The role and performance of instrumentation and monitoring in managing risk during deep shaft excavation in the Mercia Mudstone

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ABSTRACT

The HS2 Bromford Tunnel intermediate shaft has an external diameter of 21.9m and a depth to formation of 47.1m below ground surface. The shaft is formed with a 63.1m deep 1.5m thick diaphragm wall primary lining, with a cast in situ secondary lining. The shaft works started in spring 2022, and formation level was reached in late 2023.

Situated at the base of the Tame valley, the shaft excavation is predominately in the Mercia Mudstone, and is understood to be the largest and deepest excavation of its type in the Birmingham area. Instrumentation and monitoring played a vital role in managing ground risks during the diaphragm wall installation and bulk excavation. The paper covers: An overview of the shaft works and the subsequent tunnelling in the area; The geotechnical risks and parameters to be monitored; The specification, installation and performance aspects of the instrumentation, including the embedded SAAs and Vibrating Wire Piezometers; The design and performance of the specialists' subcontractors dewatering system and excavation groundwater pressure behaviour during construction; Ground movements and third-party asset monitoring during diaphragm wall installation and excavation; diaphragm wall deflections during excavation - a comparison between design model calculations and actual monitored movement.

As the shaft was constructed largely in advance of the main tunnelling works, some of the potential benefits from the experience and field observations made during the shaft works have been realised during the tunnelling.

Keywords: Shaft, Diaphragm wall, Mercia Mudstone, Groundwater Depressurization, Third-Party Asset Protection

1. Bromford Tunnel Intermediate Shaft

1.1. Overview

High Speed Two, HS2 is the UK's new high-speed railway, running from London to Birmingham Interchange, with branches to central Birmingham and Handsacre, near Lichfield. HS2 trains for Manchester, Liverpool and Scotland will join the West Coast Main Line at Handsacre. The Phase One N1/N2 Contract covers the West Midlands section, 90km from Long Itchington in Warwickshire to the centre of Birmingham, and on to Handsacre in Staffordshire. The contract was awarded to the Balfour Beatty VINCI (BBV) joint venture, including the joint venture's designers, Mott MacDonald and SYSTRA.

Bromford Tunnel will form part of the Birmingham Spur. The Bromford Tunnel intermediate ventilation shaft, which is constructed first, will be straddled by the twin mainline tunnels, with the downline passing to the south of the shaft and the upline passing to the north. The mainline tunnels are constructed using variable density tunnel boring machines (TBM).

The shaft will be connected to the mainline tunnels via sprayed concrete lined (SCL) adits (see Figure 1).

1.2. Ground Conditions

The generalised ground conditions along the Bromford Tunnel are Made Ground (Ground Surface), with localised Alluvium (ALV), overlying River Terrace Deposits (RTD) and Mercia Mudstone Group (MMG) – The Sidmouth Mudstone Formation. Weathered MMG Grades III and IV (encountered as a clay/silt soil matrix with or without lithorelicts of rock) generally overlie unweathered MMG (Grades II and I) which are typically encountered as weak mudstones with occasional siltstones bands. The MMG weather grades system is summarised in CIRIA 570 (Chandler et al, 2001).

The ground surface level varies between 77mAOD and 105mAOD along the tunnel alignment, though generally at around 80m AOD where the tunnel alignment follows the River Tame valley. The groundwater level typically ranges between 2m and 4m below the ground surface.

The ground profile at Bromford Tunnel intermediate shaft is illustrated in Figure 2, and design ground model presented in Table 1.

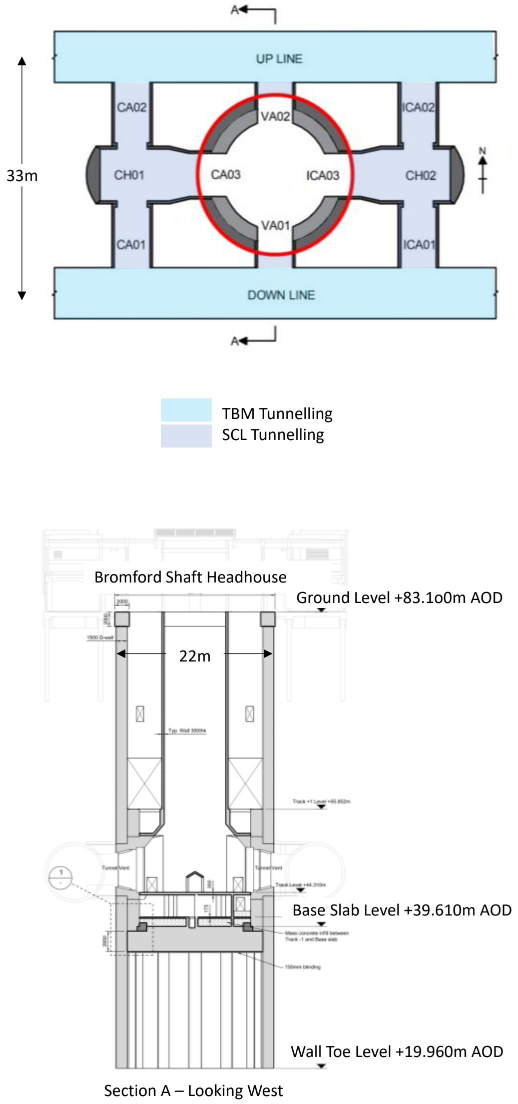

Figure 1. Bromford Tunnel Intermediate Shaft – Plan and Section

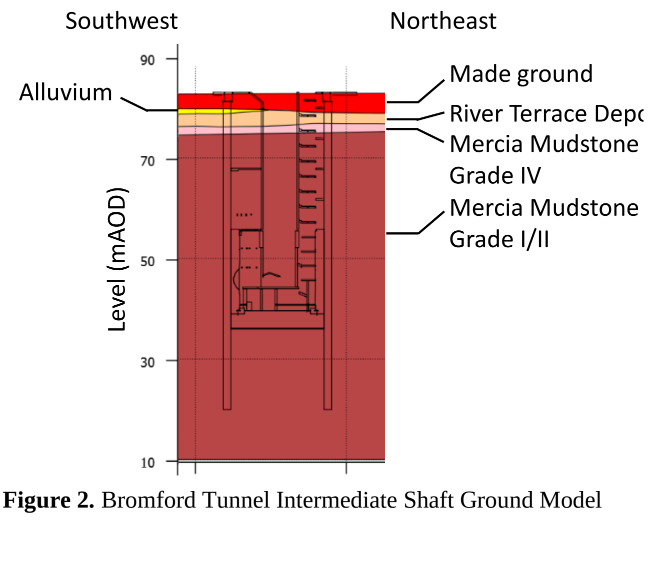

Figure 2. Bromford Tunnel Intermediate Shaft Ground Model

Table 1. Bromford Shaft Design Ground Model

Strata	Top of soil strata (mAOD)
Made ground	83.1
Alluvium	79.5
River Terrace Deposits	79.0
Mercia Mudstone Grade IV	77.0
Mercia Mudstone Grade I/II	74.5

1.3. Construction

The Bromford Tunnel intermediate shaft has an external diameter of 21.9m and a depth to formation of 47.1m below ground surface. The shaft is formed with a 63.1m deep 1.5m thick diaphragm wall primary lining, with a cast in situ secondary lining for the bottom 12m above the base slab to allow for adit connections.

The diaphragm walling involved the construction of 26 no. single bite panels excavated using a hydrofraise and bentonite support fluid. Production commenced in February and the diaphragm walling was completed in August 2022.

The bulk excavation commenced in early 2023 following the construction of the capping beam. The excavation was undertaken in several phases, with planned pauses during secondary lining and beam works. Joint designer/contractor inspections were undertaken throughout the excavation, including recording the thickness of the bentonite filter cake, and geological logging. Figure 3 presents a photograph taken during the shaft excavation. Formation level was reached in late 2023 and the base slab cast in early 2024.

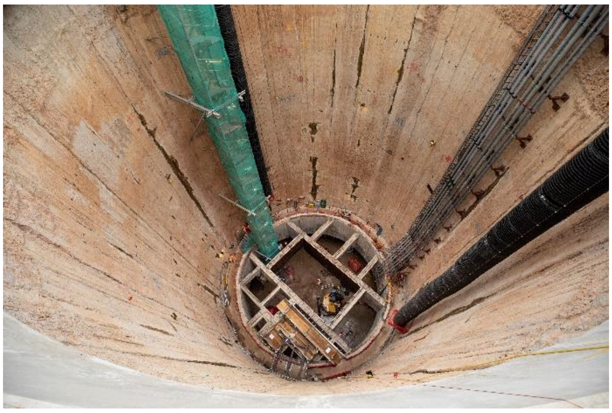

Figure 3. Bromford Tunnel Intermediate Shaft Excavation (BBV, July 2023)

2. Instrumentation Installations

Instrumentation and monitoring was planned and implemented for the shaft construction. The monitoring installations included dedicated instrumentation for the shaft construction phase, as well as monitoring installations that would remain live during the tunnelling and post-construction monitoring phases.

The instrumentation would be supplemented prior to the TBMs arrival to allow some of the additional risks associated with the tunnelling to be monitored.

2.1. Shape Accel Arrays

To monitor lateral deflection of the wall during excavation, inclinometer casings were installed in steel reservation tubes in 4 no. diaphragm wall panels spaced evenly around the shaft. The annulus between the inclinometer casing and the reservation tube was grouted. The inclinometers were extended (drilled post panel casting) 4m below the toe of the diaphragm wall to allow the casing to be anchored in stable ground and confirm the fixity of the diaphragm wall toe. The inclinometer casings were surveyed automatically by in-place Shape Accel Arrays (SAA). The performance of SAAs in measuring retaining wall deflection is described by Lipscombe et al (2014).

Spare reservation tubes (and associated inclinometer casings) were installed to provide redundancy, with base readings taken with manual probe inclinometers for the primary and spare casings prior to excavation.

3D Geodetic prisms were drilled and fixed to the capping beam adjacent to the inclinometer position as a secondary system for measuring the lateral movement of the capping beam.

2.2. Borehole Piezometers

External to the shaft footprint groundwater monitoring was undertaken using (i) standpipe installations installed during the ground investigation and design phase; and (ii) dedicated multi-level vibrating wire piezometer boreholes installed and baselined prior to the shaft construction works for monitoring during the construction phase.

Internal to the shaft footprint the groundwater temporary works contractor installed an additional 3 multi-level vibrating wire piezometer boreholes to verify the effectiveness of the groundwater control system.

Table 2 provides a summary of the vibrating wire piezometer boreholes and sensor elevation employed to monitor the pore pressures during the shaft excavation.

Table 2. Elevation of the different vibrating wire piezometer tips

Piezometer ID,	**Tip elevation (mAOD)**				**Target geological unit**	**Comments**
1MC13-BTIS-167-PV	**'A'**	**'B'**	**'C'**	**'D'**		
601(1)	29	-	-	-	MMG grade II/I	Originally, three tip VWP piezometer, only one functioning. Also referred to as excavation PV1, in Figure 4.
602	29	23	19	--	MMG grade II/I	Three tip VWP. Also referred to as excavation PV2, in Figure 4.
603	35	29	23	19	MMG grade II/I	Four tip VWP. Also referred to as excavation PV3 in Figure 4.
601(2)	75	55	35	30	MMG IV (tip A), MMG II/I (tips B to D)	Four tip VWP.

The design and performance of multi-level fully grouted vibrating wire piezometers is documented by Contretas et al (2008), Wan and Standing (2014), and Mikkelsen and Green (2003), and this method is now well established.

2.3. Precise Levelling

Construction-induced ground movement was monitored through precise levelling of the ground surface and adjacent third-party assets – a warehouse building to the south of the shaft and a third party electrical infrastructure tower to the northeast.

InSAR data was reviewed to provide an extended historic baseline for the area, although monitoring with InSAR was not explicitly undertaken during the works, the Contractor ensured that current and historic InSAR data was available to review on the project Instrumentation and Monitoring Platform, Maxwell Geosystems MissionOS.

2.4. Borehole Extensometers and Inclinometers

A combined borehole extensometer / inclinometer was installed between the shaft and the electrical tower to record sub-surface ground movement. The combined instrument was a traditional spider magnet type extensometers with an ABS inclinometer casing installed. The instrument was read manually by two different probes. The specified grout was a non-shrink 3:1 by weight bentonite/cement mixture with sufficient water to achieve a pumpable mix. The proportions of the mix were to be varied to imitate, as closely as possible, the strength or consistency of the natural ground conditions in the borehole. Levelling of the extensometer was specified in the monitoring plan; however, this was not available to the authors during data review.

3. Groundwater Control

3.1. Baseline Monitoring

Groundwater monitoring data for the Bromford Tunnel Intermediate shaft was collected during ground investigation between January 2019 and June 2020 to support detailed design, as well as during a pumping test performed in October-November 2022 to characterise the permeability of the Mercia Mudstone bedrock. Additional monitoring carried on until early 2023.

The pre-construction groundwater monitoring found groundwater to be between 77.9mAOD and 82.4mAOD in superficial deposits and between 78.1 and 82.5mAOD in the Mercia Mudstone bedrock in the shaft area. This corresponded to a groundwater table approximately between 0.1m and 4.7m below ground level (82.6 mAOD). A characteristic groundwater level during construction was established to be 79.5 mAOD at the shaft site.

3.2. Well System

The groundwater control system consisted of a ~12m diameter ring of 8 pre-drilled dewatering wells extending to within a metre of the diaphragm wall toe level. Four of the wells were dual-purpose (to allow for active dewatering with a submersible pump if required), with the remaining being passive wells. The wells were connected by a circular trench, with falls to direct flows to sumps at the locations of the dual-purpose wells. The system is illustrated in Figure 4, with details of the two well types shown in Figure 5.

Passive relief dewatering refers to the lowering of the groundwater, as the excavation proceeds, with bleeding wells flowing freely to a collection system consisting of sumps, where water is ultimately pumped from the excavation level to the surface. The flow in the wells is driven by the hydraulic head difference created as the excavation deepens with respect to the surrounding groundwater level. In this manner, as the excavation advances the groundwater level is kept equal to the excavation level (or slightly lower - controlled by the level of water in the sumps) and provides dry working conditions.

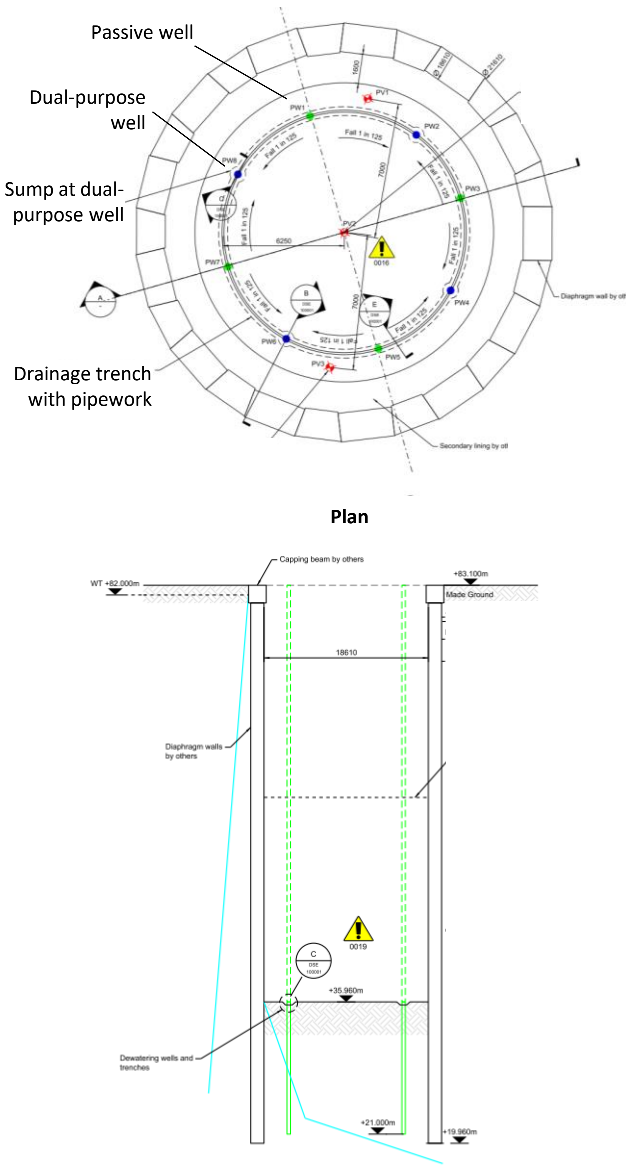

Figure 4. Depressurisation System showing Design Pore Pressure at Formation Level

As important as keeping the excavation dry the wells also reduce the groundwater hydraulic gradient below the excavation, so that the large groundwater head difference between inside and outside of the shaft excavation does not reach pressures exceeding those that the soil can resist to prevent 'blow out' of the excavation base.

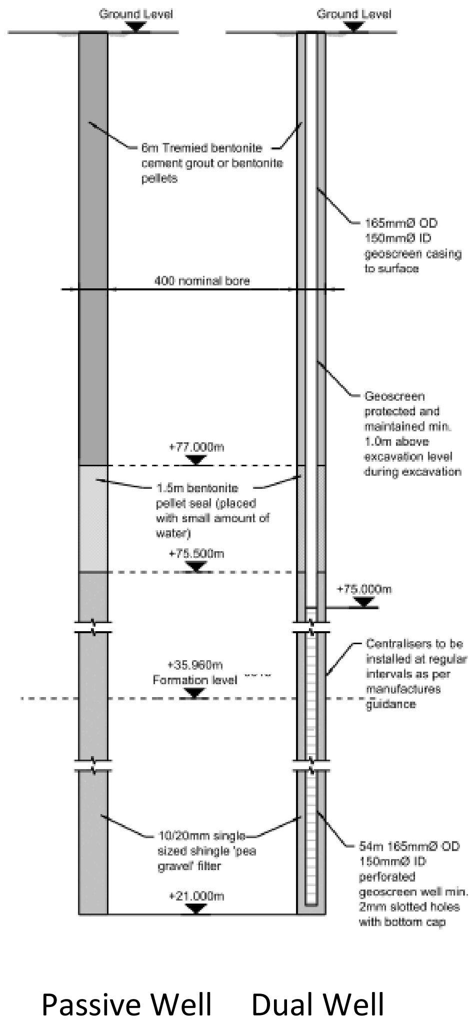

Figure 5. Passive and Dual Well Details

A traffic light system of warnings (green, amber, red) was used for the groundwater monitoring system during the construction, to warn of excessive groundwater pressure at different excavation levels - the amber trigger was 13 kPa/m and the red trigger 14 kPa/m.

The three multi-level vibrating-wire piezometers were used to verify that the designers' pore pressure profiles were being achieved.

4. Field Monitoring Observations

4.1. Ground Movement During Constriction

4.1.1. Precise Levelling

Levelling data for the warehouse building to the south of the shaft work site initially showed a response to the filling and emptying of the bentonite silos during diaphragm wall construction. These movements terminated after a few cycles of panel construction, and no further movement was observed. The warehouse building is a portal frame steel structure, and highly tolerant of such movements, which at no point exceeded 10mm.

Levelling data was predominantly collated with a view to safeguarding the electrical tower. The tower, of late 1960s construction, has four legs supported by raker pile group foundations. The record drawings indicate that the 460mm piles are lightly reinforced, and the configuration of the pile group with leg and stabilizer piles (raking externally and internally respectfully), gave concern in regard to the foundation's tolerance to construction induced ground movements. The tower is around 30m from the shaft, as indicated in Figure 6. Since the tower would also be potentially impacted by the future tunnelling works, in particular the upline TBM tunnel, it was very important to record the movements due to shaft construction such that the cumulative ground movement effect on the tower could be understood.

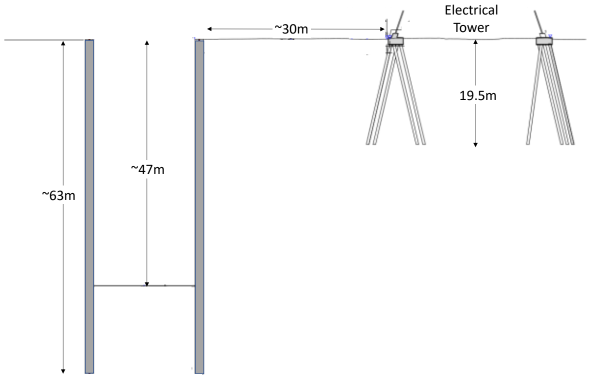

Figure 6. Section Through Shaft Illustrating Interface with the Electrical Tower

Figure 7 presents the ground surface levelling data from around the tower for the baselining period and through to the completion of shaft excavation. Levelling points LM7 and LM16 showed settlement prior to the diaphragm walling, which then stabilised. Levelling points LM05 and LM58 showed a trend of continuous on-going low rate of settlement. The observed minor settlements are thought to be related to heavy construction vehicles operating around the shaft area. The other levelling points recorded little movement.

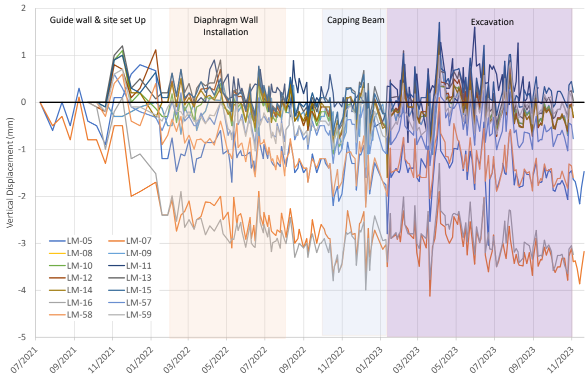

Figure 7. Ground Surface Levelling Around the Electrical Tower

Figure 8 shows the levelling of the tower bases, with pins installed in the concrete muffs on each of the legs, these show stability throughout the shaft works, and indicate there has been no settlement of the tower foundations.

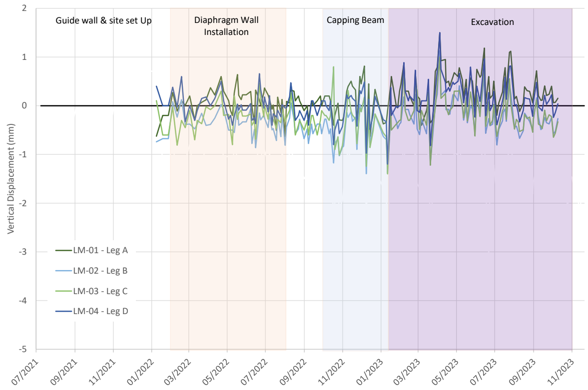

Figure 8. Levelling of Electrical Tower Bases

Figure 9 illustrates that there was minimal recorded movement of the ground around the tower during the diaphragm wall installation.

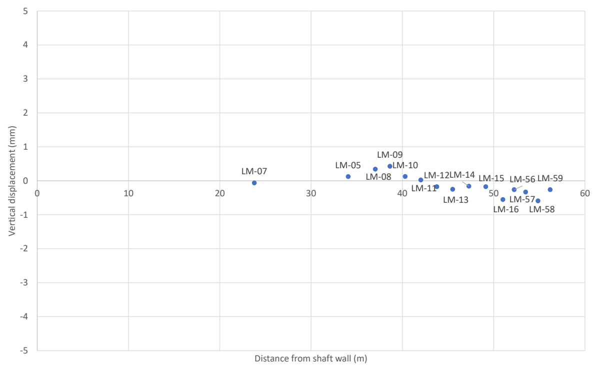

Figure 9. Ground Surface Levelling around the Electrical Tower during Diaphragm Wall Installation

The bulk excavation of the shaft commenced in early 2023 following the construction of the capping beam. The excavation was undertaken in several phases, with planned pauses during secondary lining and beam works. Formation level was achieved in late 2023.

Figure 10 illustrates that there was minimal movement of the ground around the tower during the shaft excavation, with most levelling points indicating a small amount of heave rather than settlement, likely to due to seasonal effects and assumed to be unrelated to the underground works.

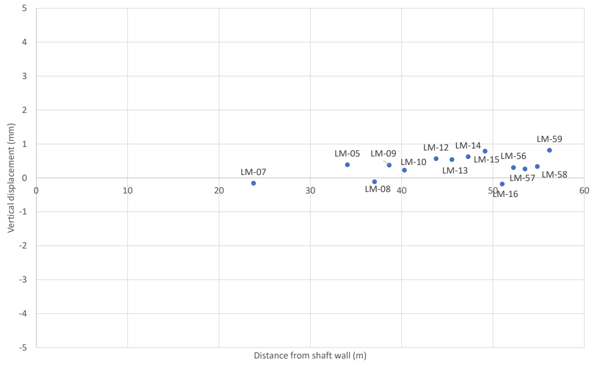

Figure 10. Ground Surface Levelling during Shaft Excavation

4.1.2. Ground Movement Boreholes

The combined borehole inclinometer/extensometer data at the shaft, showed some movement trends that are not in-line with engineering expectations. In particular, the magnetic extensometer data shows settlements/heave in the anchors in the MMG I/II, where negligible ground movement was expected, suggesting that the magnetic spiders are not well engaged with the side of the borehole, and/or that the borehole grouting was not successfully executed, and hence the magnets are moving independently of the surrounding ground.

There is a general move away from this type of instrument for the monitoring of the TBM tunnelling, with preference being given to dedicated rod or in-line extensometer boreholes.

4.2. Diaphragm Wall Deflection

Figure 11 presents the SAA measured diaphragm wall deflection during shaft excavation. The trigger levels are related to design wall movement estimations, with the red trigger level related to serviceability limit state, and the black trigger level the ultimate limit state.

Generally, a maximum of 3mm wall deflection was observed at around 50mAOD, with SAA 602 recording a maximum of between 3 and 5mm. Since the excavation reached formation level in November 2023, the SAA data has remained stable.

4.3. Groundwater Response to Excavation

As previously described the shaft excavation was progressed in stages, phased with the construction of the secondary lining. A first phase to 51mAOD was achieved by the 23rd of February 2023; to 47mAOD by the 14th September; to 43mAOD by the 21st September; and finally, to 36.0 mAOD (formation level) the 15 November 2023.

Figure 12 shows an extract from the monitoring data management system "MissionOS" used by the Contractor to control the pore-water pressure based on the traffic light system of trigger levels for one of the piezometers, 1MC13-BTIS-167-PV601, inside the excavation footprint.

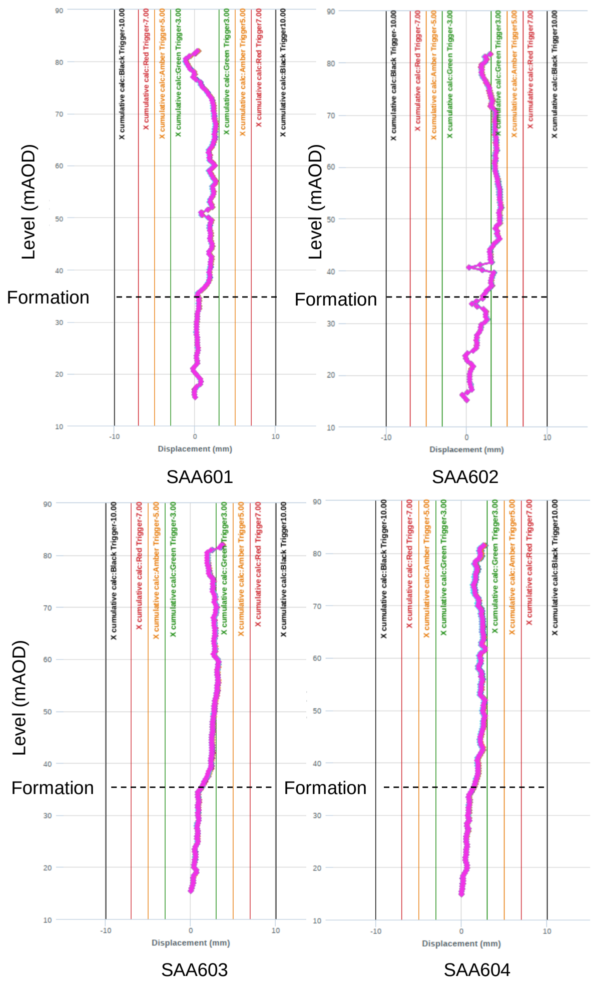

Figure 11. SAA Measured Diaphragm Wall Movement at the end of Shaft Excavation

Together with the monitoring provided by "MissionOS" the analysis of the groundwater pressure profiles both outside the shaft diaphragm wall and inside the excavation was undertaken to establish the evolution of groundwater pressure gradients.

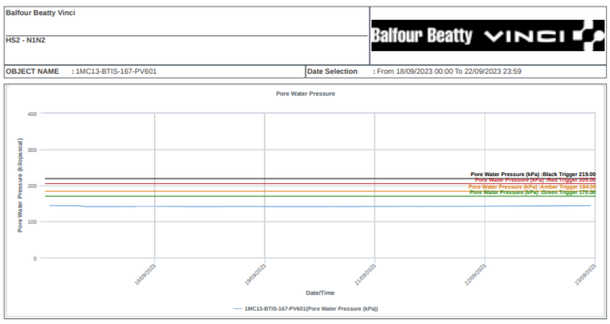

Figure 12. Contractor´s monitoring system "Mission OS" data platform output for the week from 18th September to 22nd September 2023, when the excavation reached 43mAOD.

Figure 13 presents analysis corresponding to the 20th of November 2023, after the excavation reached the formation level of 36.0 mAOD indicates a groundwater pressure gradient of 12.75kPa/m below the excavation (i.e. ~1.3 times the hydrostatic gradient) from piezometers inside the excavation. Below the toe of the diaphragm wall the groundwater pressure gradient increased at a higher rate (59 kPa/m) to rejoin the hydrostatic pressure line from the initial groundwater level before excavation at 79.5 mAOD. Outside the excavation a minor depressurisation of just below 50 kPa (at diaphragm toe elevation of 20.0 mAOD) was registered in the piezometer tip at the elevation of the diaphragm wall toe. This suggested that the impact of the shaft excavation dewatering was limited to the area close the toe of the diaphragm wall. Additional borehole installations for the future tunnelling, piezometers 1MC13-BS167-PV00002 and PV00004 (also multi-sensor vibrating wire piezometers in MMGI/II), confirmed this.

These gradients were obtained by fitting lines between the different pressures at the piezometer tips. It is noted that the groundwater pressure profiles would be in reality smooth curves rather than straight lines.

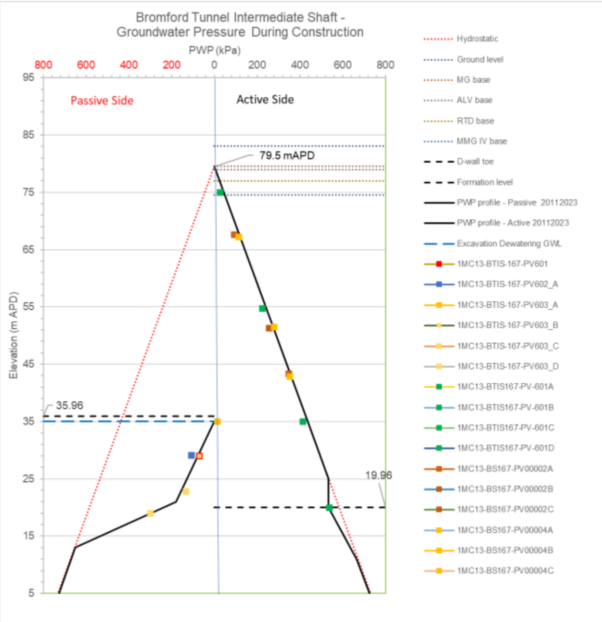

Figure 13. Groundwater pressure measured by the different vibrating wire piezometer tips after the excavation reached formation level, indicated by the horizontal blue dashed line on the passive side (excavation side). On the active side (ground side) the groundwater pressure profile indicated by tunnel alignment piezometers together with the shaft piezometer 1MC13.BTIS167-PV-601, located at the outside of the diaphragm wall perimeter.

5. Conclusions

5.1. Ground Movement

The geotechnical monitoring evidence demonstrated that there was no discernible movement of either the ground or the electrical tower during the diaphragm walling and shaft excavation. On this basis, it is reasonable to consider the potential future effects of the tunnelling in isolation, as the shaft works had little impact on the electrical tower.

5.2. Diaphragm Wall Deflection

The SAAs performed well and there was no need to resort to the backup manual inclinometers during the excavation phase. The SAA recorded diaphragm wall deflections were generally less than the design analysis values.

5.3. Groundwater

The hydraulic gradient under the excavation was adequately controlled and kept below the amber trigger level of 13 kPa/m established by the designer for the excavation.

Below the toe of the diaphragm wall the groundwater pressure gradient increased at a higher rate, this gradient reached approximately 59 kPa/m, but was also below the amber trigger level for depths below the diaphragm wall toe. The shaft excavation caused marginal depressurization (less than 50 kPa) in the ground outside the diaphragm wall.

The dewatering of the excavation and control of the groundwater pressures was successfully achieved by 8 pressure relief wells. It was not necessary to resort to the contingency of active pumping from the 4 “dual” dewatering wells.

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