Delivering added value using field measurements through the application of the Observational Method

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ABSTRACT

High Speed Two (HS2) is the new high-speed railway line in the UK currently being constructed between London and Birmingham. The designs of many HS2 retaining structures, as can be the case for some projects in the UK, were progressed concurrently with ground investigation. In this situation, to manage uncertainties in the ground, a cautious assessment of ground parameters was usually adopted. The purpose of field monitoring varies depending on the responsible or interested party. For designers, the primary aim is usually for design verification of their permanent works design. This paper describes how field observations, particularly quality instrumentation and monitoring data, were used at HS2 Bromford Tunnel East Portal to improve the existing design as construction progressed to create savings. To improve the efficiency in data processing, DAARWIN, a machine learning-based technology was used. The design and construction of the eastern end of the Bromford Tunnel East Portal were modified by eliminating the requirements of temporary support using measured field data, site observations and a carefully controlled construction through the application of the Observational Method. The portal construction programme was shortened by at least two weeks despite only three of the remaining temporary steel props being omitted. The findings revealed opportunities to extend the application of the Observational Method on adjacent structures including Bromford Tunnel West Portal and Washwood Heath Retained Cut. Given the great length of retained excavations of the two structures, the potential efficiency gains in cost, time and carbon emissions are significant whilst enhancing safety.

Keywords: Observational Method; instrumentation and monitoring; ground uncertainties; high-speed railway.

1. Introduction

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, a 5.6km twin-bore high-speed rail tunnel between Water Orton in North Warwickshire and Washwood Heath in Birmingham, will be formed by two tunnel boring machines (TBMs). The first TBM was launched on 27 July 2023 from an underground box structure that forms the Bromford Tunnel East Portal. The second TBM has been assembled and scheduled to launch from the portal structure in Spring 2024. The timely completion of the portal structure was fundamental to avoid delay in the HS2 tunnelling programme.

This paper describes how field measurement data was used to modify the design and construction of Bromford Tunnel East Portal as excavation progressed through the application of the Observational Method, enabling the construction of the portal structure to be completed in a faster, easier, and safer way. DAARWIN (De Santos, 2015), a cutting-edge ground engineering software employing machine learning-based algorithms was used to expedite the back analysis.

2. Bromford Tunnel East Portal

Bromford Tunnel East Portal is approximately 33m in width and 83m in length. The structure is formed by 1.2m thick diaphragm walls supported by one level of permanent concrete roof props at 88.55m APD (above Project Datum, this being equivalent to above Ordnance Datum). The planned excavation depth varies from approximately 16m at the western end to 11m to the eastern end. The portal base slab was cast in two stages to facilitate the launching of the TBMs. A circa 10m wide sump is located near the centre of the portal, with a depth ranging from 4.5m to 6.5m below the base slab level. Figure 1 shows the layout of the site and Figure 2 shows a typical cross section at Box 1.

2.1. Ground and groundwater conditions

The ground level at Bromford Tunnel East Portal is approximately 88.5m APD. The ground conditions consist of about 4.5m Glaciofluvial Deposits, overlying the Mercia Mudstone Group. Table 1 summarises typical descriptions of the encountered geology based on borehole data. Though the description of Mercia Mudstone Grade III is “soil-like”, the material exhibits strength characteristics that are residing between soil and rock mass.

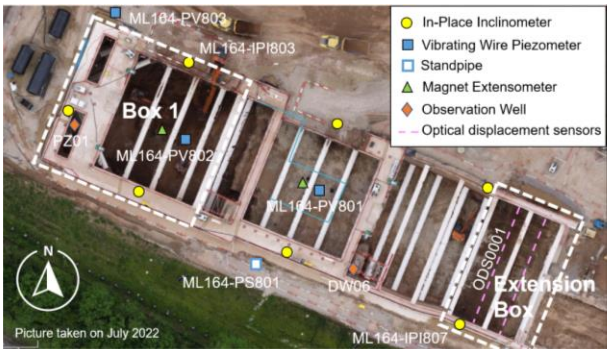


Figure 1. Site plan and instrument locations

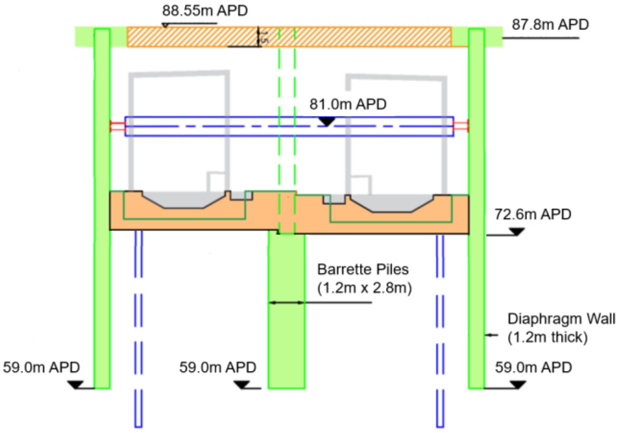


Figure 2. Typical section at Box 1

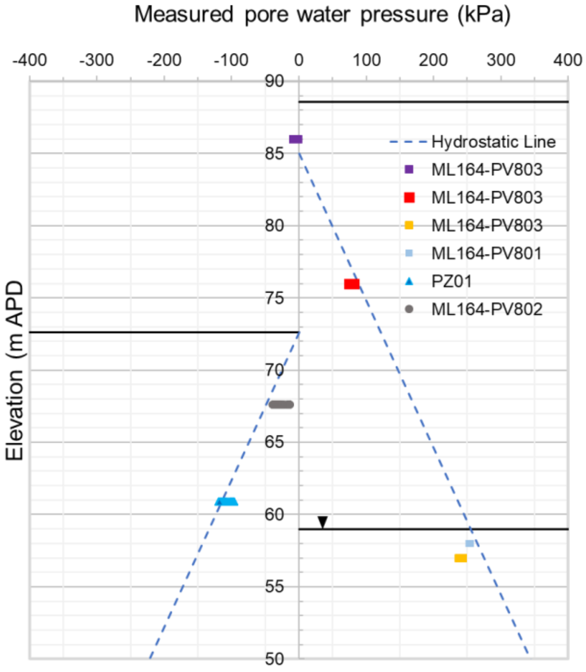


Figure 3. Measured groundwater pressure until August 2022

Table 1. Ground stratigraphy at Bromford Tunnel East Portal

Geology	Base level m APD	Typical description
Glaciofluvial Deposits	84.0	Soft to firm brown slightly gravelly sandy CLAY.
Mercia Mudstone Grade IV	81.0	Firm to very stiff reddish brown, mottled greenish, grey, slightly and sandy CLAY. Sand is fine to coarse. Gravel is subangular and sub-rounded. Fine to a medium Mudstone lithorelicts up to 25 mm.
Mercia Mudstone Grade III	79.1	Stiff to very stiff gravelly CLAY. Frequent presence of lithorelicts higher in size than 25 mm. This material is likely to be interbedded with extremely weak rock that has been softened and altered during the drilling process.
Mercia Mudstone Grade II/I	Not proven	Very weak to weak mudstone with subordinate siltstone and sandstone. Mudstones are generally structureless although some of the material does exhibit a ‘blocky’ structure. Interlaminated mudstones and siltstones occur within the formation.

Groundwater level is approximately 85m APD, 3.5m below ground level. Figure 3 shows the measured pore water pressures inside and outside the portal structure.

2.2. Design of Bromford Tunnel East Portal

The design of the Bromford Tunnel East Portal, as can be the case for design/build projects in the UK, was progressed concurrently with ground investigation. To manage the risk, the design was undertaken based on a ground investigation classification scheme developed for the project (Arnold et al. 2020), where a cautious set of ground parameters were derived to account for uncertainty in the parameters, in accordance with Eurocode 7 (British Standard Institution, 2004) as summarised in Table 2 and Table 3.

The portal structure was designed to be constructed top-down with a level of temporary steel props at 81.0m APD (Figure 2). The temporary steel props could only be removed after the portal base slab was cast and the associated minimum concrete strength was achieved. This would then be followed by the construction of the sump near the centre of the portal.

The instrumentation and monitoring plan was originally designed to verify the performance of the portal. There was no intention to perform back-analyses using the measured field data to derive material parameters so that beneficial changes could be made to the design and/or construction as excavation progressed. The primary instruments included 7 in-place inclinometers (IPIs) to monitor wall displacements. Empty inclinometer tubes were also installed adjacent to each inclinometer to provide redundancy in the monitoring scheme. To verify inclinometer readings and to increase confidence in the measured wall displacements, mini-prism survey points were installed. The secondary means of monitoring included two magnetic extensometers, three fast response vibrating wire piezometers and one Casagrande standpipe as indicated in Figure 1.

Table 2. Geotechnical parameters for Glaciofluvial Deposits and Mercia Mudstone Grade IV and III

Lithology	**γ kN/m^3**	**c' kN/m^2**	**ϕ_{peak} degree**	**E' MN/m^2**
Glaciofluvial Deposits	20.5	2	26	50
Mercia Mudstone Grade IV	21	3 to 5	27	100
Mercia Mudstone Grade III	21	10	29	150

γ: unit weight; c': effective cohesion; ϕ: effective friction angle (peak); E': effective stiffness at 0.1% strain

Table 3. Geotechnical parameters for Mercia Mudstone Grade II/I

Lithology	**γ kN/m^3**	**σ_{ci} MN/m^2**	**GSI**	**E_m MN/m^2**
Mercia Mudstone Grade II/I	23.5	2	35	200

γ: unit weight; σ_{ci}: intact uniaxial compressive strength; GSI: geological strength index; E_m: rock mass modulus

3. The Observational Method

The Observational Method is essentially an integration of design and construction control, linking design to observed performance during construction. The method provides a "feedback loop" between design and construction through close monitoring of ground and structure behaviour, as well as construction control to enable pre-planned design modifications to be implemented progressively during construction (Liew et al. 2023; Powderham 2002; Powderham and O'Brien 2021).

3.1. Field measurements

Data from field measurements, depending on the interested or responsible party, has been used to verify design intents and assumptions; to control construction procedures to meet design expectations; to safeguard third party assets; and/or to provide legal protections to asset owners. Measurement has also been used to advance the state of the art of geotechnical engineering, enabling geotechnical engineers to improve their understanding of ground behaviour and ground-structure interactions. However, measurement has rarely been used during construction to make beneficial changes in the design. The role of field measurement is more inclined to be "passive" in the construction industry, which is likely due to the conventional procedures in a traditional design model that is predominantly linear with very limited or no intention to vary the design during construction.

In contrast, the Observational Method permits the design to be modified during construction in accordance with the findings from field observations and measurement data. This method can create substantial savings by designing on the basis of more probable or less cautious set of parameters and scenarios instead of a cautious or pessimistic approach due to ground uncertainties. However, to implement the Observational Method effectively, one of the essential requirements as discussed by Powderham and O'Brien (2021) is high quality and reliable field measurement data.

Therefore, a well-designed instrumentation and monitoring plan is essential. As the need of instrumentation varies from project to project, it should never be treated as a routine tick-box exercise. The purpose of the instrumentation should be clearly defined in accordance with the need of a project. Careful attention should also be given to field instrumentation services, including installation, calibration, data acquisition, data validation, data analysis and interpretation and maintenance. As described by Dunnicliff (1988), "Geotechnical instrumentation field work should not be considered a routine item of construction work, because successful measurements require extreme dedication to detail throughout all phases of work."

Despite the well-established procedures and guidelines on field instrumentation, there are still challenges faced by the current instrumentation and monitoring industry. It is often misconstrued that value of field measurement data is directly linked to cost (such as cost associated with monitoring design or plan, procurement, installation, etc.). In fact, the value of field measurement can only be realised when the data is deemed to be accurate by the project team or key stakeholders to address the project needs. It is also often perceived that more data equals better results. However, more data also means more data processing and interpretation, and tends to generate more errors. It could potentially generate a mountain of data that can be "wasted" if they are not properly analysed. Furthermore, the current instrumentation and monitoring proposal is often quoted on its cost (supply and install), rather than value (or the value and knowledge that the responsible party could bring). It is still often viewed as a trade activity, a routine construction work managed by the main contractor. There has also been fragmentation in roles and responsibilities in the monitoring industry, and their interest in monitoring can be progressively changed throughout the project phase. Table 4 provides examples of objectives of monitoring for different parties for an idealised underground construction project (extracted from British Tunnelling Society, 2011).

To fulfil the potential in monitoring, particularly in the context of the Observational Method, the instrumentation and monitoring proposal should be more purpose or outcome driven. In terms of contractual arrangement, a more integrated and collaborative approach will be beneficial instead of traditional transactional arrangements. For example, the Project 13 programme in the UK, which is an enterprise-based approach that brings together owners, partners, advisers and suppliers, where participating organisations are incentivised to deliver better outcomes.

Table 4. The objectives of monitoring for underground construction projects

Responsible or interested party	**Objectives**
Client	Legislative compliance, delivery assurance, risk allocation, quality assurance
Designer	Legislative compliance, delivery assurance, risk allocation, risk management, design verification, construction process control, quality assurance, research
Contractor	Legislative compliance, delivery assurance, risk allocation, risk management, design verification, construction process control, quality assurance, research
Third Parties	Asset protection, reassurance
Researchers	Research
Operator	Legislative compliance, risk allocation, delivery assurance
Insurers	Legislative compliance, risk management, risk allocation, quality assurance
Statutory Authorities	Legislative compliance, risk allocation

3.2. DAARWIN Trial

In May 2022, a trial on the software DAARWIN was carried out at the western end of Bromford Tunnel East Portal, also known as Box 1. The trial was carried out in collaboration between Mott MacDonald and SAALG Geomechanics, supported by HS2 Innovation Team and Balfour Beatty VINCI JV. The primary aim of the trial was to ascertain whether DAARWIN can deliver efficiencies to enhance the implementation of the Observational Method not only for the east portal but also other retained excavations of the N1/N2 contract.

The excavation depth at the western end of the Bromford Tunnel East Portal was about 8m when the trial started. The In-Place Inclinometer, ML164-IPI803 (Figure 1) was selected to provide wall horizontal displacement data for the back-analysis due to its location and consistency in providing reliable results. The decision was made after a thorough review of the available inclinometers at Box 1. To prepare for the back-analysis, the actual construction activities were obtained, reviewed and plotted against inclinometer readings (Figure 4).

The DAARWIN back-analysis was undertaken on two excavation stages: 80.0m APD and 77.0m APD. The DAARWIN model was updated, taking into consideration the observed ground conditions, measured groundwater data, actual construction surcharges and as-built structural member properties.

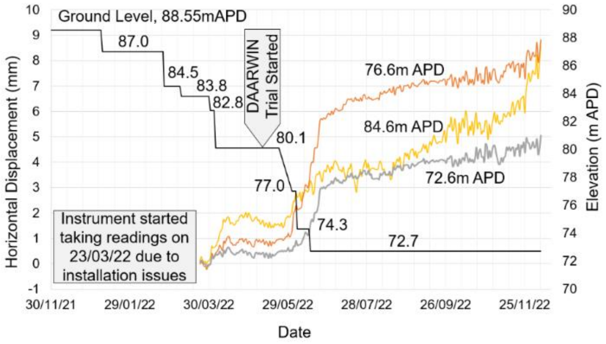


Figure 4. Measured wall displacements against time

3.2.1. Outcome of the DAARWIN trial

Figure 5 compares the wall displacement predictions using back-analysed parameters against inclinometer readings from ML164-IPI803. The maximum wall displacement was less than 10mm as compared with the deflection limit of 40mm, which was primarily driven by the structural crack width criterion of the wall (i.e., serviceability limit state criterion) and, to some extent, by the presence of an Esso pipeline on the south side of the portal. Given the maximum of the wall displacement was only a quarter of the deflection limit, it is more than likely that the temporary steel props at the western end of the portal could be omitted. This finding also revealed opportunities to modify the design of the adjacent structures, i.e. Bromford Tunnel West Portal and Washwood Heath Retained Cut to eliminate the need of temporary support through the application of the Observational Method.

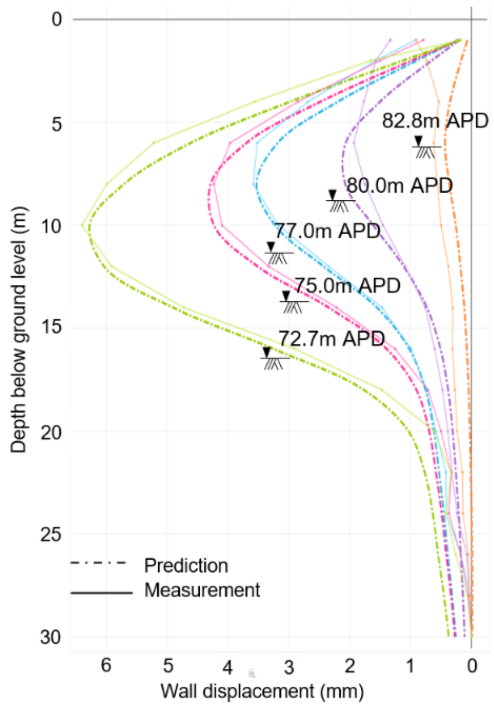
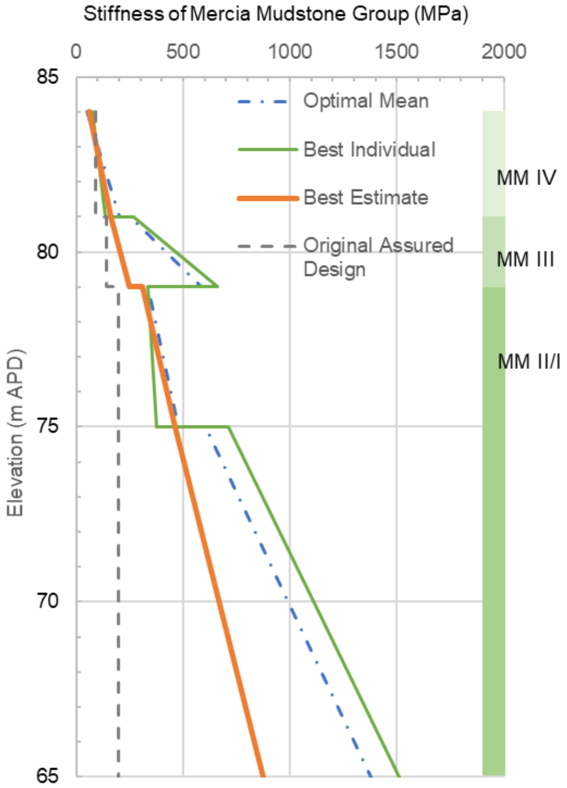


Figure 5. Field measurement (IPI803) versus predictions

The back-analysis from DAARWIN indicated that the stiffness of the Mercia Mudstone Group is the most influential set of geotechnical parameters in influencing the wall displacement. Figure 6 shows the comparison of back-analysed stiffness profiles for the Mercia Mudstone with the stiffness profile adopted in the original design. The back-analysed secant Young's modulus profiles values are significantly higher than the original values, particularly in the Mercia Mudstone Grade II/I.



"Optimal Mean": Average of back-analysed parameters; "Best Individual": Best combination set of parameters that give predictions with the least discrepancy to target measurements; "Best Estimate" – Parameters derived from engineering judgement for the use of the Observational Method. 'Stiffness' is drained secant Young's modulus.

Figure 6. Back-analysed stiffness for Mercia Mudstone

Figure 7. Left: Typical Mercia Mudstone Grade II/I borehole core example; right: Exposed geology during bulk excavation

This finding was supported by the observation of the exposed geology during bulk excavation, which indicated that the exposed mudstone is less weathered and fractured than indicated by borehole logs (Figure 7). The strength of the Mercia Mudstone Group at in-situ conditions appears to be significantly higher than the strength values that were derived from the ground investigation. This is because logging this type of material from boreholes can be challenging as the samples (even with high quality drilling) are prone to drilling-induced disturbance.

4. Application of the Observational Method

Following the success of the DAARWIN trial, the Observational Method was applied at the eastern end of Bromford Tunnel East Portal, known as Extension Box (Figure 8). The primary aim was to omit the three remaining temporary steel props at 81m APD, which were yet to be installed to accelerate the construction programme.

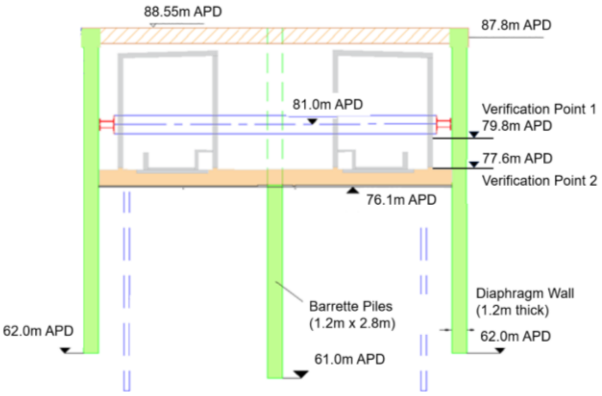


Figure 8. Typical section at extension box.

4.1. Instrumentation and Monitoring

The instrumentation and monitoring plan was comprised of primary and secondary instruments. The primary aim of the primary instruments was to control the construction procedures whilst the secondary instruments was to provide an additional insight of the ground-structure behaviour as well as to provide cross-checking of the primary instruments.

The primary instruments were in-place inclinometers embedded in the diaphragm wall with automatic readings at one-hour frequencies. As shown in Figure 1, the nearest two in-place inclinometers were located at the western end of the extension box and may be unduly influenced by 'end-effects' of the central section of the portal. Therefore, optical displacement sensors were installed on the inner surface of the exposed diaphragm walls to monitor the convergence of the walls.

The secondary means of monitoring were comprised of mini-prisms, heave monitoring on blinding slab at formation level using precise levelling, piezometers from the central section of the portal and vibrating wire strain gauges installed on the temporary steel props from the adjacent area of the portal.

4.2. Verification Points

To manage the observational procedures and fulfil project assurance requirements, two Verification Points

(VPs) were introduced (Liew et al. 2016). VP1 started when excavation level was at 79.8m APD. The targets of VP1 were to omit the temporary steel props at 81m APD and structural concrete blinding at VP2. The following activities were undertaken when VP1 was reached:

- Detailed review of instrumentation and monitoring data.
- Calibrated numerical model against selected and processed measured wall displacement data.
- Updated predictions for subsequent excavation stages.
- Assessed the potential for omission of structural concrete blinding strut at VP2.

VP2 started when excavation level was at 77.6m APD. The target of VP2 was to omit structural concrete blinding strut at formation level. The activities undertaken when VP2 was reached were similar to VP1 except that the assessment of the omission of structural concrete blinding strut was at formation level. Figure 9 shows the decision-making process for the assessment of the temporary works element.

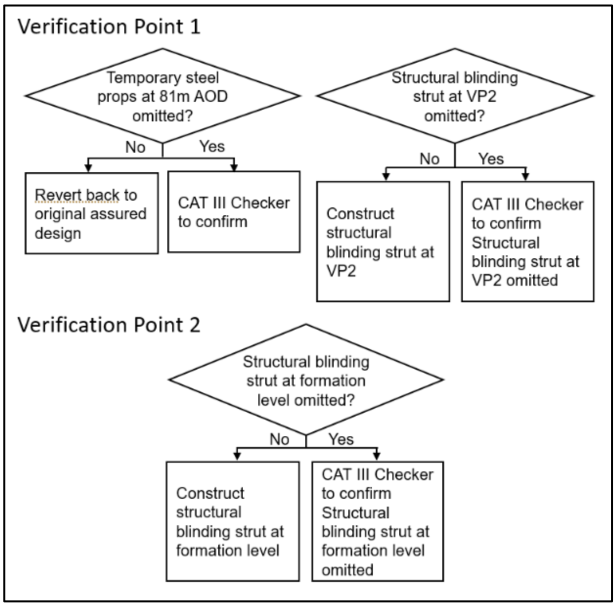


Figure 9. Assessment of temporary works element

4.3. Trigger level system

A trigger level is a pre-agreed and defined value of a measured parameter for an instrument. If a trigger level is breached, pre-agreed and defined actions will be triggered. A simple "traffic light" system was adopted, with the use of Green, Amber and Red trigger levels (Figure 10).

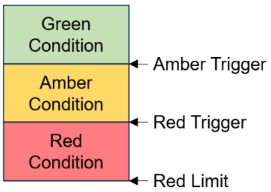


Figure 10. Trigger levels based on a "traffic light" system

Table 5. Trigger levels for wall horizontal displacement at Bromford Tunnel East Portal extension box

	VP1	**VP2**	**Formation level**
Amber trigger	7mm	10mm	12mm
Red trigger	12mm	15mm	18mm
Red limit	25mm	25mm	25mm

Table 5 summarises the trigger levels for wall displacement at different excavation stages for Bromford Tunnel East Portal extension box. Table 6 summarises the pre-agreed actions at Verification Points should a trigger level be breached.

Table 6. Pre-agreed actions at Verification Points

	VP1	**VP2**
Green condition	Recommend temporary support be omitted	Recommend excavation proceed without structural blinding
Amber condition	Recommend temporary support be omitted provided rate of wall displacement is acceptable; no adverse trends in secondary monitoring system; monitoring frequency to be increased.	Recommend excavation proceed without structural blinding provided rate of wall displacement is acceptable; no adverse trends in secondary monitoring system; monitoring frequency to be increased.
Red condition	Recommend temporary support be installed unless all parties agree Red Limit is unlikely to be breached.	Recommend structural blinding be installed unless all parties agree Red Limit is unlikely to be breached.

4.4. Predicted and observed wall displacement

Figure 11 compares measured wall phase displacements from inclinometers and optical displacement sensors against predictions. The locations of the inclinometer and optical displacement sensors are shown in Figure 1. The predictions were carried out using DAARWIN, employing a plane-strain numerical model based on the back-analysed stiffness profile (Best Estimate) from Figure 6. The predictions closely match the readings from the optical displacement sensors but are slightly higher than inclinometer data. The slight discrepancy between inclinometer data and predictions was most probably due to three-dimensional effects, especially the influence from the temporary steel props in the adjacent area.

Figure 12 shows the progression of wall displacements for three sensors, i.e., ML164-IPI807 sensors at 83.98m APD, 79.98m APD and 75.98 m APD against time, alongside excavation level. The corresponding sensors were selected as they were the elevations where the maximum displacements occurred.

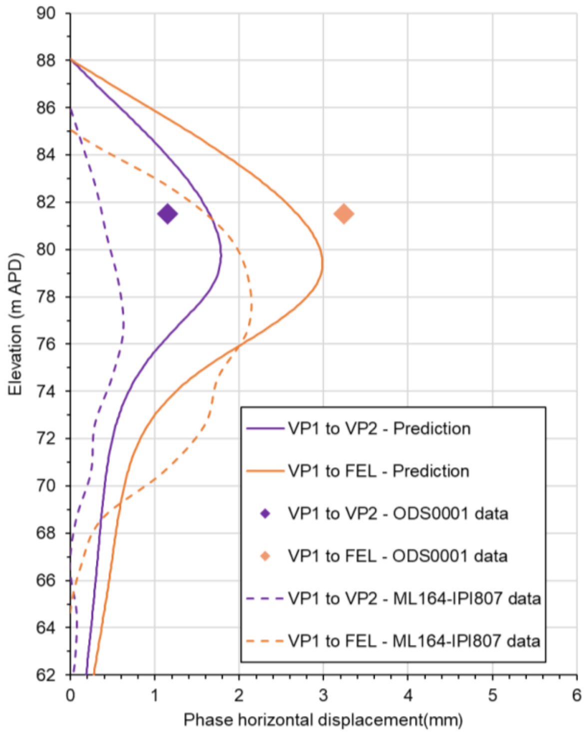


Figure 11. Prediction vs measurement

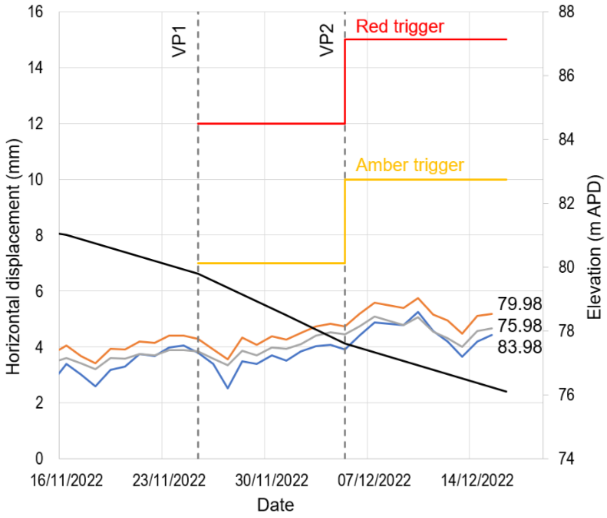


Figure 12. Progression of wall displacement with time

Figure 13. East portal extension box in March 2023

The maximum wall displacement at VP1 was less than 5mm as compared to the Amber trigger of 7mm. Therefore, the remaining temporary steel props in the portal were successfully omitted. As the excavation progressed through VP1 to VP2, there was increased confidence that the Amber triggers for the subsequent stages were unlikely to be breached. This enabled the construction of a trench up to 2.5m deep below the base slab to be carried out for the installation of a carrier pipe before casting of the portal base slab to further accelerate the construction programme.

4.5. Summary and lessons learned

Figure 13 shows the progress of the site in March 2023. The modifications in the design and construction procedures enabled at least two weeks' saving in the construction programme. This allowed the construction team to have more time to prepare for the launch of the first TBM. In addition, by omitting the temporary steel props, a larger working space was created, and handling of heavy temporary steel props was avoided. This has enhanced the health and safety practices on site. Besides, throughout the implementation of the Observational Method, focus was given to the importance of teamwork, good communication, clear procedures, construction control and pre-planned contingency measures. This had also further enhanced the safety practices and the overall productivity of the project.

The findings from the east portal revealed that wall convergence monitoring using automatic optical system could replace inclinometers as the primary system once the excavation reaches the level where the wall convergence monitoring sensors are installed. The wall convergence monitoring, if correctly implemented, can provide a direct measurement of wall behaviour, requiring minimum interpretation and enabling rapid decision making.

In addition, the findings provided a better understanding of the characteristics of Mercia Mudstone particularly the stiffness of the materials, revealing opportunities to apply the Observational Method on the adjacent HS2 assets or other projects in the region with similar geological conditions. The Observation Method has since been implemented at Bromford Tunnel West Portal and Washwood Heath Retained Cut. The construction of the two assets is still ongoing at the time of writing this paper. The length of the retained excavations, with a level of temporary steel props, is about 1km. The potential savings in cost, time and carbon emissions are significant if all the temporary steel props for the two assets can be omitted.

5. Conclusions

The Observational Method, when used effectively, can deliver major savings in cost, time and carbon emissions whilst enhancing safety. To apply the Observational Method effectively, high quality field measurements is essential. Despite the many benefits the Observational Method can offer, it is still significantly underused. The primary reasons are usually due to inappropriate contracts and an industry culture which inhibits effective collaboration (O'Brien et al. 2022). In addition, there are often misconceptions about the Observational Method that it might increase programme uncertainties or risks in projects (Liew et al. 2023). There are similarities to the challenges faced by the current instrumentation and monitoring industry. Despite many publications on good practices in field instrumentations, such as Dunnicliff (1988), and technological advancements in geotechnical instrumentations, producing high quality field measurement data can still be challenging. The industry-wide change programme, such as the Project 13 in the UK that promotes collaborative working can help to create a non-adversarial working environment to support the use of the Observational Method, delivering more value to asset owners and other project stakeholders to achieve better outcomes.

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6. References

Arnold, C., Farooq, I., Drake, A., Brook, C. “Managing uncertainty in ground conditions in design on a megaproject where ground investigation is highly variable”, HS2 Learning Legacy, 2020. https://learninglegacy.hs2.org.uk/document/managing-uncertainty-in-ground-conditions/

British Standard Institution, “BS EN 1997-1:2004 + A1:2013 Eurocode 7: Geotechnical Design - Part 1: General Rules”, CEN, Brussels, Belgium, 2004.

British Tunnelling Society “Monitoring underground construction: A best practice guide”, ICE Publishing, 2011.

De Santos, C. “Backanalysis Methodology Based on Multiple Optimization Techniques for Geotechnical Problems”, Ph.D. thesis, Universitat Politècnica de Catalunya – BarcelonaTECH, 2015.

Dunnicliff, J. “Geotechnical instrumentation for monitoring field performance”, A Wiley-Interscience publication, 1988.

Liew, H. L., O’Brien, A. S., Gelonch, L., De Santos, C. “Enhancing the Observational Method through digital innovation”, HS2 Learning Legacy, 2023. https://learninglegacy.hs2.org.uk/document/enhancing-the-observational-method-through-digital-innovation/

Liew, H. L., Farooq, I., Place, D., Steele, B. and Vitorino, S. “An innovative verification process speeds construction of Crossrail’s Moorgate shaft”, Crossrail Project Infrastructure design and construction, Volume 3, 461-474, 2016.

O’Brien, A. S., Chen, Y., Liew, H. L. “Creating value through Observational Control” 11th International Symposium, Field Monitoring in Geomechanics, 2022.

Powderham, A. J., O’Brien, A. S. “The Observational Method in Civil Engineering, minimising risk, maximising economy”, CRC Press, 2021.

Powderham, A. J. “The observational method – learning from projects”, Proceedings of the Institution of Civil Engineers, Geotechnical Engineering, 155 (1), 59–69, 2002.