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Near Real-Time Back Analysis to support the application of the Observational Method on High Speed Two retaining structures

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ABSTRACT: The Mott MacDonald / SYSTRA Design Joint Venture is working as part of an Integrated Project Team alongside Balfour Beatty VINCI and High Speed Two (HS2) Ltd to deliver 90km of civil engineering infrastructure for the HS2 route through the West Midlands. On large infrastructure projects such as HS2, the integration of advanced technologies, such as artificial intelligence, to support design and construction is rapidly growing. DAARWIN is a machine learning-based technology which, coupled with high-quality, timely and reliable instrumentation and monitoring (I&M) data, can be used to enhance the implementation of the Observational Method. This paper explores the use of DAARWIN and how Mott MacDonald (MM) developed I&M repository tools to manage and process considerable volumes of data and support the near real-time back analysis of three retained excavation structures on HS2 in the application of the observational method. From data retrieval and timely data pre and post-processing, these tools deliver back analysed wall deflections and structural capacities, and forward predictions, to inform the deployment of contingency measures, such as structural blinding, in lieu of temporary props. Washwood Heath Retained Cut will be explored, demonstrating effective omission of temporary props, resulting in efficiencies in time and cost, whilst delivering carbon savings and importantly enhancing safety on site.

KEYWORDS: The Observational Method, 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.

Large-scale infrastructure schemes such as HS2 increasingly rely on advanced digital technologies to enhance safety, efficiency, and sustainability. One such innovation is DAARWIN, a machine learning-based platform developed to support the implementation of the Observational Method through near real-time back analysis. When combined with high-quality Instrumentation & Monitoring (I&M) data, DAARWIN enables design teams to dynamically assess structure performance and make informed, data-driven decisions on site in a timely manner.

This paper presents a digital workflow case study, integrating DAARWIN for near-real time back analysis, with the development of custom Mott MacDonald (MM) I&M repository tools to support rapid data retrieval, preprocessing, and visualization. It demonstrates the application of this approach across a major excavation structure along the HS2 route, having completed Bromford Tunnel East Portal (Liew *et al.* 2024), extended to Bromford Tunnel West Portal, and focusing on the Washwood Heath Retained Cut. The trial and subsequent rollout demonstrate how this method has allowed the omission of temporary props in favour of contingency measures including structural blinding and additional dewatering, leading to time, cost, carbon, and safety benefits.

2 NEAR REAL TIME BACK ANALYSIS

The Observational Method (OM) is a well-established (but significantly under-used) construction control approach involving the systematic use of field observations to verify and, if necessary, adjust the design during construction (Powderham & O'Brien, 2021). The fundamental principles of OM were established several decades ago (Peck,1969), however implementing the method in near real-time remains relatively new and presents significant technical and operational challenges, particularly in terms of data integration, processing speed, and automation of model updates. Crucially, the success of real-time back analysis depends not only on timely data availability but also on the rigorous processing and quality review of instrumentation and monitoring data, ensuring that model updates and engineering decisions are based on accurate and reliable information.

The application of OM always requires timely interpretation of site observations and monitoring data. For mega-scale infrastructure projects with complex design assurance processes, such as HS2, the implementation of the OM can be enhanced and more efficiently implemented by integration of site performance data with predictive models. To enable a responsive and data-informed decision-making process, a near real-time back analysis framework has been developed. This framework leverages automation, cloud-based digital infrastructure, and robust data pipelines to support the rapid calibration of numerical models against field measurements.

2.1 *DAARWIN analysis*

DAARWIN is a web platform developed to support efficient back analysis of geotechnical structures. It enables the rapid recalibration of numerical models by systematically comparing model predictions with actual field data utilising the genetic algorithms (De Santos, 2015). DAARWIN orchestrates the re-running of numerical simulations, adjusts input parameters based on discrepancies between predicted and observed behaviour, and stores the resulting analysis in an accessible format. As a result, it facilitates more frequent and consistent model updates, supporting the application of the Observational Method across large infrastructure projects.

2.2 *Instrumentation and Monitoring repository*

A critical enabler of near real-time back analysis is a robust, structured data management system that ensures timely access to high-quality monitoring data. For the HS2 project, Mott MacDonald developed a bespoke solution designed to manage the vast volumes of data generated by the project's extensive geotechnical monitoring network.

To complement the DAARWIN platform, a centralised Instrumentation and Monitoring (I&M) repository has been developed on the Microsoft Azure cloud platform (Microsoft Corporation, 2023). This repository is underpinned by a relational architecture designed to store both raw and processed project data, including outputs from numerical analyses. The workflow begins with the ingestion of data from a variety of sources - such as sensors, instrumentation and monitoring data, and site reports (e.g., excavation progress and staging data). These inputs are automatically processed through a suite of cloud-based ETL (Extract, Transform, Load) Python scripts, which clean, standardise, and upload the data into the central repository.

An additional set of integration scripts facilitates seamless communication between the repository and the DAARWIN platform, enabling automated extraction and storage of updated model outputs. This integration allows engineers to readily compare and contrast the results of back analyses, original design predictions, field monitoring data and various other data related to the project (such as temperature and excavation levels data). Furthermore, the structured nature of the repository enables direct access via Microsoft Excel, allowing engineers to explore and manipulate the data without requiring advanced programming skills. This streamlined workflow has significantly reduced the time previously spent on manual data processing and transformation, thereby allowing the site team to focus more effectively on interpretation, engineering judgement, and risk-informed decision-making.

The Instrumentation and Monitoring Repository facilitates:

- Automated retrieval of data from multiple sources and formats,
- Standardised data schemas for consistency across instruments and locations,
- Cross-referencing and indexing with our site record tool to support quick retrieval and filtering against construction sequence and excavation level,
- Processing and post-processing that enable seamless integration with DAARWIN and the Mott MacDonald wall bending moment back analysis tool (a bespoke tool developed to curve fit inclinometer data and back-calculated wall bending moments using a physics-based approach).

3 WASHWOOD HEATH RETAINED CUT

The Washwood Heath Retained Cut, WHRC, forms a key part of the HS2 route through Birmingham and represents one of the most substantial structures of its type along the route. It is approximately 1.2 km in length and has a maximum retained height of nearly 20m. Along the WHRC the predominant geology is Mercia Mudstone, which can be characterized as an Intermediate Geomaterial (IGM), typically varying from a stiff clay to a weak rock. The rock mass quality was expected to be highly variable both due to several faulted zones being traversed and due to variable dip and dip direction of joints in the rock mass. The mass permeability is also variable, being mainly influenced by the nature of the rock joints, (high permeability where joints are open to low permeability where joints are closed). Hence, earth and groundwater pressures during construction would vary significantly along the WHRC, as conditions varied from worst credible to most probable.

The retaining walls, shown in Figure 1, were constructed using a 1.2 m thick diaphragm wall. The original detailed design support system comprised one level of cast in situ intermediate props, precast concrete top props and a level of temporary steel props. While this configuration provided a conservative design basis, it also introduced temporary works with significant cost, programme, and carbon implications. As a result, opportunities were explored to create a more efficient construction process by implementing the Observational Method (OM) through Progressive Modification (Powderham, 1998). This was based on previous experience at the Bromford Tunnel East Portal (Liew *et al.* 2024).

HS2 has an onerous design assurance process, which means that once a design has been ‘approved’ any subsequent changes would normally require the time-consuming assurance process to be repeated. To achieve agreement to use the OM, it was implemented by adopting the ‘verification process’. The verification process for WHRC established four verification points, or hold points, within the excavation sequence. These points aligned with key stages of excavation and support installation, acting as formal review points (with the independent checker) to assess and compare the observed wall displacements against the predicted values, the performance of structural elements and groundwater response. This process was successfully used for Crossrail (Powderham and O’Brien, 2021) and enabled OM to be implemented whilst also working within the constraints of a similar design assurance process.

At each verification point (VP), DAARWIN was used to conduct near real time back analysis, incorporating the latest I&M data from inclinometers, shape acceleration arrays and piezometers, and supported by the Optical Display Sensors (ODS), shown in Figure 2 for WHRC and Bromford Tunnel West Portal (BTWP). The outcome of this assessment enabled quick and informed decisions to be made through close collaboration with the site team and independent checker. This allowed construction either to continue to advance excavation, or where necessary, install contingency measures (such as structural blinding).

This data-driven strategy, summarised in detail in the following sections for the application to WHRC, enabled safe, staged construction while delivering efficiencies and enhancing construction site logistics, whilst also maintaining the design assurance for the structure.

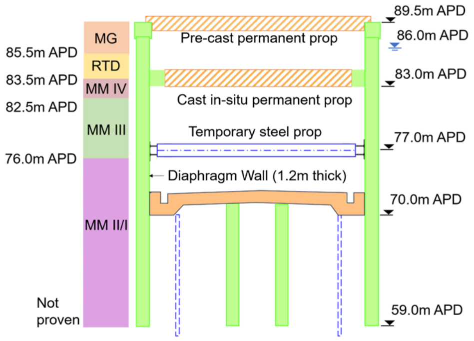

Figure 1. Typical section at WHRC (Section A).

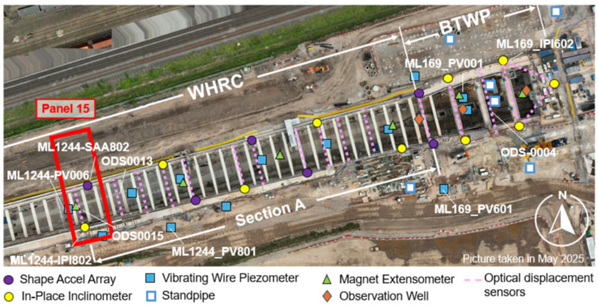

Figure 2. WHRC Instrumentation and Monitoring arrangement.

4 AN OVERVIEW OF THE OBSERVATIONAL METHOD AT WHRC

4.1 *Excavation levels and Verification Points (VP)*

Excavation progression was tracked using the Mott MacDonald site activity tool, reviewed alongside I&M data from MissionOS (a Maxwell Geosystems product) and processed in the Mott MacDonald I&M repository. The pre-defined excavation stages, or verification points, provided structured milestones for analysis and decision-making. At each verification point, DAARWIN re-processed the accumulated monitoring data and generated updated back analysis parameters and forward projections of wall deflection for subsequent construction stages, indicating the likelihood of a potential trigger breach in accordance with Figure 3. Working in near real time, the feedback on future wall displacements, and in parallel, structural capacity through the Mott MacDonald bending moment back analysis tool, enables timely decisions to be made regarding future excavation and contingencies in line with the pre-agreed actions summarised in Table 1.

This robust input framework created a feedback loop between design, monitoring, and machine learning-powered analysis, supporting timely, justifiable decisions for modifications or the omission of temporary measures such as props.

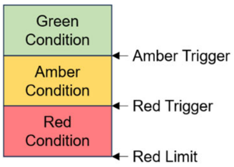

Figure 3. Trigger levels based on a “traffic light” system.

Table 1. Pre-agreed actions at a Verification Point.

Trigger Level	Actions
Green condition	Recommend proceeding with excavation without implementing contingency measures.
Amber condition	Recommend 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 implementing contingency measures unless all parties agree that the Red Limit is unlikely to be breached.

Table 2. Trigger levels for wall displacement.

Structure		VP1	VP2	VP3	VP4	FFL
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*

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

Summarised in Table 1, for WHRC, the decision was made to omit the temporary steel props in Section A, and should displacements trend towards a red condition, or exceed a red condition (Table 2), pre-agreed contingencies would instead be implemented. The pre-agreed contingency measures included: a 300mm thick structural concrete blinding strut made of C35/45 concrete mix; to be implemented within 24 hours of reaching the excavation level; and to cover the entire plan area, be flat or level, and have a clean contact with the wall.

4.2 *Back analysis inputs*

To facilitate the timely implementation of OM in accordance with Table 1, accurate and responsive back analysis requires reliable and up-to-date input data. For the observational method and application of DAARWIN to facilitate near real time site support and decision making, several key input parameters were defined and subsequently refined through feedback loops that supplied up-to-date site-specific observations and instrumented feedback. The key considerations are summarised below.

4.2.1 *Wall properties*

Retaining wall properties were defined using stiffness values derived from early-age thermal effects on the concrete and adjusted through a modified section modulus approach. This approach follows the methodology proposed by Eadington *et al.* (2024) considering the age of the wall at the start of construction.

4.2.2 *Ground model and stratigraphic boundaries*

During excavation to the first verification point (VP), the detailed design ground model was adopted for the commencement of back analysis. The ground model was refined and updated regularly at the verification points, based on site observations during excavation, allowing for the adjustment of stratigraphic boundaries to reflect actual conditions based on feedback and reporting from the Construction Phase Support (CPS) team via the site reports.

4.2.3 *Modified mudstone stiffness parameters*

At WHRC, stiffness parameters for the Mercia Mudstone, summarized in Liew *et al.* (2026) based on the results of back analysis at the Bromford Tunnel East Portal (BTEP) were initially adopted (Table 3). These were updated based on excavation performance through review of instrumentation data via DAARWIN feedback loops

Table 3. 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

4.2.4 *Groundwater levels*

Piezometer readings were used to characterise both the initial and evolving groundwater regime during the excavation sequence, a critical factor for retaining wall performance. These inputs were updated at each verification point, in conjunction with the site observations recorded in Sections 4.1 and 4.2 allowing DAARWIN to model a representative cross-section of excavation.

5 SUMMARY OF WHRC CONSTRUCTION

The following sections summarise each stage of the construction sequence for Washwood Heath Retained Cut Section A and the use of the Mott MacDonald near real time back analysis framework, supported by DAARWIN, to assist decision making with respect to pre-agreed actions at a verification point.

6 EXCAVATION TO VP2 (80.0mAPD)

6.1 *Delay of precast prop installation*

The implementation of the Observational Method at WHRC enabled a more efficient construction sequence to be adopted. At the early stages of the construction sequence during excavation of the capping beam, a decision was made to delay the installation of the precast top prop shown in Figure 1, based on the initial forward projection from parameters summarised

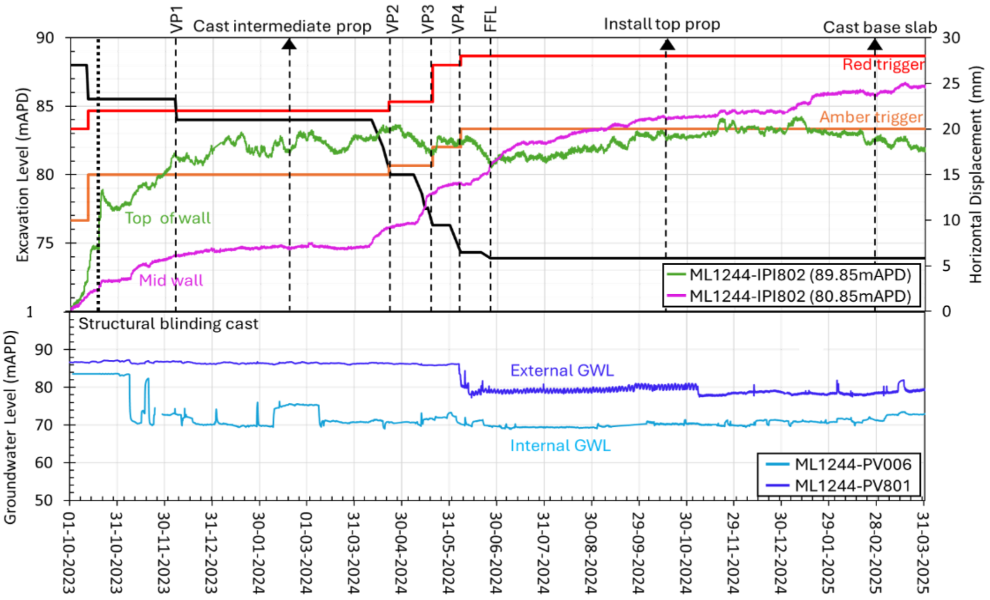

Figure 4. Time history of WHRC Panel 15

in 4.2.3, that demonstrated that during initial stages of excavation, the wall could instead act as a cantilevered section whilst remaining well within structural capacity.

This delay of top prop installation significantly enhanced the ease of site access, removing headroom constraints and enabling more efficient plant movement and excavation operations within the retained cut. Furthermore, without headroom constraints, the health and safety risk of the site area, as a result of propping restriction and the risk of prop strike, was eliminated for this stage of construction.

6.2 *Deploying contingencies*

Excavation toward VP1 (84.8mAPD) advanced through Made Ground and River Terrace Deposits under cantilever wall conditions. This stage was characterised by predominantly stable displacement trends once excavation level was reached, remaining within green trigger thresholds defined by the project's observational framework.

However, on 17 October 2023, excavation activities were impacted by the occurrence of Storm Babet, which brought prolonged heavy rainfall across the West Midlands. The event resulted in temporary ponding of groundwater locally behind the south wall (panel 15) of the retained cut which led to a temporary acceleration in wall movement in this area; identified through inclinometer monitoring via MissionOS and assessed in detail through the MM I&M repository tool. While the movements remained within acceptable thresholds, shown in Figure 4, the elevated rate of displacement triggered a review.

Since the wall was acting as a cantilever, due to the decision to delay the precast top prop, the DAARWIN analysis model was recalibrated at VP1 to account for the additional wall movements induced by peak seasonal groundwater conditions, coupled with the latest observation data obtained from site. Using DAARWIN, the model and parameters were back analysed using inclinometer data from ML1244-IPI802 at Panel 15, shown in Figure 2 for the top sensor and mid-wall sensor. The rapid assessment demonstrated the contribution to trajectory of movement recorded locally along the south wall through the I&M data and repository reviews was attributed to the rainfall event and enabled projection of wall displacement (Figure 7) and structural capacity (Figure 5) for future stages of excavation.

In parallel, the bending moments were back calculated using the I&M data following each stage of excavation and were confirmed to remain within the structural capacity of the diaphragm walls using the MM tool (Figure 5).

Recognising the change in system support from top-propped to cantilevered and given the early stage in the excavation sequence and open excavation time expected due to cast in-situ intermediate prop construction, a risk reduction meeting was held in conjunction with the Contractor, BBV, and independent checker within hours of recorded localised movement to maintain confidence. Through close collaboration with the site construction team, a decision was made to cast a 300 mm structural blinding strut as a local contingency measure at Panel 15 in advance of casting the in situ intermediate prop. This intervention provided additional restraint at the base of the retained height and helped to slow the rate of wall displacement at Panel 15, shown in Figure 4 notably at the top of the wall. Deploying the contingency allowed work to continue to progress safely for the intermediate prop construction in this area, while preserving the option to adjust the support strategy and install the pre-cast prop at a later stage in the construction sequence.

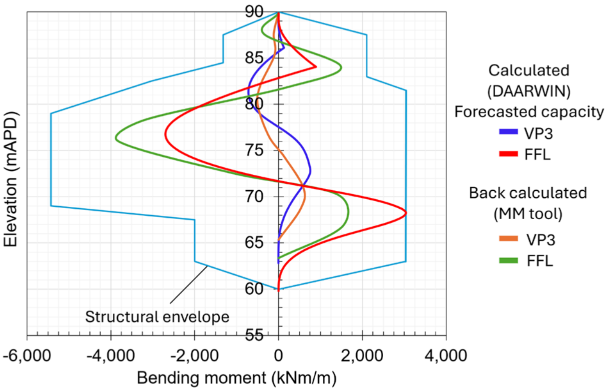

Figure 5. Assessment of structural capacity for stages of excavation

Following this assessment, and with the implementation of additional groundwater control bunds behind the wall and dewatering wells switched on inside the excavation in November, demonstrated by ML1244-PV006 inside the excavation in Figure 4, construction of the in-situ intermediate props and subsequent excavation to progress toward Verification Point 2 (VP2) commenced.

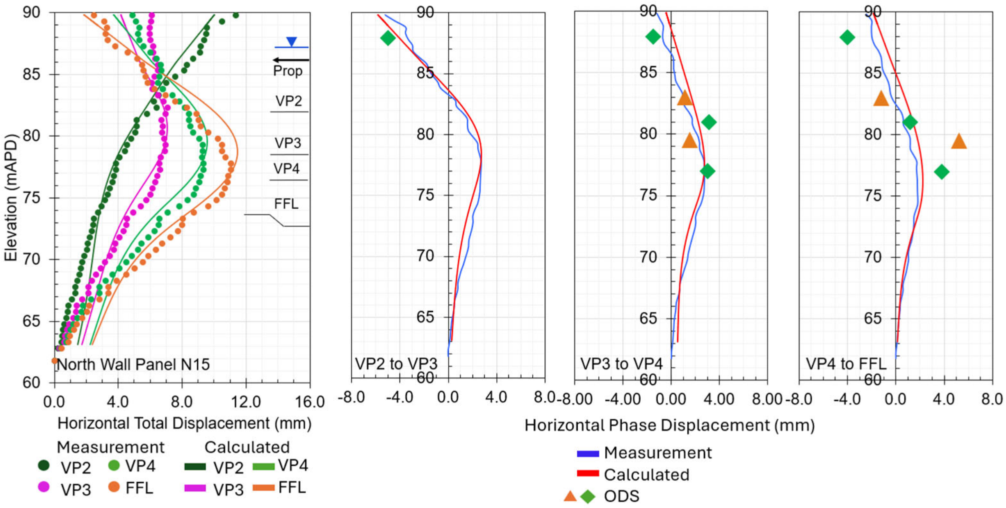

Figure 6. Results of projected wall deflection calculated using back analysed parameters at North wall Panel N15 (ML1244-SAA802).

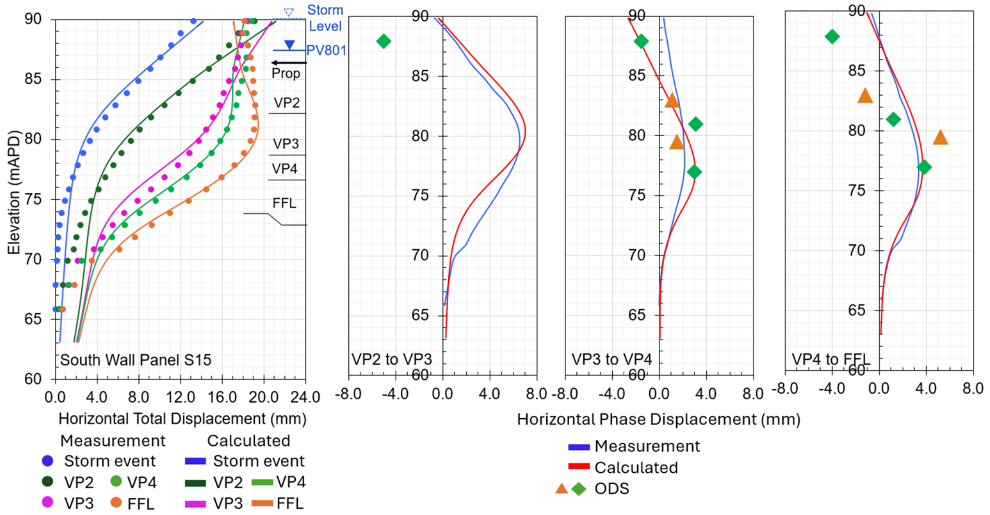

Figure 7. Results of projected wall deflection calculated using back analysed parameters at South wall Panel S15 (ML1244-IPI801).

7 EXCAVATION FROM VP2 (80.0mAPD) TO VP3 (76.3mAPD)

Following the installation of the cast in-situ props, as demonstrated in Figure 4, excavation proceeded quickly to Final Formation Level (FFL). ODS were installed upon reaching VP1, VP2 and VP3, enabling a convergence of the north and south walls to be incorporated into the I&M repository and near real time analysis feedback loop.

This afforded an opportunity to validate the displacements recorded from the inclinometer and shape array sensors in each wall. Figure 6 demonstrates the near real time back analysis undertaken for the North wall panel, showing the measured wall displacements against the calculated DAARWIN displacements. In addition to examining the total horizontal displacements, the phase or incremental displacements between each set of verification points is also compared, allowing assessment against the convergence obtained from the installed ODS. Figure 7 shows the same near real time back analysis for the South Panel.

During excavation from VP2 to VP3, post the casting of the in-situ intermediate prop, the location of maximum displacement shifts from the top of the wall to a sensor towards the belly of the wall, denoted “mid wall” in Figure 4. A notable disparity emerged between the walls whereby the majority of movement was recorded on the north wall, with negligible incremental displacement observed on the south wall for the equivalent level.

Comparison with the (ODS) between VP2 and VP3 revealed discrepancies in the magnitude of incremental displacement compared to the inclinometer and back analysed projection in the south wall. A close agreement was found in the north wall, demonstrating all convergence of the ODS could be attributed to the north wall movement. Captured in the DAARWIN analysis feedback loop, via the site observations records and piezometer readings through the I&M repository, it was identified this is likely a result of lateral sway in the south wall, attributed to damming effects and elevated ground and groundwater levels to the south of the scheme compared to the north. This subsequently provided further validation of the back analysis as excavation continued to advance beyond VP3.

8 EXCAVATION FROM VP3 TO VP4 (76.8mAPD) AND FINAL FORMATION LEVEL (73.9mAPD)

Excavation from Verification Point 3 (VP3) to the final formation level demonstrated strong alignment with DAARWIN-derived projections in terms of total and cumulative wall displacements. This agreement reinforced confidence in the modelling and monitoring framework adopted for the retained cut. The project displacements demonstrated that it was likely further contingencies would not need to be deployed and subsequently supported the delay of the pre-cast top prop until after excavation had been completed.

Table 4. Stiffness values of the Mercia Mudstone Group based on the back analysis of panel 15

Lithology	Stiffness (MN/m^2) Back-analysed for WHRC Panel 15	UCS (MN/m^2)
Mercia Mudstone Grade IV	$65 + 42z^1$	N/A
Mercia Mudstone Grade III	$136 + 25z^2$	2
Mercia Mudstone Grade II/I	$300 + 42z^3$	2

z^1, z^2 and z^3 are depths from 83.5m, 82.5m and 76m APD, respectively

Given the quick excavation from VP2 to formation shown in Figure 4, it was vital that back analysis parameters could be validated and projections assessed in a timely manner for approval to excavate to the next verification point. Beyond excavation to FFL, the maximum wall displacement gradually increased and approached the red trigger level since the base slab could only be cast in early 2025, an elapsed time period of approximately 9 months, as summarised in Table 6 of Liew *et al.* (2026). The wall displacement stabilised after the base slab was cast (Figure 4) and achieved the design strength.

Coupling the site observation records and the I&M repository, provided a holistic real time assessment of site activities, geological records and I&M data, generating a reliable feedback loop to enable up-to-date analysis that captures present site conditions and support and inform decision making on site. The back-analysed parameters, derived from near real time back analysis using DAARWIN, provided close agreement with the measured excavation induced displacements when advancing through the construction sequence. The derived parameters for this location of WHRC are summarised in Table 4. Most notably, there is a decrease in the stiffness of the MMG III when compared to the back analysed stiffness at BTWP and BTEP. Normalised small strain stiffness (G/G_0) for this location at WHRC was determined to be 65%, compared to 95% at BTWP – demonstrating the mobilisation of stiffness as a result of both wall displacement and change in structural arrangement from a propped (BTWP) presented in Liew *et al.* (2026) to cantilevered (WHRC) system for this section of wall.

8.1 *The use of ODS*

The integration of Optical Displacement Sensors (ODS) provided a valuable layer of verification within the instrumentation suite, supporting data confidence across all verification points. ODS offered simple direct surface displacement measurements between the north and south diaphragm walls—critical for understanding the system's overall structural response. The ODS played a key role in identifying and validating local sway-induced behaviour. The readings confirmed that the structure was not exhibiting symmetric convergence; instead exhibiting a unidirectional displacement pattern at panel 15 due to the "locked in displacements" from the storm event and subsequent intermediate prop casting. By providing independent confirmation of displacement trends, ODS measurements:

- Corroborated readings from embedded inclinometers and shape array sensors,
- Confirmed structural interaction between opposing walls, validating the global deformation models,
- Enhanced the reliability of back analysis and contingency assessments during critical excavation phases.

The use of ODS as a primary system that was quick to install and cost effective, strengthened the observational methodology by adding a robust cross-check mechanism, ensuring that decisions were grounded in multi-source near real time evidence.

9 CONCLUSIONS

The Washwood Heath Retained Cut case study demonstrates the critical role of instrumentation, intelligent analysis tools, and agile decision frameworks in delivering complex infrastructure safely and efficiently.

In materials such as Mercia Mudstone, which are difficult to characterise through field and laboratory testing due to their complexity and variability, the Observational Method enabled the uncertainty of mass strength and stiffness behaviour to be safely and cost-effectively managed. This included safely managing the local effects of an extreme weather event. The back analysis undertaken identified that the Mercia Mudstone stiffness increases rapidly with depth, whilst from UCS testing this profile would conventionally be assumed to be constant. Near real time back analysis via the feedback loop presented, has proved invaluable in characterising the stiffness of the Mercia Mudstone. The case study presented illustrates the importance of these back analysed parameters to support the application of the Observational Method.

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