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Westmead metro station excavation: Design challenges and ground performance

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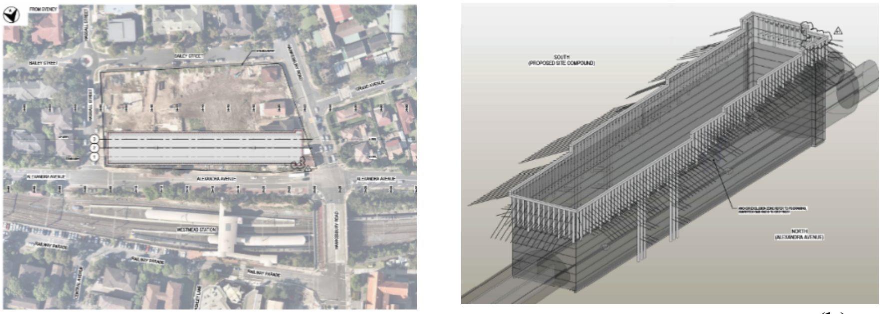
ABSTRACT: The excavation of Westmead metro station, as part of the Sydney Metro West – Western Tunnelling Package, required careful consideration of complex geological conditions and urban constraints. Risk management relied on robust design strategies, real-time monitoring, and adaptive decision-making. This paper outlines key design considerations, including the retention system, anchor exclusion zone management, and ground stabilisation measures, which were essential to excavation stability and limiting impacts on nearby infrastructure. Observations during excavation, including geological mapping and ground monitoring, provided valuable insights into ground behaviour. Comparing monitoring data with design predictions helped assess excavation performance and informed design adjustments to improve safety and efficiency. This case study highlights the value of robust monitoring systems, adaptive design, and effective collaboration in managing excavation risks. The lessons learnt support best practice development for future underground construction in Australia.

1 INTRODUCTION

Sydney Metro West (SMW) is a new underground railway connecting Greater Parramatta to the Sydney CBD. As part of this project, the Western Tunnelling Package (WTP) involves the construction of 9 km of twin railway tunnels between Sydney Olympic Park and Westmead.
This paper focuses on the excavation of Westmead metro station, highlighting key design considerations and observations made during construction.

The Westmead metro station site has excavation depths varying from approximately 30 m to 38 m. The site is bounded by four roads: Alexandra Avenue and the existing Westmead railway station to the north, Hawkesbury Road to the west, Hassall Street to the east, and Bailey Street to the South. The site features sloping terrain, with a level difference of approximately 12 m from west to east and around 5 m from south to north. The site topography and urban constraints combined with tight project boundaries, presented significant design and construction challenges. The station excavation is adjoining two caverns at its two ends, namely station cavern and crossover cavern respectively (Figure 1). The station is located predominantly within Ashfield Shale.



(a) (b)

Figure 1. Westmead metro station: (a) layout plan, (b) 3-d illustration

2 EXCAVATION DESIGN CONSIDERATIONS

2.1 *Retention system design*

The excavation of the Westmead metro station box required a robust and well-engineered retention structure to address the site's topography, geological and urban constraints. The retention system consists of soldier pile walls (with a pile diameter of 0.75 m) around the perimeter of the station box with the piles installed at a nominal centre-to-centre spacing of 2.0 m and typically socketed 1.5 m into Class I/II Shale (SH-I/II), generally corresponding to the upper third of the excavation (approximately 8–12 m) rather than extending through the full excavation depth. In zones of competent rock mass (e.g., SH-I/II), reinforced shotcrete and patterned rock bolt were provided without soldier piles, as additional support from the piles was not required in these zones. The Ashfield Shale has substantial variation in joint sets with a significant potential for wedge formation during excavation. Hence, a staggered pile toe arrangement with a pile socket of 3.0 m into SH-I/II for every third pile was adopted to mitigate the geological risk.

The retention structure design assessment was carried out using PLAXIS 2D, which accounted for the staged construction of the retention structure and stress relief of the rock strata. The excavation was designed as a drained excavation. The soldier piles were adopted to support both lateral earth pressures within the soils and weaker rock masses, as derived from the PLAXIS 2D analysis, as well as axial loads from ground anchors, an acoustic shed and other construction activities. A shotcrete wall of 200 mm was provided in front of the piles to retain the ground between the piles.

Ground anchors and pile bolts were adopted to provide lateral stability for the soldier pile wall. All elements of the retention system were required to be outside the minimum clear openings (MCO) specified by Sydney Metro. Multiple step levels across the capping beam were required to accommodate the site topography. In critical areas where the piles were required to resist high vertical loads from the acoustic shed or other construction activities, mandatory rock bolts were installed beneath pile toes to provide additional support to the rock mass. Piles supporting gantry systems were designed below the full excavation length (FEL) with minimum 3 m into SH-I/II to resist additional structural loads.

The excavation was predominantly in SH-I/II below the pile toes, where kinematic instability of localised wedges was a key concern. Geotechnical investigation indicated that the typical wedge was a steeply dipping tetrahedral wedge formed by joint intersections between north-northeast (NNE) and east-southeast (ESE) joint sets and random joints. The typical wedge volume was approximately 1 m^3. In addition, a ubiquitous sliding block with a volume of 6.4 m^3 was considered in the design based on the method outlined by Anderson & Pells (2002). The block was assessed to be large with respect to conditions typically encountered in excavations in SH-I/II. Large-scale blocks and wedges associated with persistent geological discontinuities, such as shear zones and faults, were not identified during the design phase—at least none deemed critical to the global stability of the station box retention system. If previously unidentified persistent geological features, such as major faults, were encountered during progressive excavation and face mapping, a formal design review process was implemented. This allowed the contractor to request a reassessment of required supports by the designers and implement any necessary modifications as required to maintain overall excavation stability.

The assessment of rock wedge / block stability was performed using UnWedge, SWedge, and RocPlane. Pattern rock bolts (with a bolt length of 6.0 m and spacing of 2.40 m horizontal x 1.75 m vertical) and 150 mm steel fibre reinforced shotcrete were adopted to retain the typical wedges and blocks expected in vertical excavations in SH-I/II (see Section 3). Additional spot bolting was provisioned when adverse discontinuities (e.g. faults, joints, etc) were encountered during the excavation. Smaller wedges and blocks formed by tighter defects may not be visible during geological mapping and/or intersected by the pattern bolts. The design intent was to utilise an integrated shotcrete lining to retain the typical wedges that were not intersected by the pattern bolts. Wedges / blocks formed underneath the pile toes carrying significant axial loads were a critical concern. The pile axial loads were also considered in the wedge/block stability assessment, and a rock bolt below the pile toe was provisioned in the design.

A nominal constant groundwater pressure of 10 kPa was considered in both the shotcrete wall in front of the soldier piles and reinforced shotcrete lining analyses to account for localised build-up of groundwater pressure. Mandatory strip drains and/or weep holes (as required) were also installed behind the shotcrete during construction.

2.2 *Anchor exclusion zone*

An anchor exclusion zone of approximately 14 m in length was required along the north wall of the station box, where the ground anchors were prohibited to allow for the future construction of a pedestrian connection to the existing Westmead railway station. A specific design solution was developed for this area, comprising soldier piles supported by two rows of steel walers, which were restrained by ground anchors outside the anchor exclusion zone (Figure 2). Glass fibre reinforced polymer (GFRP) pile bolts were installed through the piles to provide additional support to the retention system. A simplified PLAXIS 3D model was also adopted to study structural interaction between the ground anchors, walers, and retention system within the exclusion zone.

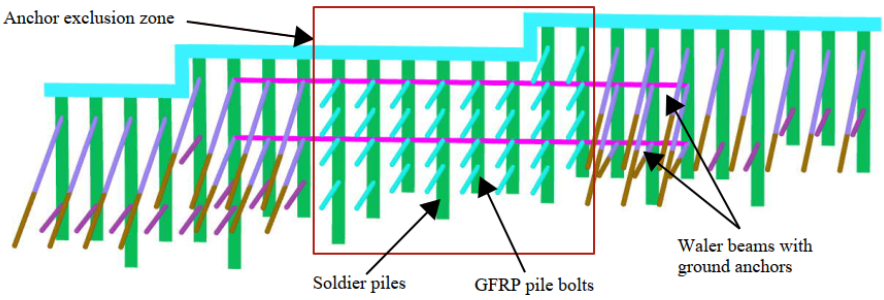


Figure 2. Anchor exclusion zone retention structure

2.3 *Cavern excavation at east wall and west wall*

Excavation of two mined caverns, located along the east and west walls of the station box, was planned to commence from within the box footprint. The design of the soldier piles and ground anchors in these areas was tailored to avoid interference with the future cavern excavation. Modifications included shorter pile toe embedment and ground anchors installed at flatter angles, with bond lengths located in Class III and IV shale. The design also accounted for the effects of cavern excavation on the retention system, resulting in increased design loads for both piles and anchors. GFRP rock bolts were adopted in place of conventional steel bolts to facilitate excavation within the cavern zones.

2.4 *Assessment results – predicted displacement*

Excavation within stressed rock strata, such as Ashfield Shale, can result in ground displacements due to stress relief. Historical data published by Oliveira & Wong (2012) indicate typical cumulative displacements in the range of 0.5–1.5 mm/m of excavation in Sydney region, with rare cases reaching up to 2 mm/m.

For the Westmead metro station excavation, assessment results indicate that predicted horizontal ground movements in soil and weaker rock masses are generally less than 10–15 mm. Within SH-I/II, estimated lateral displacements range from approximately 1.0–1.9 mm per metre of excavation. These estimates are consistent with displacement values recorded in similar geological conditions across Sydney. The predictions were based on lower-bound rock stiffness to account for variability in ground behaviour and to ensure moderately conservative displacement estimate for ground impact assessment. In deep, confined excavations, full stress relief may not develop, which can further reduce observed displacements.

3 OBSERVATIONS DURING EXCAVATION

3.1 *Geological mapping and site conditions*

The station box excavation was expected to be predominantly in Ashfield Shale, only encountering the Mittagong Formation contact towards the base elevation. The Ashfield Shale, distinct from the well-known Sydney sandstone, represents the basal unit of the Wianamatta Group. When fresh, it typically consists of dark grey to black claystones and siltstones, with laminites of fine sandstone. Its formation in low energy lacustrine or brackish marine depositional environments, allowed for the accumulation of fine-grained sediments up to 60 m in thickness. Bedding is invariably horizontal to slightly inclined, with little cross bedding. Sedimentary 'slump' structures within the unit, however, are known to influence the presence of joints and faults. A typical Class I/II exposure of Ashfield Shale is shown in Figure 3.

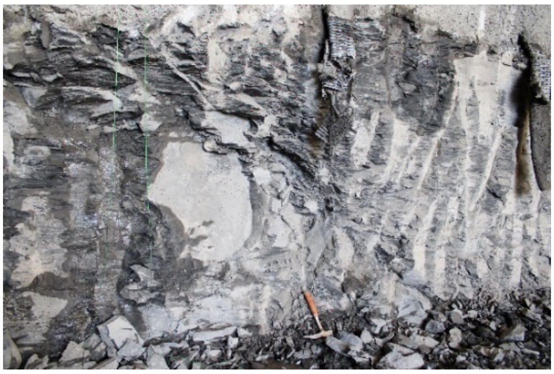


Figure 3. Fresh Ashfield Shale (Class II to Class I) with typical defects

Detailed and extensive field mapping was conducted throughout construction of the Westmead metro station box. The Ashfield Shale excavated at Westmead was mostly fresh to slightly weathered. The residual soil to moderately weathered profile transition comprised the top third of the excavation (i.e. 8–12m on average). The remaining two-thirds of the excavation had consistently fresh to slightly weathered rock mass with UCS values of 6MPa and above. Rock strength was assessed through field tests and limited lab samples. These characteristics remained the same even in areas which were more defect affected. It became clear during construction that Ashfield Shale ground behaviour was defect controlled. Unlike sub-vertical to low-angle horizontal defects in Sydney Sandstone however, these joint and fault defects in shale were predominantly mid-angle. When intersected by horizontal bedding partings, the potential for wedge failure increases. Joints at Westmead were planar, smooth, and clean or clay coated. Although usually of low persistence, these joints still proved challenging due to their random orientations leading to wedge formation such as in Figure 4. Where joints became more persistent – such as in proximity to large-scale fault features, wedge size even approached that of the design wedge, discussed in Section 2. Large moderately dipping faults were also encountered during the Westmead metro station box construction (Figure 5). These persistent features had significant crushed zones of rock fragments and clay, and closely spaced jointing. Other examples can be found in Salcher et al. (2024).

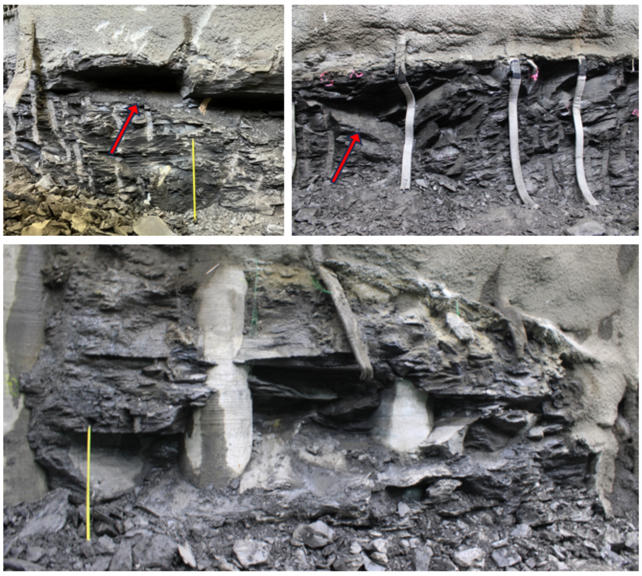


Figure 4. Typical wedges along mid angle defects in Ashfield Shale exposed during excavation. Wedge limited by piles (bottom).

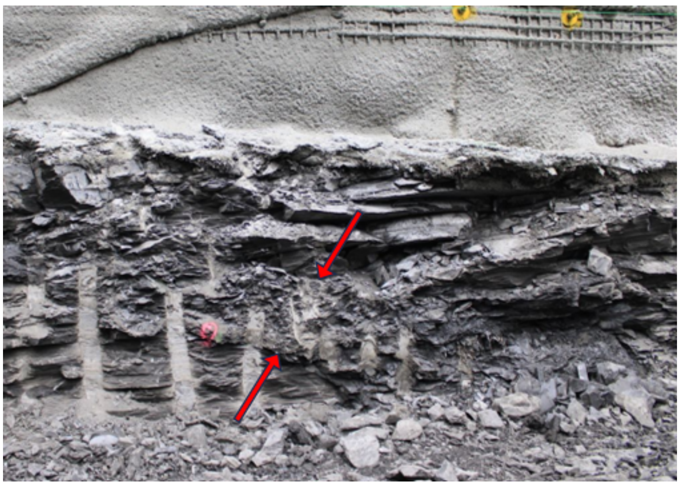


Figure 5. Mid angle fault with crushed zone and rock fragments (red arrows) in Ashfield Shale

3.2 *Comparison of ground monitoring data and design predictions*

The excavation performance of the Westmead metro station box has been comprehensively evaluated through monitoring data from anchor loads and pile displacement surveys, providing critical validation of the original design assumptions while revealing important insights into ground behaviour.

The survey monitoring data demonstrated ground displacement patterns largely consistent with established behaviour for excavations in Sydney's shale formations. Horizontal displacements in the Ashfield Shale ranged between 0.5–1.5 mm/m of excavation. It was observed that monitoring data at pile P126 (anchor exclusion zone) recorded displacements of up to 45 mm (i.e. approximately 1.5 mm/m of excavation), which is higher than the 32–35 mm recorded movements at other sections. While being consistent with design predictions, this larger movement was primarily attributed to the performance of the retention structure with steel waler beams and GFRP pile bolts in this localised anchor exclusion zone, by comparison to active anchors at other locations.

The monitoring data at both east and west wall, where two mined caverns were excavated, provided some insights on the impact of the cavern excavation to the station retention structure. On the east wall, the pile P176 displacement and anchor load were within design expectations, confirming the validity of the original geotechnical assumptions. The monitoring data demonstrates that no noticeable increase of the anchor load was recorded due to the cavern excavation.

However, the ground anchor installed on P85 (west wall) exhibited more than 20% increase in anchor load due to cavern excavation on west wall. The values at the West wall were still within design predictions as the design model was conservative. Nevertheless, the greater increase of anchor load was directly correlating with encountered fault zones and shear planes in this area interfacing with the adjoining mined tunnel excavation (see Figure 6). The station retention system, including the soldier piles and ground anchors, was designed for the potential impact of the cavern excavation to avoid overstressing of the system. Figure 7 illustrates a conceptual approach that was explored, involving the use of multiple instrumentation groups to verify ground performance specific to this scenario. This method, which simulates a desk study using automation tools for identified instruments, highlights a potential to improve efficiency—particularly valuable in projects requiring rapid excavation or mining advance.

The divergence between east and west wall anchor load data highlights how the uniform design assumptions were successfully adapted to address real-world geological heterogeneity. The monitoring data shows that the Ashfield Shale mostly behaved predictably throughout the entire excavation, fault interactions were properly mitigated through the adaptive design and the monitoring protocols effectively identified and managed variance from design conditions. This case study demonstrates how robust numerical modelling, engineering judgements combined with real-time instrumentation can successfully accommodate both expected shale behaviour and unforeseen geology challenges in deep excavations.

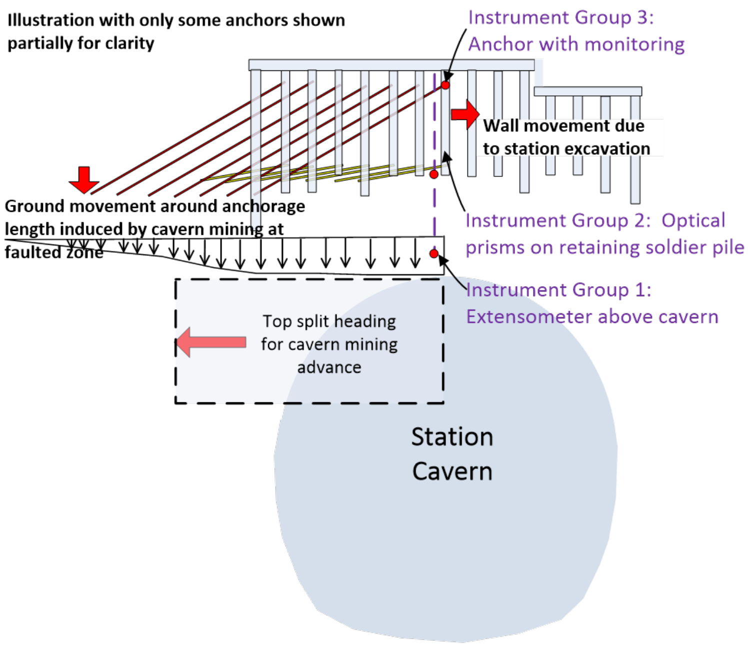


Figure 6. Illustration of interaction between station excavation headwall and cavern excavation

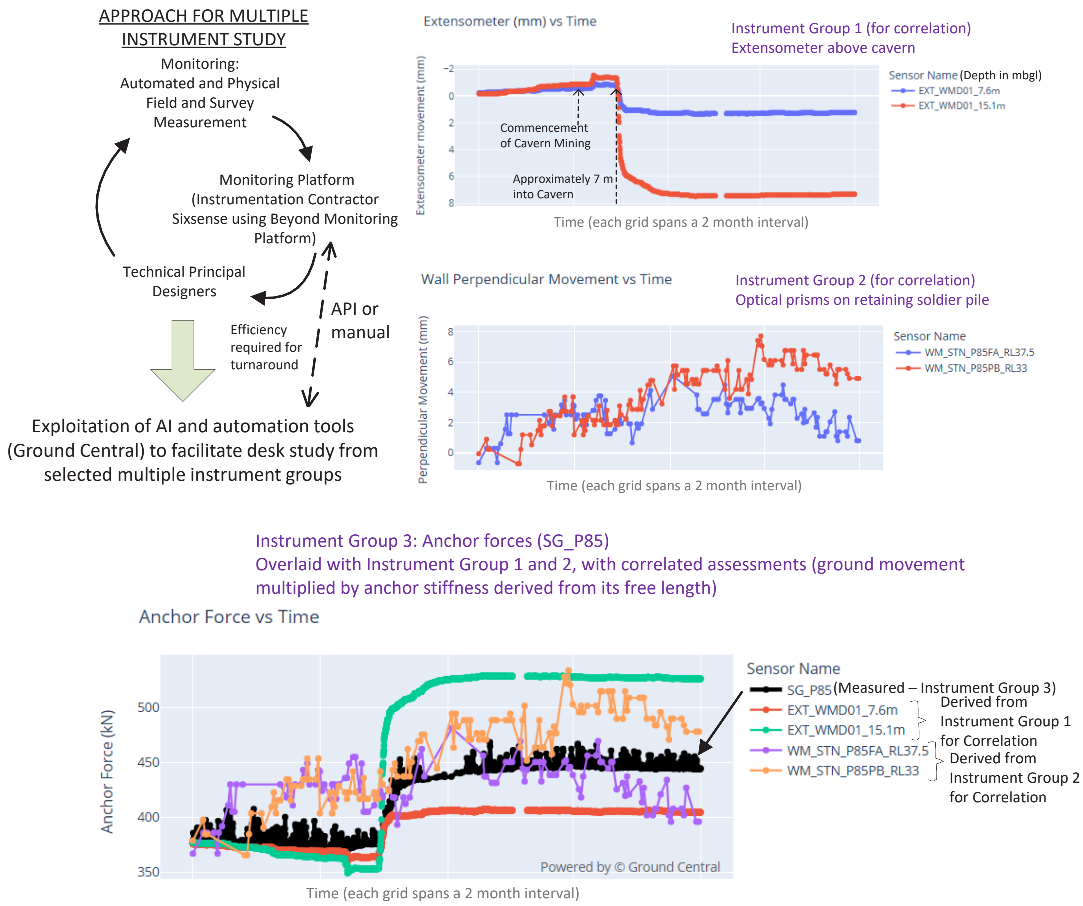


Figure 7. Explored approach using selected multiple instrumentation groups synced in advanced automation dashboards linked to monitoring platform to support desk study objectives aiming at reconciling monitoring performances with technical understanding and confirming trends against expectations

4 ADAPTIVE DESIGN MODIFICATIONS

The excavation of the Westmead metro station box in Ashfield Shale required continuous design adaptations to address the geological variability observed during construction. The initial design assumptions, based on available geotechnical investigation data and developed geotechnical models, were systematically refined through real-time geological mapping and monitoring feedback. This adaptive approach ensured stability while improving construction efficiency.

Detailed and extensive field mapping was conducted throughout construction of the Westmead metro station box to verify the assumed ground conditions. As excavation progressed, detailed geological mapping revealed localised variations in joint frequency, faulting, and rock mass quality. The presence of steeply dipping joint sets necessitated supplementary stabilisation measures beyond the initial pattern bolting design. Where mapping identified critical wedges or unstable blocks, additional spot bolts were installed, often at reduced bolt spacing than originally specified. This proactive approach prevented localised failures from propagating into larger wedge instabilities. In faulted sections, where rock mass behaviour deviated significantly from the design assumptions, pattern bolts were re-designed and adjusted, with bolt lengths extended beyond the potential wedge to ensure adequate load transfer into stable strata. Additional monitoring instruments, e.g. survey prisms, were also installed to mitigate the geotechnical risk.

Instrumentation data played a pivotal role in validating design assumptions and guiding modifications. Anchor load cells and inclinometers successfully captured the impact due to the fault zone and provided early warnings of anomalous behaviour, prompting timely interventions. Displacement trends were compared against predicted thresholds, with exceedances triggering additional bolting or shotcrete reinforcement before instability could develop.

This iterative process—where geological mapping, monitoring data, and numerical modelling continuously informed design adjustments—demonstrated the importance of flexibility in deep excavation projects. By integrating field observations with engineering judgment, the project team successfully mitigated risks while maintaining schedule and safety objectives. The lessons from the Westmead metro station box underscore that in complex geological settings, an adaptive design approach is not merely beneficial but essential for project success.

5 LESSONS LEARNT AND BEST PRACTICES

The construction of the Westmead metro station box within the Ashfield Shale formation provided invaluable insights into the challenges of deep urban excavations in geologically complex environments. The project highlighted critical lessons that can inform future excavations in similar conditions, along with best practices to enhance safety, efficiency, and cost-effectiveness.

5.1 *Geological and geotechnical considerations*

While pre-construction geotechnical investigation data provided a general understanding of site conditions, real-time geological mapping during excavation revealed localised variations—such as unanticipated fault zones and joint concentrations—that required immediate design adjustments. Future projects can consider incorporating higher-density investigations in areas with suspected geological discontinuities.

The behaviour of Ashfield Shale under excavation-induced stress relief also reinforced the importance of robust modelling assumptions. Lower-bound stiffness parameters in numerical models helped accommodate variability, but the project demonstrated that even these could underpredict localised displacements in faulted areas. Adopting probabilistic modelling approaches, which account for geological uncertainty, could further refine predictions.

5.2 *Design and construction adaptions*

The success of the retention system hinged on adaptive design principles, particularly the ability to modify support measures in response to encountered conditions. The use of staggered pile toe embedment proved highly effective in mitigating wedge instability. This strategy should be considered a best practice for excavations in jointed rock masses.

Another key takeaway was the effectiveness of hybrid support systems in constrained areas. The anchor exclusion zone at the north wall necessitated innovative solutions, such as steel walers and GFRP bolts, which provided stability without compromising future construction. Such flexible design approaches should be pre-planned for urban projects where space or functional requirements limit conventional retention methods.

The combination of shotcrete and pattern bolting was critical in the project to secure jointed rock mass. While re-mobilisation of site investigation rigs to verify uncertainty in faulting was commissioned for this site, additional verification via probing was still necessary midway during excavation to verify persistency of discontinuities. The excavation advance depth may need to be improvised depending on the ground conditions encountered.

5.3 *Instrumentation and monitoring*

The project validated the critical role of real-time monitoring in managing excavation risks. Anchor load cells and inclinometers provided early warnings of stress anomalies, enabling proactive interventions. However, the data also revealed that monitoring frequency should increase in faulted or highly jointed zones, where ground behaviour is less predictable.

Establishing predefined response protocols was another best practice. Salcher et al. (2024) provides good recommendations on the instrumentation and monitoring for deep excavations. Clear action thresholds—such as displacement rates exceeding 1.5 mm/m or anchor load deviations beyond 20% of design values—ensured swift decision-making. As demonstrated in this paper, future projects can similarly consider integrating these protocols into automated alert systems and linked to advanced cloud-based dashboards to facilitate desk study beyond display of factual monitoring data for instant team visibility (Figure 7).

6 CONCLUSION

In conclusion, this paper discussed a few design and ground performance challenges in a deep excavation case history sited in Ashfield Shale. The technical challenges and solutions for accommodating an anchor exclusion zone and adjoining cavern excavations were discussed. The collaboration between designers, contractors, and geotechnical specialists was instrumental in addressing these challenges. Contractor design involvement in the earlier design phases facilitated practical solutions, such as the optimised stepped capping beam elevation profile, soldier piling, bolt sequencing and access planning. Automation of review of case specific monitoring data was explored. The benefit of this approach is to increase efficiency of reviews when encountering more complex ground conditions.

7 ACKNOWLEDGEMENTS

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