels, nor the pile performance under load and they remained within allowable tolerance. For building S3 (where views from pile installation can be seen in Fig. 6) the PRAD data did not reveal any instances where the design specified verticality was exceeded.

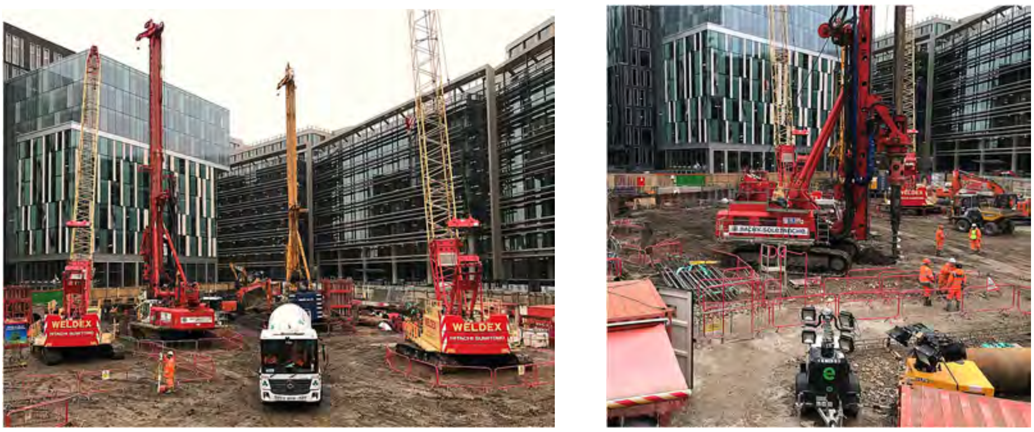

Fig. 6. View from building S3 construction site

TUNNEL MONITORING

Movement monitoring of the Up and Down Thameslink Tunnels was undertaken before, during and after the construction works at buildings S1 and S3. Movement monitoring of the lining segments was carried out using instrumentation which had previously been installed within the tunnels to monitor neighboring developments. This comprised prisms attached to the axes, shoulders and crown of each tunnel at 10 m intervals along the chainage of the tunnels. The movement of the prisms was recorded by a series of automated total stations operating at an hourly frequency. All recorded movement was referenced to a set of control points located outside of the tunnels and beyond the influence zone of all construction works.

The sensitivity of the monitoring system had been assessed during the extensive baseline period lasting over a year (the monitoring system had been operational during preceding developments at King’s Cross Central). Evidence that the monitoring system was effective at detecting small magnitudes of displacement had unexpectedly been gained during the earlier Ground Investigation for building S1 where small magnitudes of tunnel heave were recorded during the progression of rotary drilled boreholes between the two Thameslink Tunnels. Procedures for the implementation of the movement monitoring of the tunnels, the trigger levels on tunnel movement and the corresponding response actions were developed during the design process in collaboration with Network Rail.

The detailed monitoring results were reviewed as piling progressed and have been further analyzed since construction completion. For the purposes of this paper, the monitoring results presented have been referenced to a null value set at the start date of the piling programs for buildings S1 and S3. Furthermore, a rolling average of the data set covering the preceding seven days has been considered in order to remove background effects (such as instrumentation accuracy and temperature fluctuations) which displayed an amplitude of ±1mm. Considering the data in this way enables the monitoring data attributable solely to the effects of pile construction to be interrogated. All transverse tunnel movements recorded during the piling periods were less than or equal to 1 mm and in the context of a reticulated tunnel lining, which is capable of redistributing stress, this diminutive response requires no further elaboration. With regards to vertical movement, the tunnel response during the construction of a single pile was of sufficiently small magnitude for it not to be discernable within the monitoring results. The monitoring data also confirms that displacement of the tunnels was predominantly translational with small magnitudes of cross-sectional distortion of less than 1mm occurring with diametric changes calculated to be less than 0.01% of the tunnel diameter.

For summary purposes, the recorded tunnel settlements are displayed below as a set of response envelopes. Figure 7 presents the change to the recorded peak displacement envelope versus time for the piling periods at buildings S1 and S3. The predicted idealized settlement responses have also been presented for comparative purposes. Figure 8 presents the peak displacement envelopes versus the longitudinal distance along the tunnels. The positional reference point for this graph can be considered to be at a similar location to the zero-zero point presented within Fig. 4.

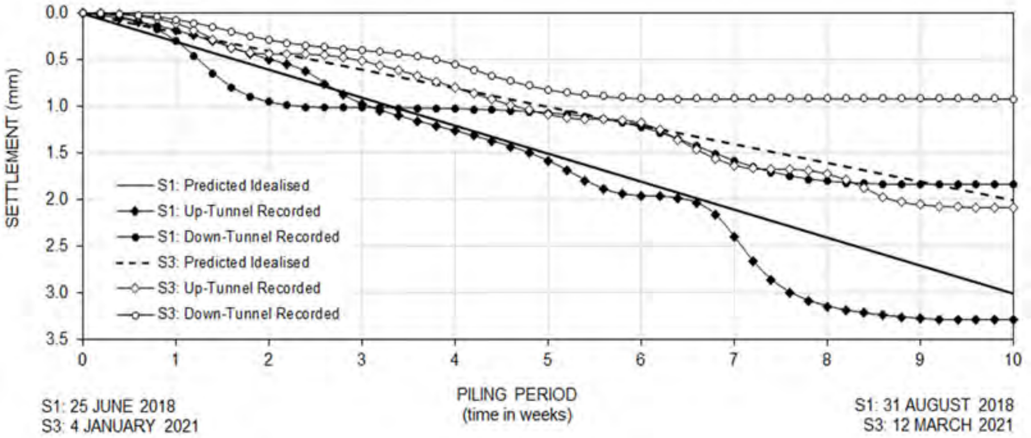

Fig. 7. Settlement response envelope of the Thameslink Tunnels

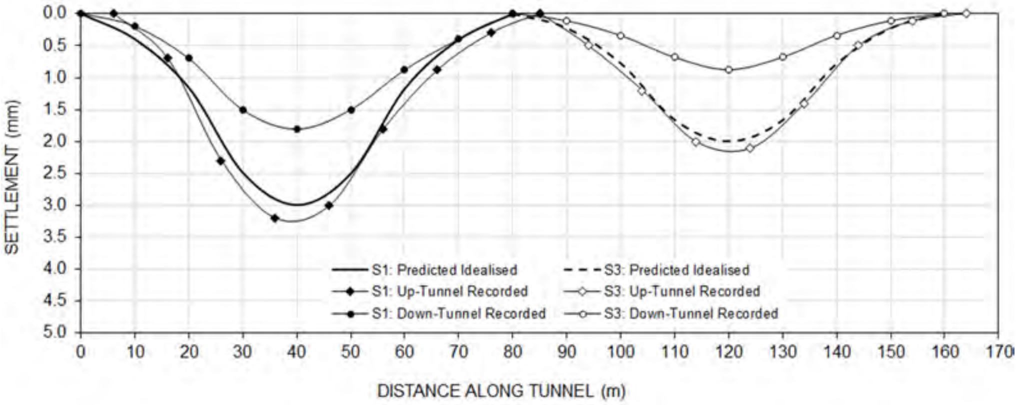

Fig. 8. Peak longitudinal settlement profiles of the Thameslink Tunnels

The results confirm that settlement of the tunnels during piling was measured to be no greater than 3.3 mm. The results also show that settlement of the tunnels occurred in a smooth manner consistent with the behavior one might expect of a tubular segmental structure which inherently has a good balance of strength and stiffness with a degree of flexibility. The reasonably symmetric arrangement of piles either side and between the tunnels is also expected to have contributed to the observed uniform displacement response.

The overall response of the tunnels was reasonably consistent with expectations. Cumulative vertical displacement of the tunnels manifested as progressively increasing magnitudes of settlement. The magnitude of settlement was observed to be a function of the number and size of the piles as well as the proximity of piles to the tunnels. Piling for building S1, where a greater number of larger piles (diameter and length) were constructed within close proximity to the tunnel than for building S3, greater magnitudes of tunnel settlement was induced. It is not expected that the piles installed greater than 3 m from the tunnels contributed to the displacement of the tunnels; however, due to the overlapping nature of the piling sequences, it is not possible to ascertain this as part of this case study.

SUMMARY AND CONCLUSIONS

The site for buildings S1 and S3 in the King's Cross Central Development area overlies the Thameslink Tunnels. The buildings' structures bridges over the tunnels and sits on lines of piles between them, positioned within the exclusion zones from the tunnels, as close as 1.35 m distance from the extrados.

Ramboll, Bachy Soletanche and BAM worked together to help Argent, the Client, to maximise the development potential of the site, bringing value whilst demonstrating to Network Rail that the proposals would not have a detrimental effect on the safe operation and serviceability of their tunnels. The collaborative approach allowed unexpected ground conditions and problems encountered during the design process to be resolved in an efficient manner. The adopted solution that resulted from this meant that a more economic and sustainable scheme was arrived at. The project was successfully completed and delivered on time and to a high standard of quality, fulfilling the Client's expectations.

For future piling schemes that are reasonably equivalent to that which is presented herein, an enhanced degree of confidence can be gained from the recorded tunnel displacements. Equivalent magnitudes of tunnel movement could be expected to arise provided that the following are implemented:

- the site-specific ground and groundwater conditions are investigated to an appropriate degree, and the soil encountered during piling is equivalent to the design assumptions;
- a robust piling methodology is in place and appropriate plant is used;
- the works are well planned, with a sufficient program available;
- the site is well organised with sufficient space for the movement of large piling plant and allocated areas for the storage of materials away from the works;
- the use of more powerful CFA piling rigs with longer augers, not requiring the use of long kelly bars, are key to avoid displacements in excess of those reported within this paper;
- the works are undertaken by a competent Contractor with experience of installing piles under similar conditions.

It is also recommended that supervision of the piling works is undertaken by an experienced Engineer with responsibility for the design, a detailed knowledge of the specific site conditions as well as a thorough understanding of the piling methodology and associated risks.

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