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Application of the Observational Method on High Speed Two retaining structures

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ABSTRACT: Mott MacDonald SYSTRA Design Joint Venture is working on behalf of High-Speed Two's (HS2's) main works contractor for the West Midlands, Balfour Beatty VINCI (BBV), who are responsible for constructing 90 km of the HS2 project. As part of an Integrated Project Team (IPT), Mott MacDonald identified opportunities to apply the Observational Method (OM) to progressively modify the design and construction of two of HS2's underground portal structures: Bromford Tunnel East Portal (BTEP) and Bromford Tunnel West Portal (BTWP), including the adjacent Washwood Heath Retained Cut (WHRC). These structures are built through Mercia Mudstone, which fluctuates between a very stiff clay and very weak rock. These ground conditions, known as Intermediate Geomaterials (IGM) in North American practice, are notoriously difficult to characterise through conventional ground investigations, typically the strength and stiffness being underestimated. As the construction of the BTEP progressed, it became evident that the wall's performance was better than calculated on the basis of strength/stiffness parameters from the available ground investigation data. This observation was further supported by the observed ground conditions that appeared less weathered and significantly less fractured than indicated by borehole logs. After the agreement to use OM was granted, OM was applied to omit the remaining three temporary steel props at BTEP. Despite there being only three props, the construction programme was shortened by at least two weeks. The OM was subsequently applied to BTWP and WHRC using the knowledge gained from BTEP, aiming to omit over hundreds of temporary steel props as specified in the original design to gain efficiency in construction. This paper details the case studies and results of using OM on the three structures, showing improvements in cost, time, carbon emissions, and safety.

KEYWORDS: The Observational Method, case histories, machine learning, high-speed railway line

1 INTRODUCTION

High Speed Two (HS2) represents one of the most ambitious infrastructure projects in the United Kingdom, delivering high-speed rail connectivity across the country. The Mott MacDonald SYSTRA Design Joint Venture, as part of an Integrated Project Team with Balfour Beatty VINCI and HS2 Ltd, is responsible for designing and delivering 90km of complex civil engineering works through the West Midlands.

Bromford Tunnel is a 5.6 km twin-bore high-speed rail tunnel connecting Water Orton in North Warwickshire with Washwood Heath in Birmingham. The tunnels, once completed, will be the longest railway tunnels in the West Midlands. The tunnels reach a depth of 40m and have an internal diameter of 9 to 10m. The construction of this tunnel involves the use of two tunnel boring machines (TBMs) named Mary Ann and Elizabeth. The Bromford Tunnel East Portal (BTEP), located near Water Orton, serves as the launch site for the TBMs, whilst the Bromford Tunnel West Portal (BTWP) at Washwood Heath functions as the reception point. TBM Mary Ann successfully broke through at the West Portal in May 2025, and TBM Elizabeth is currently advancing through the second bore. The timely completion of the portal structure was essential to prevent delays in the HS2 tunnelling programme.

Diaphragm wall installation and excavation for the BTEP began in 2021. Field measurements indicated that the wall's performance was better than calculated. This finding was further supported by results from a trial on DAARWIN (De Santos, 2015), an advanced ground engineering software that uses machine learning-based algorithms to enable near real-time back analysis (RTBA) at the western end of BTEP. Liew et al. (2023) discussed the trial and concluded that the back-analysed ground parameters were significantly higher than those initially adopted. The trial also identified opportunities to use the Observational Method (OM) to optimise the existing design and construction at BTEP and adjacent structures, including BTWP and the adjacent retained cut, known as Washwood Heath Retained Cut (WHRC) with similar geological conditions. Approval to use OM was obtained from BBV and HS2, along with an optimised workflow to expedite the OM assurance process. This paper details the case histories and results of applying OM to the BTEP, BTWP, and WHRC.

2 PROJECT DESCRIPTION

2.1 *The portal structures and retained cut*

The BTEP is an underground box, 80m long, 33m wide, and up to 16m deep (Figure 1 and Figure 2). The BTWP is slightly smaller, 60m long, 33m wide, and up to 22m deep (Figure 1 and Figure 3). Importantly there is a sump structure, up to 7m deep, located near the centre of each portal, which substantially increases the effective depth of each retained structure. The WHRC is a 1.3km open-cut structure connecting to the BTWP at its eastern end and transitioning to ground-level embankments near Washwood Heath Depot in the west. The base slab features "haunches" at wall junctions to accommodate drainage channels (Figure 1 and Figure 4).

Figure 1. Site plan and instrument locations at BTEP (above) and BTWP and WHRC Section A (below).

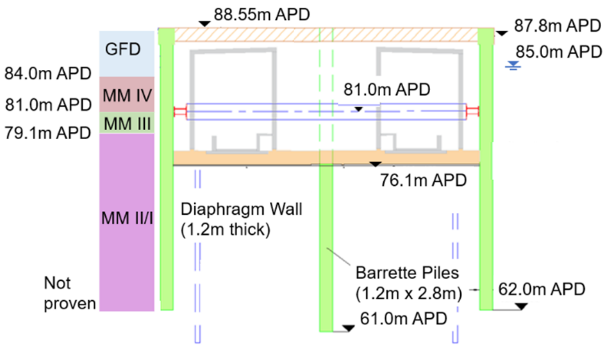

Figure 2. Typical section at BTEP (Eastern End).

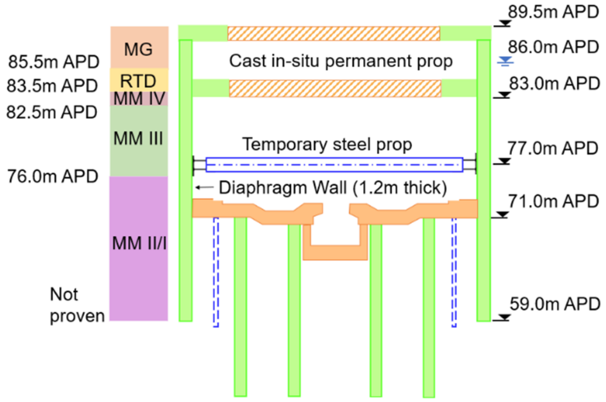

Figure 3. Typical section at BTWP.

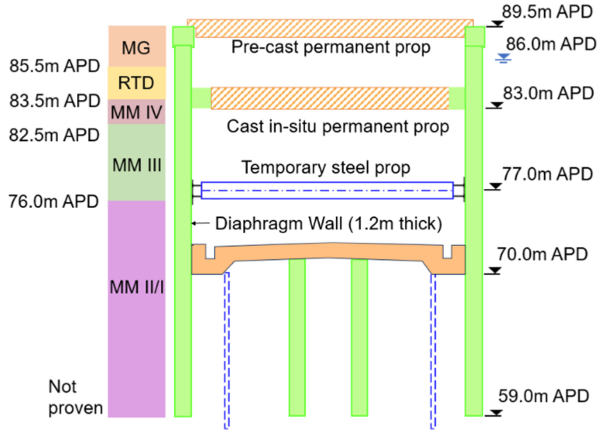

Figure 4. Typical section at WHRC (Section A).

2.2 *Ground conditions and parameters*

The solid geology consists of the Mercia Mudstone Group (MMG). Table 1 summarises typical descriptions of the MMG based on borehole data. Though the description of Mercia Mudstone Grade III is “soil-like”, the material exhibits strength characteristics that are fluctuating between very stiff clay and very weak rock. The MMG, in general, is intrinsically difficult to characterise due to its vulnerability to sampling disturbance, which means laboratory derived strength/stiffness data is rarely representative of in-situ mass behaviour. In-situ testing is also challenging due to varying bands of hard layers interbedded with softer materials, together with groundwater seepages leading to local softening. The overlying superficial deposits at the BTEP are Glaciofluvial Deposits, whilst Made Ground, Alluvium and River Terrace Deposits overlie the MMG at the BTWP and WHRC.

Liew et al. (2023) discussed the discrepancy in the degree of weathering and fracturing of the exposed mudstone at the BTEP. The exposed mudstone was found to be less weathered and significantly less fractured than indicated by borehole logs.

The in-situ mass strength and stiffness of the MMG appear to be significantly higher than the values derived from the ground investigation, predominantly due to drilling-induced disturbances. Table 2 compares the MMG stiffness values, which are the most influential parameters affecting wall displacement, from the original design with the back-analysed values at BTEP. At depth within the MMG the back-analysed stiffness was typically more than double (for Grade III) and more than three times (for Grade II/I) the original design values and exhibited a rapid increase of stiffness with depth. The back-analysed stiffness parameters from the BTEP were then used for the re-assessment of the BTWP and WHRC.

Groundwater level is approximately 85m APD at the BTEP, whilst 86m APD at the BTWP and WHRC (Figure 2, Figure 3, Figure 4). The groundwater pressure is increasing hydrostatically with depth.

Table 1. Description of the Mercia Mudstone Group.

Geology	Typical description
Mercia Mudstone Grade IV	Firm to very stiff slightly sandy reddish brown, mottled greenish, grey CLAY. Sand is fine to coarse. Occasional presence of mudstone lithorelicts up to 25mm.
Mercia Mudstone Grade III	Stiff to very stiff gravelly CLAY. Frequent presence of lithorelicts greater 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	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.

Table 2. Stiffness values of the Mercia Mudstone Group at BTEP.

Lithology	Stiffness (MN/m^2)	
	Original design	Back-analysed
Mercia Mudstone Grade IV	100	$65+40z^1$
Mercia Mudstone Grade III	150	$185+40z^2$
Mercia Mudstone Grade II/I	200	$300 + 40z^3$

z^1, z^2 and z^3 are depths from 84m, 81m and 79m APD, respectively

Table 3. Washwood Heath Retained Cut – support system.

Section	Length (m)	Max. Depth* (m)	Support system
A	145	19	Two-level permanent props: pre-cast and in-situ beams; one-level temporary props
B	185	16.5	One-level permanent props; one-level temporary props
C	290	13	One-level permanent props
D	125	10.5	One-level temporary props
E	200	7.5	One-level temporary props

*Depth includes haunches

2.3 *Design of the structures*

The portal structures, formed by 1.2m thick diaphragm walls, were originally designed to be supported by one or two levels of permanent concrete props and a level of temporary steel props (Figure 2 and Figure 3). The sump structure for the BTEP and the BTWP was retained by a 1.2m thick diaphragm wall and a 1.2m diameter contiguous bored pile wall, respectively. The design of WHRC was divided into Sections A to E due to their differing depths (Table 3). Sections A to D are formed by 1.2m thick diaphragm walls, whilst Section E is formed by 1.2m diameter secant pile walls (Figure 4). The original design required a level of temporary steel props for most of the sections, as summarised in Table 3.

2.4 *Construction sequence*

The portal and retained cut structures were designed for top-down construction. Before excavation, abstraction wells were installed to lower the groundwater level inside the structures. In the original design, the temporary steel props could only be removed after the portal base slab was cast and the concrete reached the required minimum strength. For the portal structures, this would be followed by the construction of the sump. For the retained cut, this would be followed by the construction of the Washwood Heath Depot retaining wall.

2.5 *Field instrumentation*

The instrumentation and monitoring plan comprised primary and secondary instruments (Figure 1). The purpose of the primary instruments was to control the construction procedures, whilst the secondary instruments provided additional insight into the ground-structure behaviour and allowed for cross-checking of the primary instruments.

The primary instruments were in-place inclinometers (IPIs) and Shape Accel Arrays (SAAs) embedded in the diaphragm wall, with automatic readings taken every hour. Empty inclinometer tubes were also installed adjacent to each inclinometer to provide redundancy in the monitoring scheme. Optical displacement sensors (ODSs) were installed on the inner surface of the exposed walls to monitor wall convergence. The ODSs, which require minimum interpretation and enable rapid decision-making, could replace inclinometers as the primary system once the excavation reaches the level where the ODSs are installed (Liew et al. 2024).

The secondary means of monitoring included fast-response vibrating wire piezometers, observation wells, magnetic extensometers, and vibrating wire strain gauges in areas with temporary steel props.

3 THE OBSERVATIONAL METHOD

The OM integrates design and construction control by linking design to observed performance during construction. This method creates a “feedback loop” between design and construction through close monitoring of ground and structure behaviour, enabling pre-planned design modifications to be implemented progressively during construction (Liew et al. 2024, Liew et al. 2023; Powderham 2002; O’Brien et al. 2022; Powderham and O’Brien 2021).

3.1 *Application of the Observational Method*

Following the success of the DAARWIN trial (Liew et al. 2023) and the subsequent approval from BBV and HS2, the OM was applied at the eastern end of the BTEP, BTWP and WHRC. The primary aim was to eliminate the temporary steel props to speed up the construction programme. Additionally, the aim was to remove the “sequence constraint” by completing excavation before installing precast concrete props at WHRC Section A. The construction of WHRC is still ongoing at the time of writing this paper. Only Sections A and B are completed. Therefore, this paper will only discuss these two sections.

3.2 *Verification Points*

To manage the observational procedures and fulfil project assurance requirements, Verification Points (VPs) were introduced (Liew et al. 2016). The following activities were undertaken when a VP was reached: A detailed review of instrumentation and monitoring data was conducted. The numerical model was calibrated against selected and processed measured wall displacement data. Calculations of wall displacements for subsequent excavation stages were updated. The potential for making beneficial changes to the design and construction was assessed, as well as the potential to implement pre-planned contingency measures. A meeting with HS2, BBV and the independent checker to be held to agree the next steps.

3.3 *Trigger level system*

A trigger level is a defined value of a measured parameter for an instrument, and if breached then pre-agreed actions will be implemented. A simple “traffic light” system was adopted, using Green, Amber and Red trigger levels (Figure 5). Table 4 outlines the pre-agreed actions at each VP if trigger levels are breached, whilst Table 5 specifies the trigger levels for BTWP and WHRC Sections A and B.

Figure 5. Trigger levels based on a “traffic light” system.

Many factors need to be considered when selecting a particular trigger level (Powderham and O’Brien, 2021), including the instrument’s measurement accuracy and the time required to implement the pre-agreed actions or contingency measures.

Table 4. Pre-agreed actions at a Verification Point.

Trigger Level	Actions
Green condition	Recommend omitting temporary steel props or proceeding with excavation without implementing contingency measures.
Amber condition	Recommend omitting temporary steel props or proceeding with excavation without implementing contingency measures, provided the rate of wall displacement is acceptable and there are no adverse trends in the secondary monitoring system. Increase monitoring frequency.
Red condition	Recommend installing temporary steel props or implementing contingency measures unless all parties agree that the Red Limit is unlikely to be breached.

Table 5. Trigger levels for wall displacement.

Structure		VP1	VP2	VP3	VP4	VP5
BTEP	AT	7	10	-	-	-
	RT	12	15			
	LV	79.8	77.6			
BTWP	AT	5	7	10	13	15
	RT	12	14	17	20	23
	LV	*82.5*	78.5	75.0	71.5	*69.0*
WHRC A	AT	10	15	16	18	20
	RT	20	22	23	27	28
	LV	84.8	80.0	76.3	74.3	*70.0*
WHRC B	AT	9	11	13	15	18
	RT	18	20	22	24	25
	LV	*86.0*	*83.0*	*79.0*	76.3	*73.0*

AT: Amber Trigger, mm; RT: Red Trigger, mm; LV: level, m APD; value shown in italics represents the average value.

3.4 *Contingency measures*

The pre-agreed contingency measures included a 300mm thick structural concrete blinding strut made of C35/45 concrete mix. These measures would be implemented within 24 hours of reaching the excavation level. The concrete would cover the entire plan area, be flat and level, and have a clean contact with the wall. This was challenging at WHRC due to the presence of the “haunch” structure (Figure 4). Regardless of whether contingency measures were needed, the excavation and nominal blinding were designed to be carried out in two stages before the base slab could be cast. This ensured that the contingency measures could be implemented promptly and effectively.

4 FIELD OBSERVATIONS

4.1 *Observed ground conditions*

The observations on site at BTWP and WHRC, as per the observations at BTEP (Liew et al. 2023 and Liew et al. 2024), indicated that the in-situ MMG rock mass characteristics were significantly better than indicated by available borehole logs. The observed MMG was generally less weathered and significantly less fractured, with higher mass strength than values derived from ground investigations and used in the original assured design. The level of MMG grades was observed to be shallower in the sequence than the design ground model, especially the top of Grade II, due to difficulties in obtaining representative samples of weak mudstone during GI. MMG Grade IV and III thicknesses were thinner than anticipated in design, with beds of less weathered siltstone or sandstone observed within MMG Grade III and IV, and beds of siltstone and sandstone up to 300mm thickness within MMG Grade II. Figure 6 shows the observed MMG Grade III (reddish brown) and Grade II (bluish grey) at WHRC.

Figure 6. The exposed Mercia Mudstone Group at WHRC.

4.2 *Observed wall deflections*

4.2.1 *Observed wall deflections at BTEP*

Figure 7 (left) compares measured wall phase displacements from IPI (ML164-IPI807) and ODS (ODS0001) against RTBA calculated values. The locations of these instruments are shown in Figure 1. The calculations were undertaken using DAARWIN with a plane-strain numerical model based on the back-analysed stiffness summarised in Table 2. The RTBA calculated values closely match the ODS readings but are slightly higher than IPI data. This discrepancy is likely due to three-dimensional effects, particularly the influence of propping in the adjacent area. The DAARWIN back-analysis was discussed by Liew et al. (2024).

Figure 7 (right) shows the progression of wall displacements for three sensors (ML164-IPI807) at 83.98m APD, 79.98m APD, and 75.98 m APD against time and excavation level. These sensors were chosen because they recorded the maximum displacements. The maximum wall displacement at VP1 was less than 5mm, below the Amber trigger of 7mm. This allowed the omission of the remaining temporary steel props in the portal. As excavation progressed from VP1 to VP2, confidence grew that subsequent Amber triggers would not be breached. This enabled the construction of a trench up to 2.5m deep below the base slab for the installation of a carrier pipe before casting the portal base slab, further accelerating the construction program.

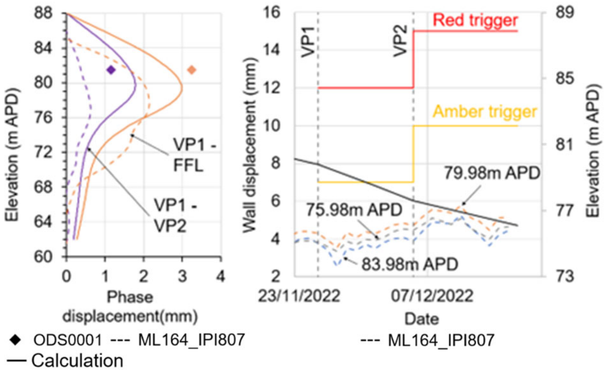

Figure 7. Measurement vs calculation (left) and progression of wall displacement over time (right) at BTEP Eastern End.

4.2.2 *Observed wall deflections at BTWP*

Figure 8 shows the measured and RTBA calculated horizontal wall displacements across VPs for both total and phase displacements at BTWP. The IPI, ML169_IPI602, was selected for the back-analysis due to its good repeatability and consistency, further supported by its strong correlation with the corresponding ODS0004 data. The RTBA calculated horizontal wall displacements were derived from the back-analysis conducted using DAARWIN, starting with the back-analysed parameters from the BTEP. At each VP, DAARWIN recalibrated the numerical model using live data from the selected IPI, enabling forward calculations of wall displacements, which were then checked against the pre-defined trigger levels. This feedback loop allows Mott MacDonald to assess excavation performance, validate model calculations, and determine whether temporary support was required at each VP. The back-analysed stiffness values of the MMG were within 15 percent of those at BTEP.

Figure 8 also shows that the wall displacements were less than the pre-defined Amber trigger levels at each VP, as summarised in Table 5. The maximum measured wall displacement was about 10mm at VP5, compared to 15mm and 23mm for the Amber and Red trigger levels, respectively. Given the good match between the measured and RTBA calculated values, the reliability of the instruments, and the significant margin between the measured and trigger values, Mott MacDonald proposed proceeding with the construction without any temporary support at each VP. This decision was made during the weekly CTC (Contract Technical Committee) meetings attended by BBV, HS2 and the independent checker. The agreement to proceed with the excavation was sought and signed by the relevant parties to as part of the assurance process. Figure 11 shows the completed BTWP with TBM Mary Ann's arrival. Table 6 outlines the BTWP construction sequence.

4.2.3 *Observed wall deflections at WHRC*

Figure 9 compares measured and RTBA calculated horizontal wall displacements across VPs, showing both total and phase movements at WHRC. Figure 10 presents a Gantt-style timeline of wall displacement progression during key construction stages alongside trigger levels and groundwater movements inside and outside the excavation.

The IPI, ML1244_IPI802, was selected for the DAARWIN back-analysis for the same reasons mentioned earlier. The reliability of the selected IPI was also supported by its strong correlation with the adjacent ODSs (ODS0013 and OCS0015). The back-analysis followed the same process as the BTWP, starting with the back-analysed parameters from the BTWP. Wride et al. (2026) discussed the DAARWIN back-analysis in detail. The RTBA calculated horizontal displacement profiles matched very well with the measurements, as shown in Figure 9.

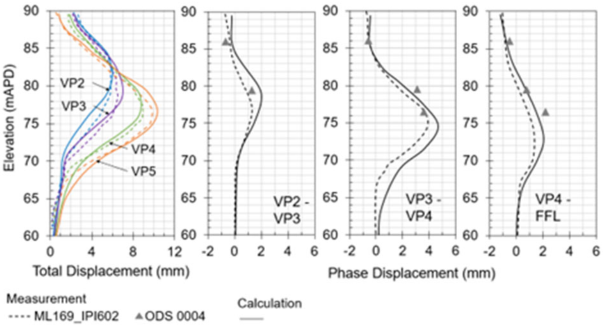

Figure 8. Measurement vs RTBA calculation – total and phase displacement at BTWP.

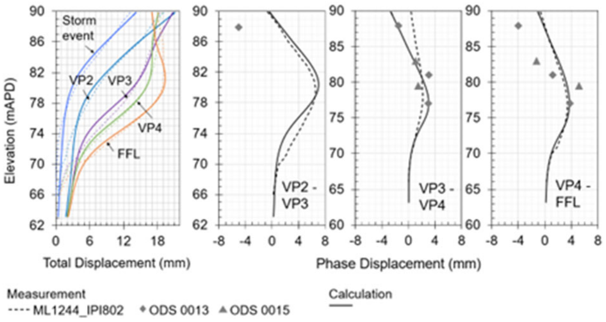

Figure 9. Measurement vs RTBA calculation – total and phase displacement at WHRC Section B.

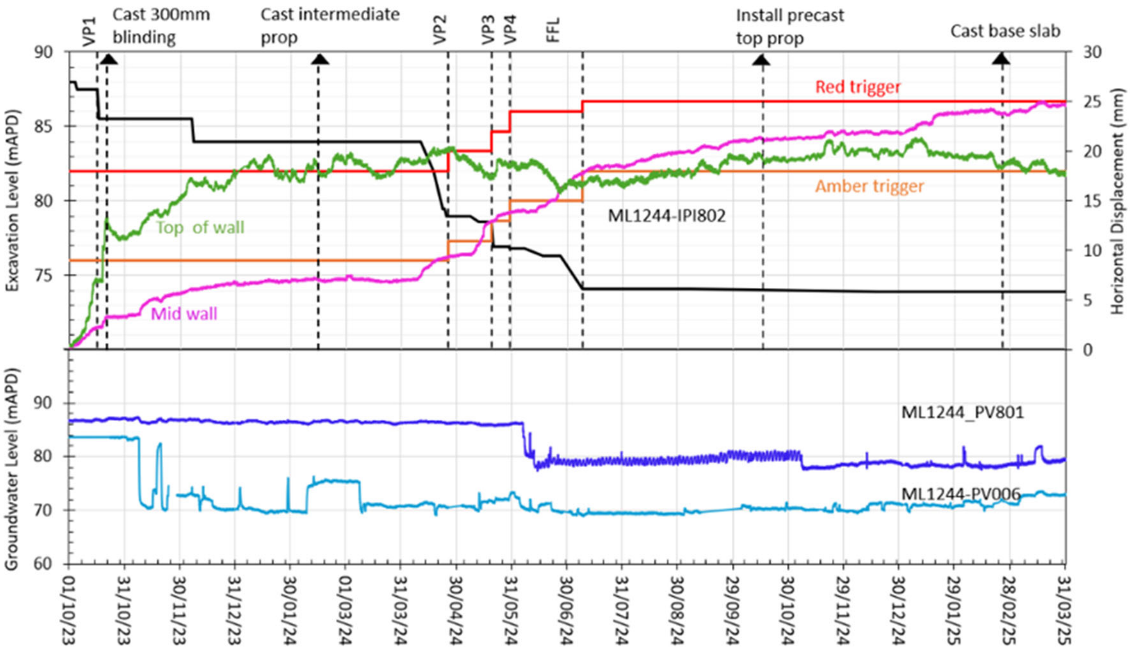

Figure 10. Progression of wall displacement and groundwater level over time at WHRC.

Table 6. Summary of construction sequence at BTWP and WHRC Sections A and B.

Construction Activity	Bromford Tunnel West Portal			Washwood Heath Retained Cut – Section A			Washwood Heath Retained Cut – Section B		
	Start Date	End Date	Duration (Days)	Start Date	End Date	Duration (Days)	Start Date	End Date	Duration (Days)
Excavation to VP1	07/07/2023	31/08/2023	55	26/06/2023	13/10/2023	109	04/10/2023	11/07/2024	281
Cast intermediate prop	22/09/2023	01/12/2023	70	08/12/2023	07/02/2024	61	22/03/2024	13/05/2024	52
Excavation to VP2	23/11/2023	24/01/2024	62	19/01/2024	23/04/2024	95	23/04/2024	30/08/2024	129
Excavation to VP3	12/01/2024	26/02/2024	45	01/03/2024	23/05/2024	83	13/05/2024	06/09/2024	116
Excavation to VP4	07/02/2024	06/03/2024	28	11/03/2024	09/07/2024	120	20/06/2024	05/09/2024	77
Excavation to FFL	14/03/2024	09/04/2024	26	23/04/2024	27/06/2024	65	11/07/2024	14/10/2024	95
Install precast top prop	—	—	—	03/10/2024	09/10/2024	6	—	—	—
Cast base slab	30/05/2024	24/07/2024	55	08/10/2024	07/05/2025	211	11/11/2024	16/05/2025	186

Figure 11. TBM arrival at BTWP, May 2025.

Figure 10 shows a temporary acceleration in wall displacement in October 2023, resulting in the maximum measured wall displacement exceeding the Amber trigger levels. This acceleration was due to heavy rainfall from Storm Babet, which caused groundwater to accumulate behind the south wall. As a contingency measure, a 300mm structural concrete blinding was deployed at this location (10m wide) after a risk reduction meeting was held between BBV, Mott MacDonald and the independent checker, slowing the wall movement and enabling safe work continuation.

As excavation progressed, the wall displacement approached the Red trigger level. This was likely due to the delay in constructing the intermediate props (Table 6), which only started in early 2024, causing the exposed ground to soften. Nevertheless, the wall displacement began to stabilise after the intermediate props were cast, and subsequent groundwater control measures outside the excavation lowered the groundwater level behind the wall, as indicated by ML1244_PV801 in Figure 10. The subsequent excavation activities from VP2 to FFL took about two months, and the maximum wall displacement remained well below the Red trigger level. However, the maximum wall displacement gradually increased and approached the Red trigger level since the base slab could only be cast in early 2025. The wall displacement stabilised after the base slab was cast and achieved the design strength.

Figure 12. A view from BTWP towards WHRC, August 2023.

Despite the challenges described above, the close collaboration among all parties enabled the ultimate goals of the OM to be achieved: no additional temporary support was required over 300m of WHRC after the localised 300mm structural blinding, and the time constraint for the installation of top precast props was successfully removed. Installing the precast props at a later stage brought many benefits, including improved construction flexibility, enhanced site access by eliminating headroom constraints (making it easier for machinery and personnel to move within the retained cut and BTWP), increased operational efficiency with fewer physical obstructions, and health and safety improvements (Figure 12).

5 CONCLUSIONS

This paper presents the successful application of the OM to three major HS2 retaining structures. At the BTEP site, targeted modifications to the design and construction procedures enabled a reduction of at least two weeks in the construction programme, despite the omission of only three temporary steel props. This time saving allowed the construction team to better prepare for the launch of the first TBM. More significantly, the omission of over 60 temporary steel props across the BTWP and WHRC Sections A and B resulted in substantial benefits. These included significant savings in the construction programme, a reduction in carbon emissions of approximately 3,000 to 4,000 tonnes CO_2e and enhanced safety achieved by eliminating restrictive temporary works and fostering a unified team approach focused on clear procedures and construction control. These outcomes demonstrate the value of the OM, when used effectively, in delivering both technical and environmental efficiencies whilst enhancing safety.

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