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Construction of a deep shaft for Crossrail

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Abstract

An 8.2m diameter, 36m deep shaft has been successfully constructed from within the basement of Moorhouse near Moorgate in the City of London . At its closest point the shaft is less than 2m from the large diameter piles that support Moorhouse and the presence of these foundations placed tight constraints on acceptable ground movements associated with construction of the shaft. The depth of the shaft is such that it penetrates through stiff London Clay and is founded at the bottom of the Lambeth Group. The paper describes the contingency measures to deal with potentially difficult ground conditions including the water bearing layers of the Lambeth Group. The construction processes included a complex temporary works dewatering system around the shaft with the option to carry out additional dewatering from within the shaft during excavation. Provision was also made for radial grouting to "restress" the ground, to prevent long-term settlement of the Moorhouse piles, should the need arise. The success of the project was due, in no small part, to the detailed planning and consideration of contingency measures to deal with perceived risk.

Construction of a deep shaft for Crossrail

Introduction

This paper describes the construction of an 8.2m diameter by 36m deep shaft. The shaft is part of Crossrail works in Central London and is formed of precast concrete segments. The segmental lining is deemed to have a temporary function (design life 20 years) and will in due course be fitted with the permanent (secondary) cast-in-situ lining. The construction of the shaft was unusual in that it was carried out from within the 10m deep triple level basement of the newly constructed Moorhouse building with the top of the shaft at approximately +0mOD and the final formation level at -38mOD. The shaft was constructed by ‘underpinning’ and at its closest point was within 2m of the large diameter bored base grouted piles supporting the new 16 storey building above. Significant problems arose during construction of the shaft but careful planning, with contingency measures to respond to all key foreseeable eventualities, proved critical to the success of the project.

Project outline

The Moorhouse development, the Crossrail shaft and the proposed adjacent running tunnels are shown schematically in Figure 1; out of view of Figure 1 is a proposed deep Crossrail station cofferdam box immediately beyond Moorhouse. The cofferdam box, tunnels and cross passages to the shaft will be built as and when Crossrail is constructed. Detailed information on the design basis for the shaft can be found in Morrison et al (2004) and are summarised as follows:

- The shaft has a total (internal) length of 36m through the London Clay and Lambeth Group strata.
- The internal diameter of the shaft is 8.2m and was sized to accommodate the secondary lining and future Crossrail equipment.
- Primary shaft segment thickness is 0.35m for the full depth of the shaft. Each ring comprises 10 No. ordinary segments and 2 No. tapered joint segments.
- “Special” segments were fabricated for the rings through which secondary dewatering of the Upper Lambeth stratum may have been necessary by means of inclined wells constructed from within the shaft.
- A concrete grade C45/55 mix (Class 2 sulphate resistance) with 30kg/m3 Dramix steel fibre reinforcement was used for segment construction.
- Low friction (taped and sealed PTFE) bearings were used on every fourth circumferential joint to allow for relatively easy shear distortion of the shaft during the main phase of Crossrail construction (tunnels and cofferdam box). These PTFE bearings act to limit bending bending stresses in the shaft that would result in a sub-standard design factor of safety. All bearings (standard or PTFE) were 4mm thick thereby avoiding the need for special segments or gaskets.

- A trial erection of the precast concrete ring segments was carried out in the manufacturer's yard to confirm that the segments would enable the shaft to be constructed within tolerance.
- The shaft was designed using finite element calculation to provide detailed information relating shaft construction to changes in ground conditions and ground movements at the adjacent piled foundation of Moorhouse.
- Deep ground inclinometers were used to monitor shaft construction against trigger ground movements; these trigger movements were obtained from the finite element analysis of the shaft construction. If construction ground movements exceeded these trigger movements secondary grouting would be used to restress the ground at depth (the pile design for Moorhouse relies on this ground in the long-term for support). Trigger levels were assigned for both "Warning" and "Action" movements. "Warning" triggers required increased monitoring and, where possible, modifications to the construction methodology. "Action" triggers required specified remedial works. The aim was clearly to avoid the need to carry out remedial works.
- A complex dewatering scheme was installed in the Lambeth Group and Thanet Sand. Full dewatering of the Lambeth Group was required by means of ejector wells whilst the Thanet Sand was dewatered using wells pumped submersible pumps.
- A temporary acoustic screen was constructed around the area of the shaft to prevent noise rising above the ambient level outside the site at night thereby allowing 24 hour working in a residential area.

Preparation for shaft construction

Ground conditions and dewatering system

The site stratigraphy consisted of 2.5m – 3.5m of Made Ground and Terrace Gravel over about 30m of London Clay, underlain by about 16m of Lambeth Group clays, silts, sands and gravels, Thanet Sand and Chalk. The shaft was founded in the Upnor Formation at the bottom of the Lambeth Group.

Groundwater level monitoring and test pumping was carried out in the area of the shaft as part of the site investigation works. Water bearing granular horizons were identified in the Lambeth Group, particularly at a level of –31 to –32mOD and –35 to –38mOD. Standing groundwater levels in these horizons were recorded at approximately -20mOD (12m excess head) and –30mOD (8m excess head) respectively. The Thanet Sand and Chalk form the lower aquifer in London and monitoring of groundwater levels indicated a standing groundwater level of –34mOD, 4m above the shaft formation level (Figure 2).

Pore pressures in the water bearing granular horizons in the Lambeth Group needed to be fully controlled to facilitate the shaft construction in a safe manner that would not impact on the foundations of Moorhouse. In addition drawdown was required in the Thanet Sand and Upnor Formation to below formation level to avoid the risk of base heave in the temporary condition during excavation to formation level. The outline specification for the dewatering system used is given in Table 1. This involved installation of a total of 17No. dewatering wells around the shaft.

The shallower wells were targeted at the granular horizons in the Lambeth Group and used ejectors driven from a pumping station located at the new B2 level basement at 2.5mOD. The well annulus was grouted through the London Clay to provide a seal. This allowed the ejectors to generate a vacuum to promote drainage of the target horizons. The deeper wells were targeted at both the Thanet Sand and the Lambeth Group. These were pumped with electric submersible borehole pumps installed close to the base of the wells.

The dewatering system was sized to comfortably accommodate the anticipated discharge of 5l/s, the majority of which was expected to be derived from the Thanet Sand. In the event, the actual discharge was approximately 3l/s. The discharge was led to a tank at the B2 level from where it was pumped to the main sewer. The dewatering system was provided with full back-up facilities including auto-start standby generators and standby pumps. The discharge flow, piezometers and pump operation were monitored with an online data-logger system which also provided an alarm function via a telephone link in the event of a system fault.

The site temporary power supply proved to be unreliable and during the early stages of dewatering it was found that the supply was frequently interrupted, albeit for short periods; with hindsight, a dedicated power supply should have been provided. Any interruption meant that the ejectors, which were dealing with the small flows from the Lambeth Group, would need to be manually restarted. The deep wells in the Thanet Sand, which were critical for a considerable period of time when the shaft excavation neared completion until the base plug was constructed and cured, automatically restarted. Experience gained during installation and testing of the system indicated that groundwater recovery time was about 2 hours in both the Thanet Sand and Lambeth Group. The travel time to site for someone to restart the system in the event of failure was about 1 hour. In view of the critical nature of the works it was decided to have an operative permanently on site monitoring the dewatering system during excavation through the water bearing layers of the Lambeth Group and until the shaft base plug was concreted and cured. This decision was vindicated when both the electricity supply and the alarm system failed (owing to the telephone wire having been accidentally cut) at 2 o’clock one morning. In this instance the system was manually reset without any interruption to shaft construction.

Management and planning of construction.

Skanska UK Building managed the shaft construction as the design and build contractor but always in close collaboration with the design team from Arup Geotechnics and the key specialist sub contractors, WJ Groundwater and Skanska Cementation Mining. Frequent meeting were held for a significant period before and during construction to ensure that all eventualities and concerns were properly addressed. All parties were able to scrutinise all aspects of the design and proposals for construction. This meant that, upon commencement of construction of the shaft, the team members operated with a spirit of openness and co-operation that undoubtedly aided the project and allowed any new problems to be addressed and resolved collectively with a minimum of disruption. During shaft excavation a weekly review meeting was convened in which all parties, including the category 3 checkers, were able to discuss monitoring results and any other issues of concern.

Drilling for dewatering and instrumentation installation

All activities associated with preparation for and construction of the shaft were programmed to be off the critical path of the main Moorhouse construction project. Whilst this allowed a high degree of flexibility over timing it meant that the physical constraints imposed by the site conditions often made access extremely difficult. The first preparatory work for shaft construction was installation of the dewatering system and instrumentation. When these works commenced the Moorhouse superstructure was nearly complete and a 14 tonne drilling rig had to be accommodated on the ground floor slab at +13.42mOD with only 7.5m of headroom (which was achieved by temporarily omitting a mezzanine slab). Figure 3 shows schematically the set up for drilling whilst Figure 4 shows the reality of access difficulties on site.

Drilling was carried out from the ground floor slab through two basement voids as it would have been impossible to accommodate the drilling rig within the basement where headroom was extremely limited. The ground floor slab in the area of the shaft was dominated by large service holes for future Crossrail use and which at this stage were temporarily infilled with precast concrete panels to allow access. However, it was also necessary to strengthen the ground floor slab over the entire area to allow for the heavy plant associated with shaft construction to operate. Despite the absence of the mezzanine slab it was still frequently necessary for the drilling rig to lower its mast to avoid clashing with downstand beams at the underside of the first floor slab when moving between drilling positions. Whilst the rig had reasonable access over the position of the shaft at ground level the profile of the basement structure below ground level dictated the use of wells inclined at angles up to 6° in a number of positions to ensure that the spacing and position of the wells at depth was correct. This further added to the complexity of the drilling operation and required careful setting out of temporary access holes in the Ground, B1 and B2 slabs to allow for the angle of the drill string. Table 2 shows the structural slab levels and sequence of stratification below the new structure.

Instrumentation and monitoring

An extensive monitoring system to determine ground movements associated with shaft construction was devised and implemented. The main aim was to enable cumulative movements to be observed as construction progressed such that measures could be taken to prevent excessive movement and also determine the need, if any, for remedial measures following completion of the shaft. Monitoring included the use of precise levelling, inclinometers, extensometers and piezometers. The same drilling rig used to install the wells was also used to install the instrumentation as shown in Figure 5. Precise levelling of studs at ground floor level was carried out throughout the period of shaft construction. Prior to commencement of shaft construction, these levels were related to corresponding studs at B1 and B2 levels. Following completion of the shaft, the stud levels at ground floor were again related to those at B1 and B2. This method of working enabled increased accuracy owing to the fact that it was not necessary to transfer readings from basement level more than twice (once at the start of the exercise and once at the end). Monitoring of the studs commenced one week before commencement of the shaft excavation to enable baseline readings to be established and related back to a temporary benchmark about 80m from the site in Moorfields. The studs were monitored once a week throughout the period of shaft construction. Once baseline readings were established for all other instrumentation they were monitored twice a week initially with increased activity during excavation through the Lambeth Group.

The performance of the dewatering system was assessed throughout the construction period using an array of 9No. piezometers installed in three boreholes. Continuous monitoring was achieved using vibrating wire transducers connected to a data logger. Similar systems have been shown in the past to be reliable, however, as a precautionary measure; the piezometers were also manually dipped weekly to check for anomalies. Monitoring of piezometers in the period before and during excavation within the Lambeth Group was essential to determine the effectiveness of the dewatering system. Prior to commencement of shaft excavation a trial of the dewatering system was carried out to assess its performance with respect to the design intent and to undertake a switch-off test. The switch off test gave information on pore pressure recovery rates which provided a rational basis for reviewing monitoring arrangements, standby plant and call-out facilities.

Shaft construction

Logistics

The permanent columns of the new Moorhouse superstructure imposed severe restrictions, particularly on the movement of excavated spoil across the ground floor slab. Traffic congestion around the site was such that all vehicle movements associated with the project needed to be carefully controlled within a restricted period between 8.00am – 6.00pm Monday to Friday owing to the close proximity of residential accommodation and enforced via a Section 61 Noise Restriction Agreement. This proved to be less of a limitation on shaft construction activities than the fact that disposal of the excavated spoil could not continue beyond 4.00pm because of the working hours of the tip. Excavation and segmental ring building was a continuous 24 hour operation between 8.00am on Monday morning and 6pm on Saturday and there was consequently a need to be able to store a substantial volume of excavated material on site. Excavation for each 1m deep ring generated about $100m^3$ of spoil (with bulking) and allowance was made for storing up to two rings worth on site. A muck store was formed on a ground bearing area of the B1 slab. The store was filled by placing the muck skip on a tipping frame at ground floor level (Figure 6). The muck skip was moved from the shaft area to the store area by means of a curved runway beam supported on temporary steel gantries; one over the shaft and the other outside the superstructure building line but supported on the basement structure. A 20 tonne excavator was used to empty the muck store during the day. Limited space and restrictions on slab loading meant that only two complete rings of shaft segments could be stored on site at any time also segment delivery had to be carefully co-ordinated with other deliveries and muck away. 24 hour working imposed additional restrictions relating to noise in a residential area. This was overcome by the erection of an acoustic screen that was designed to prevent noise rising above ambient levels at night around the site. The acoustic screen reduced ventilation in the area of the shaft and night shift work was carried out in uncomfortably hot conditions.

The shaft excavation was carried out using a 6 tonne track mounted excavator which was lowered into the shaft using the gantry hoist and lifting slings. The excavated spoil was loaded into a 5.5m^3 bottom opening circular skip which was hoisted up the shaft and discharged into the store using the curved runway beam and tipping frame (Figure 7). Final trimming of the ground was carried out using hand held clay spades to allow a gap of approximately 40mm behind the segments; the gap was specified not to exceed 100mm at any location (Figure 8).

Only sufficient depth of ground at the formation was excavated in order to allow the building of the segments. This was generally kept to a maximum of 200mm below the segments, which provided sufficient space for the ring build. However deeper excavation was required locally at the key segment to allow it to be lifted into position with the additional space needed to accommodate the radial taper (Figure 9).

The segments were mounted on a building frame, and were moved into position using a track mounted hoist located around the shaft perimeter. The segments were connected with spear bolted cross joints and tightened to the correct torque to compress the sealing gasket. The segments were fitted with EPDM gaskets at the factory with bitumen packers on all the segment joint faces. The ordinary segments were built first followed by the taper joint segments, the ring was then checked for level and the position at each segment and thereafter adjusted as necessary.

Each ring of segments were bolted using through bolts to the underside of the ring above. The joint between each ring had a 4mm polymer packer fitted along with alignment dowels and each ring was also rotated relative to the last ring to stagger the cross joints. Where necessary additional polymer packing strips were inserted on the ring face (but not across the gasket) to correct for any parts of the ring which were out of level. Grouting was carried out as soon as possible after the ring building was completed. A seal was formed to prevent grout loss from the back of the segments by using air hose, cement bags and clay to 'fluff up' the joint. The ring was then grouted using an OPC cement grout, with a water cement ratio of approximately 0.4, which was mixed in a vertical grout mixer on the surface and pumped down a grout hose and through grout holes in each segment. Grouting commenced in one location and was then continued systematically around the full ring. Each segment had a grout vent at the top and grouting continued until grout was present at the vent hole which was then capped off. The grouting operation typically took 2 to 3 hours with grouting pressures kept below 1 bar owing to the need to avoid leakage from beneath the bottom of the segments.

Predicted and measured ground movements

Details of the finite element analyses associated with the shaft construction are given in Morrison et al (2004) and the calculated and measured deformations at inclinometer IG1 are shown in Figure 10 for four intermediate dig stages and the final conditions with the base of the shaft constructed. These show the general trend of increasing ground movement with depth in keeping with the larger stress release at depth compared to shallow positions. These computed movements were assessed to be acceptable in terms of stress relief around the piles supporting Moorhouse and were the basis for the warning and action trigger values. Due to the location of the inclinometers and their inclination, trigger values needed to be assessed independently for each installation. Warning trigger levels were set at ⅔ action trigger levels and varied from 10 - 14mm (warning levels) corresponding to 15 – 21mm (action levels).

Shaft flood

Excavation and construction of rings proceeded as planned until the excavation reached ring 8, whereupon the ring was built and grouted at the end of a Friday night shift and the shaft was left until the following Monday morning. In the early hours of Sunday morning a coupling on the site water main failed causing extensive flooding to the basement of Moorhouse including the partially constructed shaft. The water from the main filled the shaft to a depth of about 2m, implying about 100m^3. Excavation of the shaft was at a relatively early stage, in a substantial layer of stiff London Clay, and the formation was at about –8.5mOD. Pumping to remove the water by means of a high lift submersible pump commenced at about 4pm on the Monday and this operation was complete by mid-evening, a few hours later. The water therefore remained in the shaft for a maximum period of about 36 hours. Excavation for ring 9 was completed by the morning of the Wednesday at which point the ring was built.

The material exposed to the water was stiff, fine grained, over-consolidated clay, and was relatively impermeable. Water could not be expected to penetrate very far into the excavated surfaces, especially given the duration of exposure, and as a result significant softening did not occur. When the shaft was entered following removal of the water the softened material was found to extend to a depth of about 100mm. It would seem reasonable to assume that much of this material was left over excavation arisings that had not been removed from the shaft. Inclinometer tube profiles showed that the maximum inclinometer movement was 2mm. This movement is thought to be genuine but, when viewed in the context of previous and subsequent displacements, was not particularly significant or excessive.

<u>Secondary dewatering in the Upper Lambeth Group</u>

Throughout construction of the shaft the ground conditions and dewatering performance and output were monitored and recorded by the shift engineer as excavation proceeded. Although excavation through London Clay was straightforward probing ahead of the excavation, from within the shaft, was carried out when the shaft was approximately 3 metres above the upper granular horizon in the Lambeth Group (between –31mOD and –32mOD) and the hole checked for water (Figure 11). This was because, despite the dewatering system functioning well, the water levels monitored in the Upper Lambeth Group (notably between –30.7mOD and –32mOD) remained above the design level of 0m head of water (Figure 12).

As the excavation approached the level at which two of the three piezometers were indicating about 1m of water the issue of secondary dewatering had to be addressed. Whilst the trial pits indicated that water was not present inside the shaft it was not possible to know whether a water bearing layer existed in close proximity outside the shaft. In order to deal with such an occurrence provision had been made to install an array of secondary, inclined dewatering wells using a mini rig from a working platform inside the shaft as shown in Figure 13.

Apart from the obvious disruption to progress on the shaft, one major problem with the use of secondary dewatering was in deciding when it was necessary to use it and from where it was best installed. Two special sets of segments had been manufactured with provision for drilling the inclined wells for secondary dewatering. These could be installed at any level but, owing to the offset nature of the joints in alternate rings (to maximise the stiffness of the shaft), the positions of the individual wells was governed not only by the ring elevation but also by its orientation. These restrictions were, in turn, exacerbated by a third logistical problem in that there was only sufficient space on site to store two complete rings of segments. This meant that a special ring of segments would have to be installed almost immediately if it was brought to site. The time taken to install the secondary dewatering wells would in itself result in increased movements around the shaft. Therefore, the decision to use secondary dewatering and the timing of its installation was critical.

Shaft excavation and construction continued until trial pits could be excavated from about 2m above the water bearing layer. Three trial pits at third points around the perimeter of the shaft remained dry following excavation. On this basis all parties agreed to proceed with excavation through the water bearing layer. Upon excavation the silty sand appeared relatively dry but during the course of the ring build, about 2-3 hours, small amounts of material continually fell from the sides (Figure 14). At this point the piezometer reading had dropped and recorded a small suction. When the ring build was complete the space behind the segments was about 400mm, gauged from the quantity of grout that was used to fill the void. Excavation continued for subsequent rings and the piezometer reading recovered to show 1m head (Figure 12). The additional movement resulting from excavation through this layer became apparent from the inclinometers near to the shaft. A maximum displacement of 7mm was recorded on inclinometer IG2 (Figure15). This movement represented nearly 50% of the total movement for the entire shaft construction.

Excavation for the base plug of the shaft entailed undermining the bottom ring of segments by 2m in a layer of clayey coarse gravel to fix a heavily reinforcement cage. This excavation was nearly twice the depth of the ring excavations and greater movements could therefore be expected. Additionally, the excavation was to remain open for much longer whilst the base plug was constructed. This layer was the Upnor Formation and had also been targeted by the ejectors with the aim of eliminating the excess head of about 5m. All of the piezometers around the shaft indicated that the head had been successfully drawn down and the excavated faces were gunited to maintain stability during the two weeks needed to fix steel and pour the base. Dewatering continued until the base plug achieved design strength and monitoring continued for a further month. Inclinometer readings showed additional movement during this period with the most movement being recorded at IG2 (Figure 16) where a warning trigger level was reached. However, considering the time taken to complete the construction of the base plug, this was not excessive and the overall movement remained well inside the action threshold .

<u>Grouting to re-stress the ground</u>

Any need for grouting to re-stress the ground around the shaft was dependent on the results of the ground monitoring. If the acceptable inclinometer movement limits were exceeded then the grouting was deemed necessary to "restress" the ground around the shaft and adjacent piles. If required, the grouting would be carried out after the shaft was complete and the base concreted. Several of the shaft rings had additional large grout holes which could be used to allow radial drilling and subsequent grouting to be carried out. In the event, the maximum movement in relation to a trigger level was about 15mm, on inclinometer IG2 which exceeded the warning trigger movement of 12mm but did not exceed the action trigger movement of 18mm.

Conclusion

An 8.2m diameter by 36m deep shaft has been constructed within the basement of a new 16 storey building. The shaft has been constructed through about 20m of London Clay and then through the soils of the Lambeth Group where two water bearing layers were encountered. At its closest point the shaft was within 2m of the new heavily loaded piled foundations of Moorhouse. The proximity of the existing foundations and the influence of the proposed developments associated with Crossrail posed significant problems to the design and construction team with respect to limiting the impact of the shaft's construction on Moorhouse. A sophisticated dewatering system was devised and installed to enable excavation and construction through the Lambeth Group and also to enable the shaft to be excavated to within 2m of the underlying Thanet Sand. Elaborate precautions were taken to ensure that construction solutions were in place to deal with foreseeable events and a detailed monitoring exercise was carried out to help control ground movements and thereafter demonstrate that ground movements did not exceed acceptable limits.

The movements that did occur were linked very strongly to two significant events in the shaft construction. The first event was excavation through a layer of water bearing silty sand that had been dewatered but still contained about 1m head. Although this layer was only about 1m thick, and the excavation rapid, this accounted for nearly 50% of the maximum horizontal movement measured by an inclinometer near to the shaft. The second event was excavation below the silty sand layer and construction of the base plug. This was carried out over a period of 18 days and involved a deeper excavation than had been necessary for the pre-cast concrete rings. This process occupied approximately 30% of the time taken to construct the entire shaft and contributed another 8mm or just over 50% of the maximum horizontal movement at the base of the shaft.

Acknowledgements

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Reference

Morrison, PRJ, McNamara, AM, Roberts TOL (2004) Design and construction issues relating to a deep shaft for Crossrail. Geotechnical Engineering Vol 157 Issue GE4.

Target Strata	Lambeth Beds	Thanet Sand and Lambeth Beds
No. of wells	11 No	6 No
Well location	In ring 3 to 5m from shaft at 3m nominal spacing	
Depth	53m (+14 to –39mOD)	61 m (+14 to –48mOD)
Bore size	200mm nominal	200mm nominal
Well liner size	101mm bore	125mm bore
Screen length	Lower 15m	Lower 24m
Pumping	Ejector system driven by pumping station located at B2 level, 2.5mOD	Submersible pump near base of well

Table 1 Outline specification for dewatering system

Element	Top of slab or stratum mOD
Ground floor slab (drill patform level)	+13.42mOD
B1 slab	+7.45mOD
B2 slab	+2.55mOD
London Clay	+0.00mOD
Lambeth Beds	-23.00mOD
Thanet Sand	-41.00mOD
Chalk	-53.00mOD

Table 2 Structural slab levels and sequence of stratification below the new Moorhouse structure

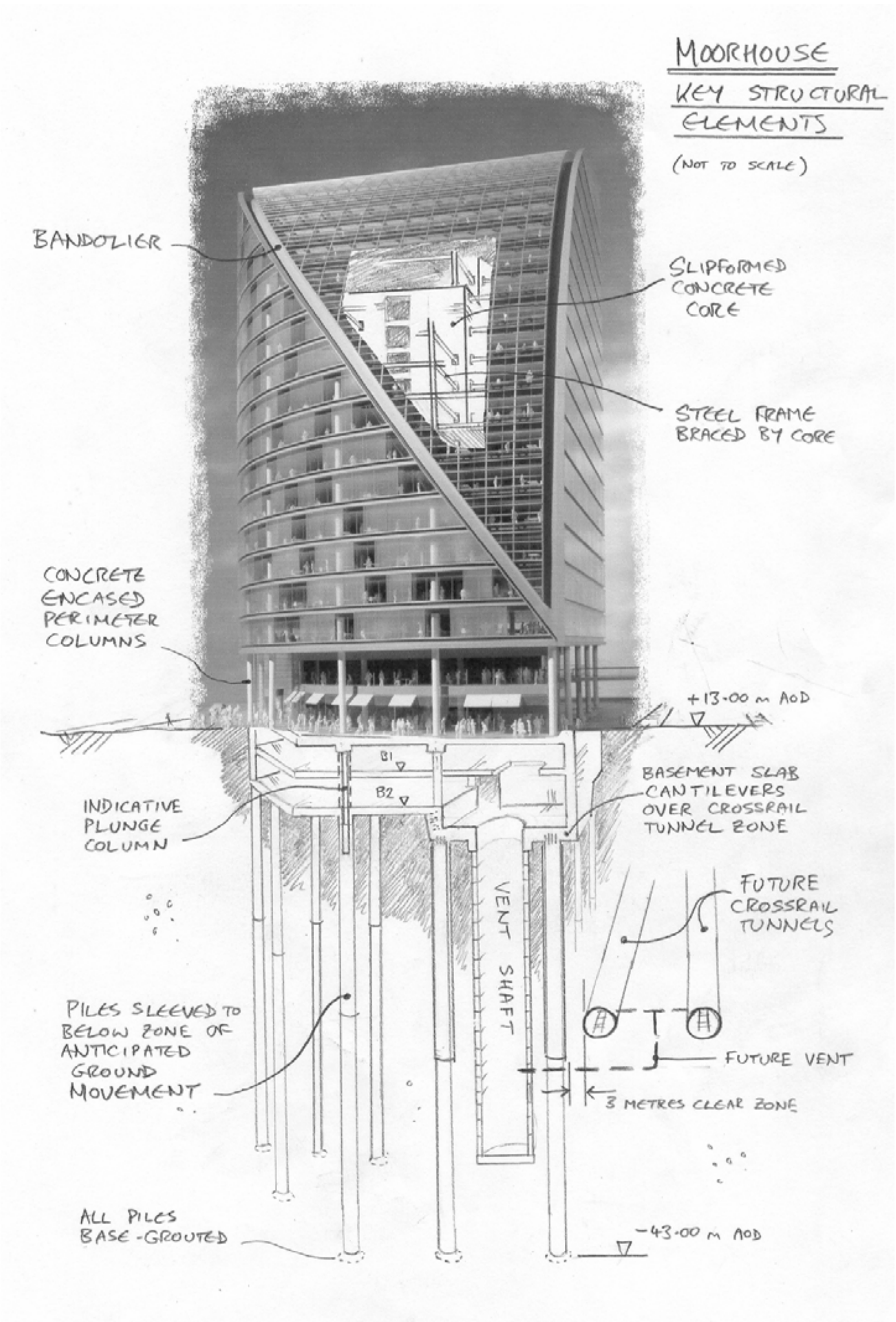

Figure 1 Schematic view of Moorhouse and the Crossrail shaft and running tunnels

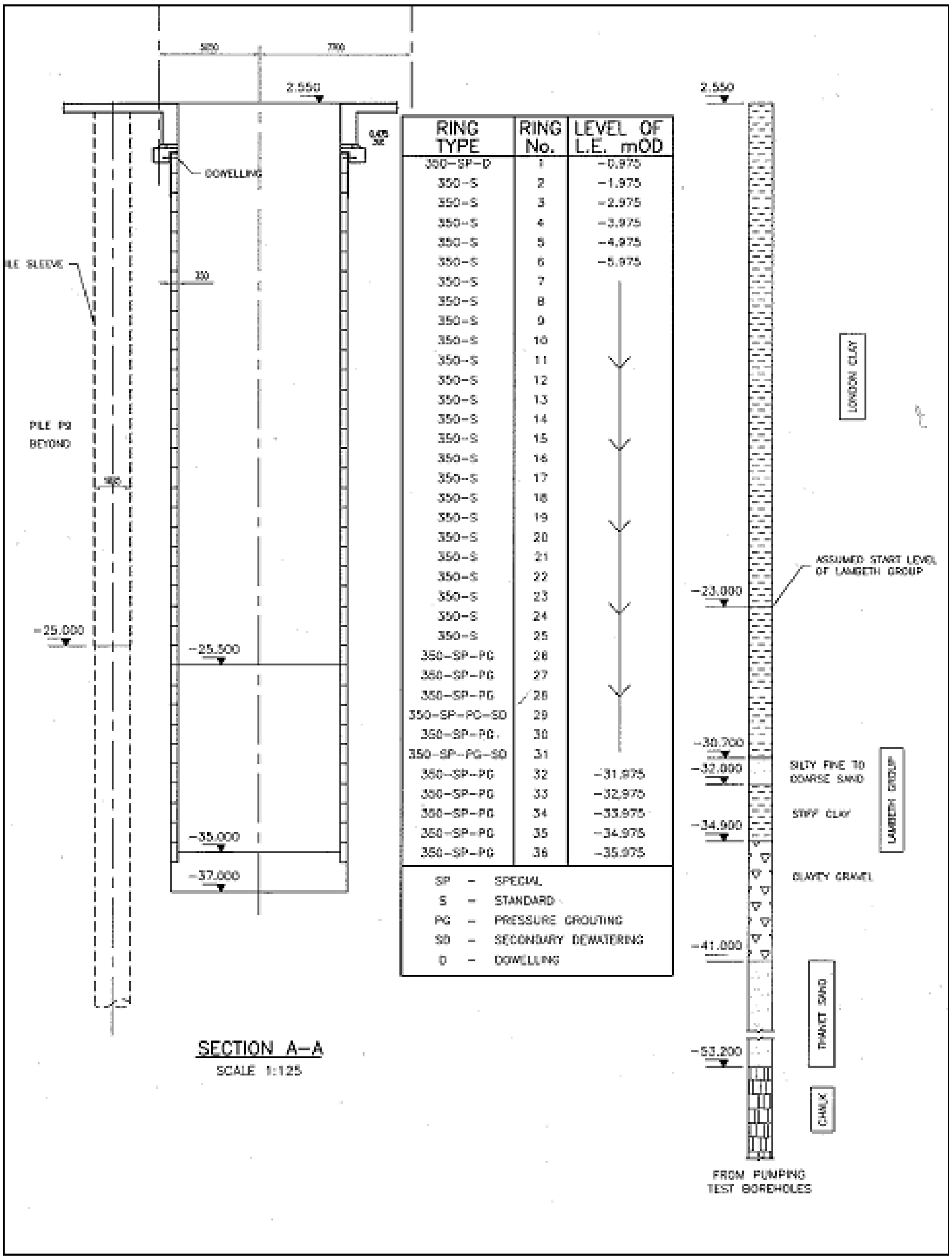

Figure 2 Section of Draught Relief Shaft with pile and ground condition details

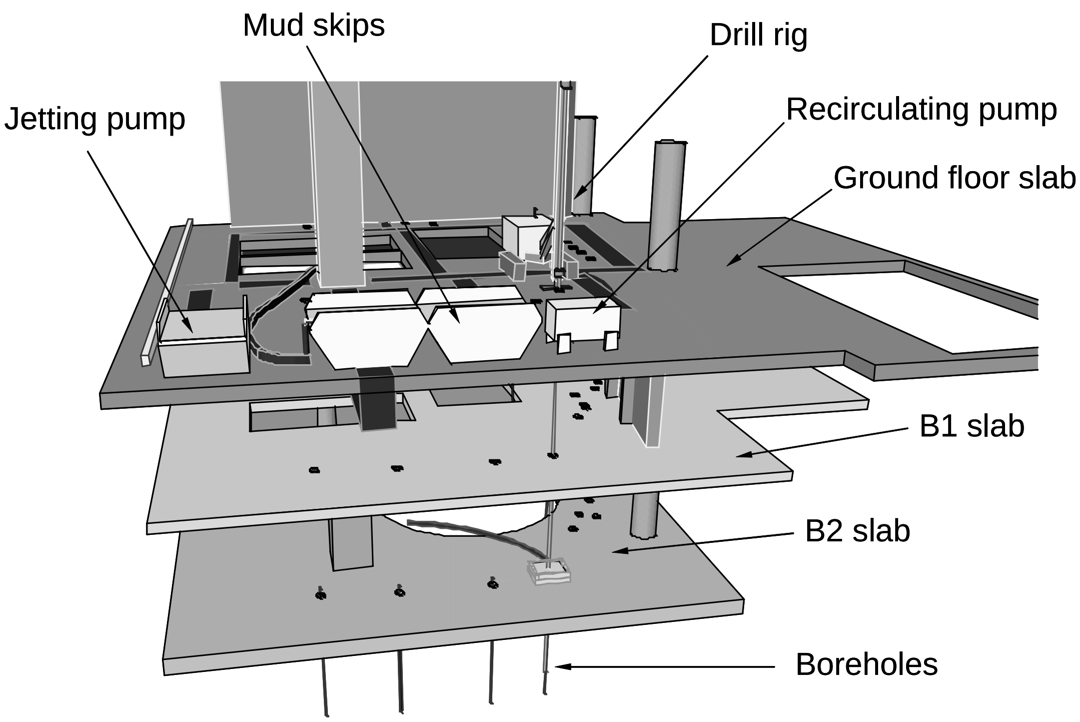

Figure 3 Schematic showing dewatering and instrumentation installation on site.

Figure 4 Congested site access with 14 tonne drilling rig operating on ground floor slab.

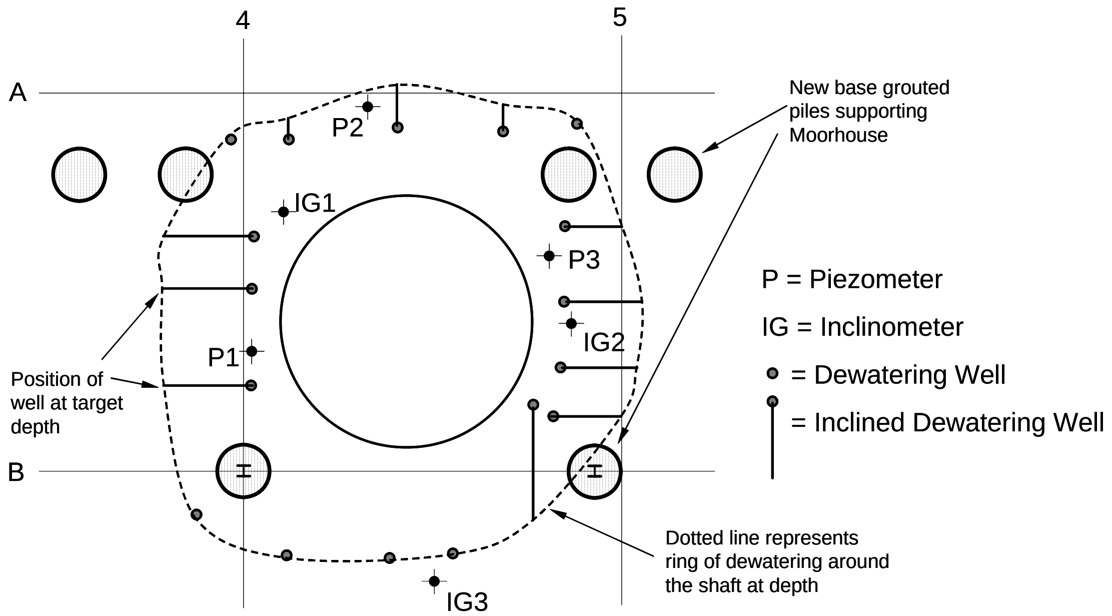

Figure 5 Layout of dewatering wells, piezometers and inclinometers around shaft position

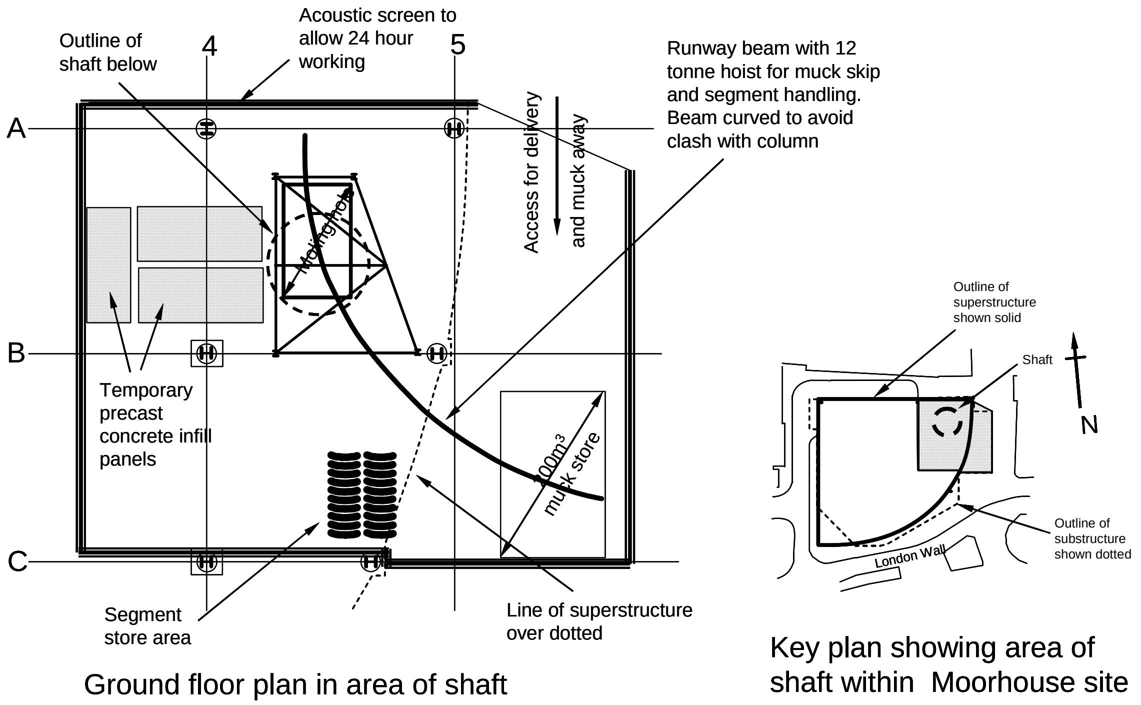

Figure 6 Layout of ground floor slab during shaft construction

Figure 7 Muck skip under runway beam on ground floor slab immediately before commencement of shaft construction. Moling hole in background.

Figure 8 Final trimming to allow a gap not exceeding 100mm behind the segments was carried out using clay spades

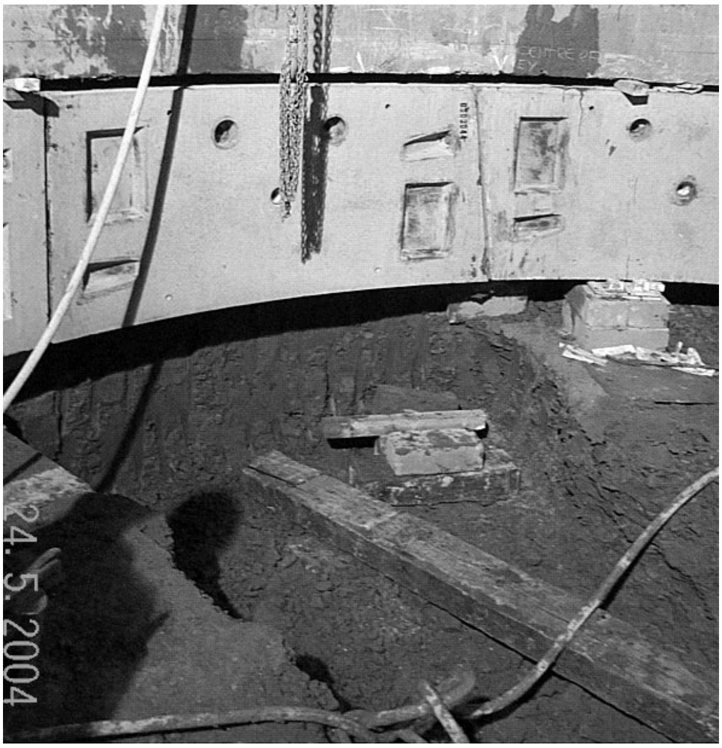

Figure 9 Overdig at position of key segment

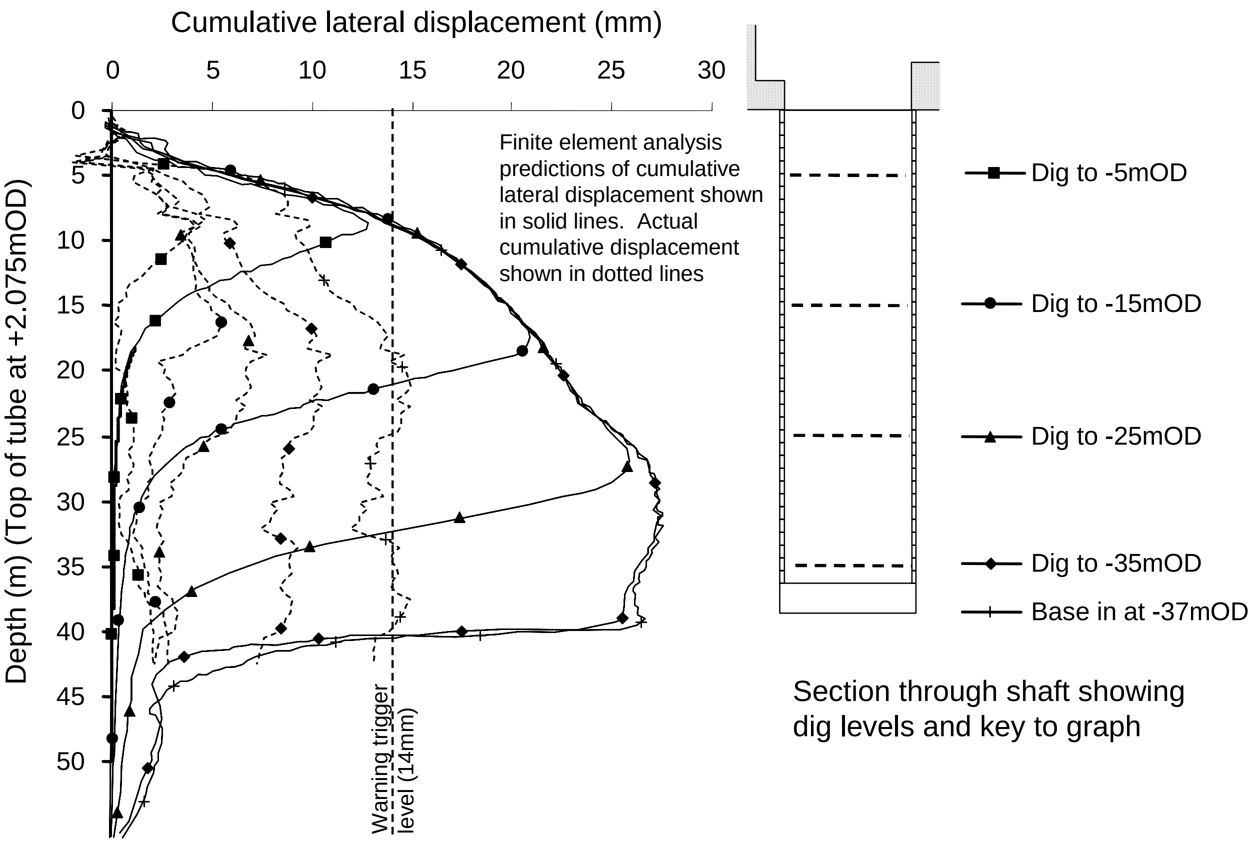

Figure 10 Predicted and measured ground movements during construction of the shaft at inclinometer IG1

Figure 11 Trial pit at perimeter of shaft in water bearing strata of Upper Lambeth Group

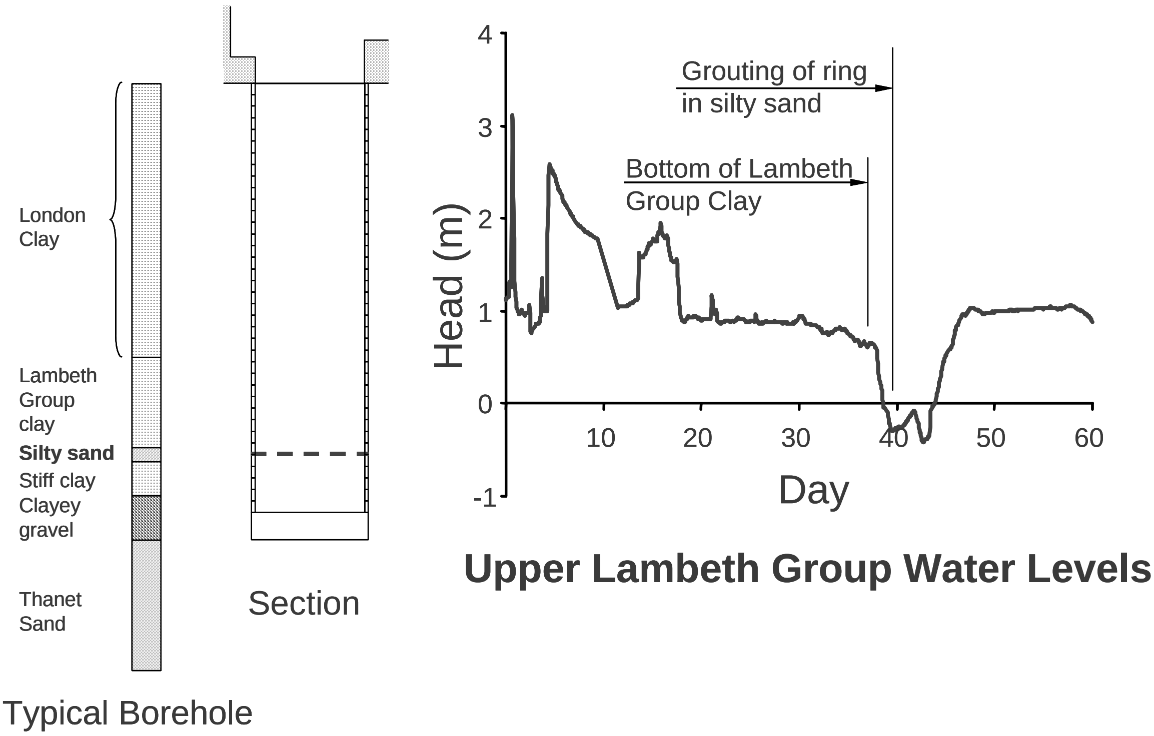

Figure 12 Head in Upper Lambeth Group during construction of the shaft.

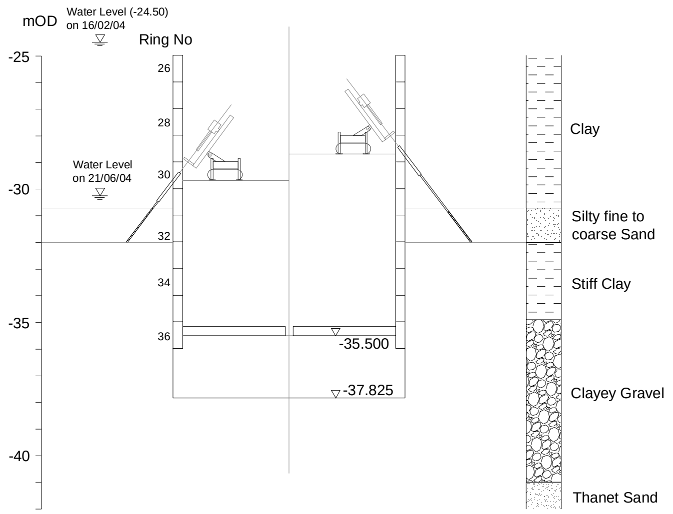

Figure 13 Secondary dewatering system using inclined wells from within the shaft.

Figure 14 Silty sand slumping from the excavated face during ring build in water bearing layer in Upper Lambeth Group

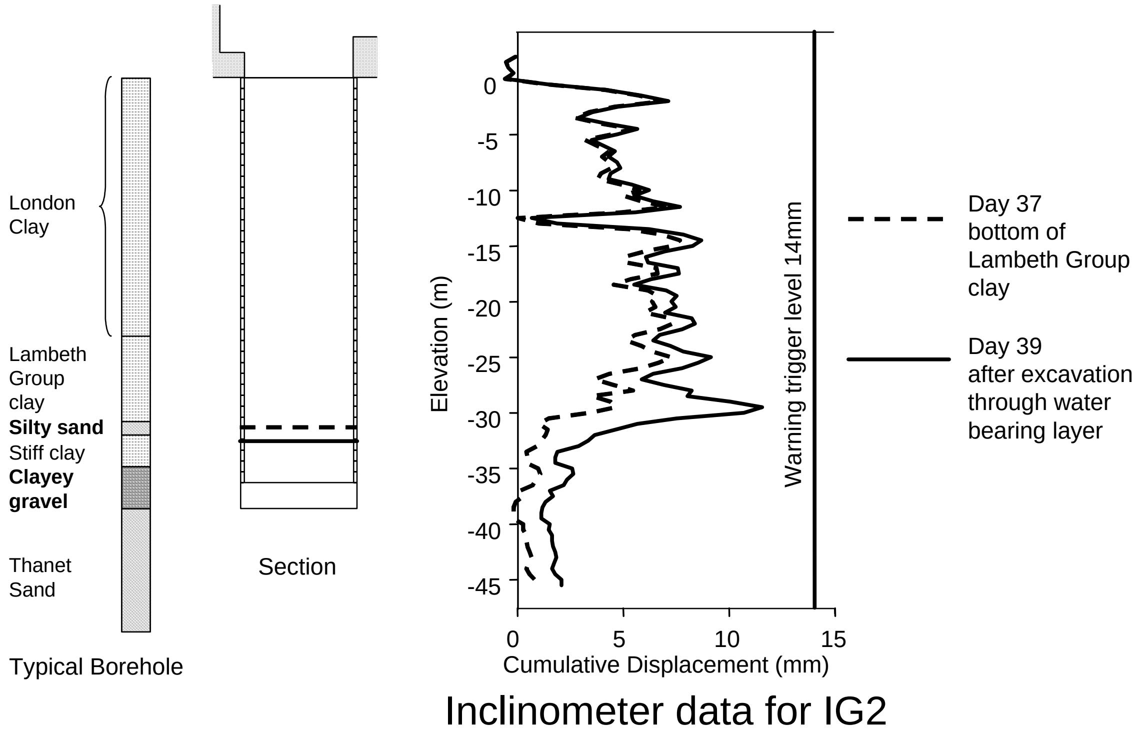

Figure 15 Inclinometer data reflecting the movement associated with excavation through water bearing layer in the Upper Lambeth Group.

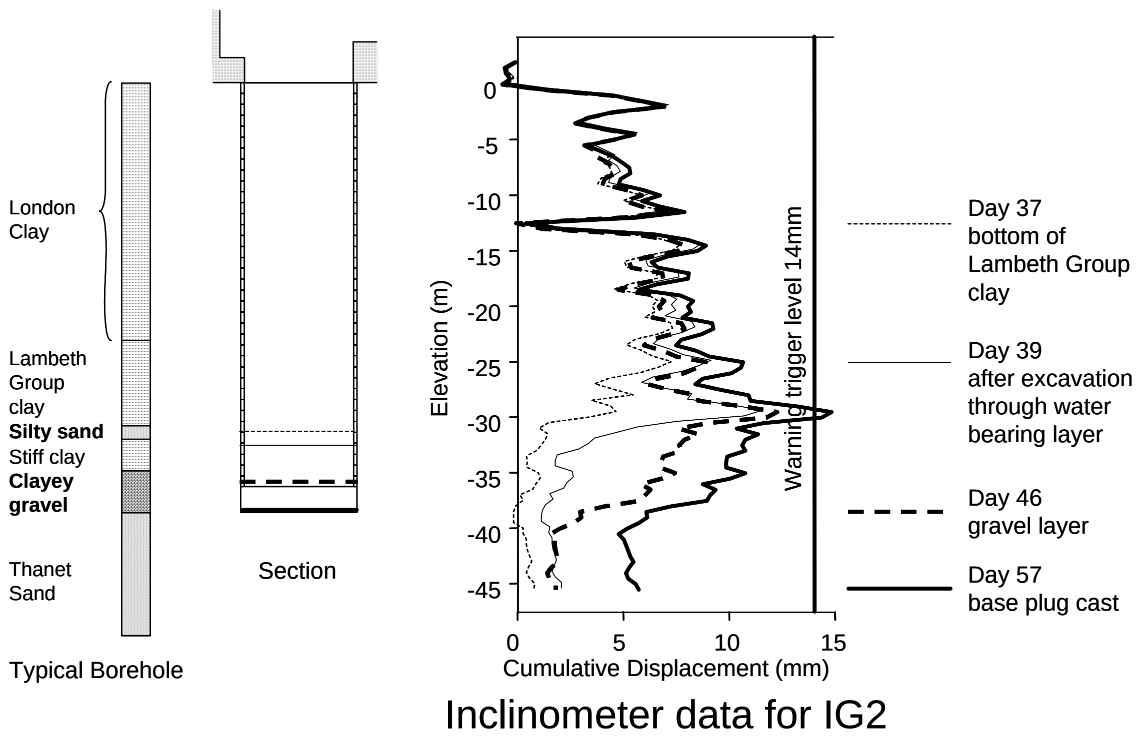

Figure 16 Inclinometer data reflecting the movement associated with excavation through the clayey gravel and construction of the base plug.