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Reducing cost and carbon emissions through rapid design optimisation during construction.

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ABSTRACT: Major excavations are often designed in the face of considerable geotechnical uncertainty. During the design phase, limited site data and conservative assumptions on the expected geology and geotechnical parameters are typically used to manage this uncertainty. However, as construction progresses and site conditions are observed, much of this uncertainty is reduced. The Observational Method (OM) is a structured framework that takes advantage of this evolving understanding by enabling real-time design optimisation based on actual performance. This paper presents a retrospective case study using machine learning back-analysis platform DAARWIN to investigate how the OM could have optimised ground support for a deep station box excavation. By integrating monitoring data with automated model calibration, the study captures how the evolving understanding of the geological conditions could have enabled design optimisation in real time. Estimated benefits include ~\$8 million in cost savings, ~2 weeks in program acceleration, and 120 tonnes of CO_2 avoided. These represent the opportunity cost of not implementing an observation-led approach. The paper concludes by addressing institutional barriers to broader OM adoption.

1 INTRODUCTION

The Observational Method (OM) is widely recognised as a tool for managing geotechnical uncertainty, yet its full potential remains underutilised in modern infrastructure delivery, particularly in its full framework. While contingency-based triggers are commonly employed to address adverse outcomes, the opportunity to optimise designs through progressive modification is seldom realised. This paper explores what could have been achieved had the OM been fully implemented during the excavation of The Bays Station Box, a structure within the Sydney Metro West project. Using DAARWIN, a cloud-based back-analysis platform, we conducted a retrospective analysis of construction-phase monitoring data to identify missed opportunities for design refinement. The aim is not to critique past decisions, but to illustrate how real-time digital tools can enable performance-driven optimisation, improving cost, carbon, and program outcomes. In doing so, we highlight the practical, institutional, and contractual barriers that currently limit OM adoption—and point to a pathway forward.

2 OBSERVATIONAL METHOD

2.1 *Background*

Designing deep excavations in urban environments often involves limited geological information, requiring conservative assumptions about stratigraphy, strength parameters, and hydrogeology. However, knowledge gained during construction provides an opportunity to refine this understanding based on direct and indirect geological observations. The OM is a structured process for managing uncertainty by integrating prediction, monitoring, and adaptive decision-making during construction. Originally formalised by Karl Terzaghi and Ralph Peck (Peck 1969) and later adopted into guidance such as CIRIA 185 (Nicholson et al., 1999) and Eurocode 7 (CEN, 2004), the OM provides a feedback loop between design and observed performance. Rather than relying solely on conservative assumptions, it involves establishing a working design based on moderately conservative conditions, defining acceptable limits of behaviour, and preparing pre-agreed design modifications that can be triggered in response to monitored ground and structural behaviour. The intent is not to design by improvisation, but to enable data-driven refinement in real time—enhancing safety, efficiency, and confidence as the project progresses.

2.2 *On why the observational method remains underused*

Despite its reputation as one of the most elegant frameworks for managing geotechnical uncertainty, the OM remains underutilised in contemporary practice. This underuse is not due to a lack of theoretical support, indeed, the OM has been celebrated by generations of engineers, as much as it is due to a confluence of practical, institutional, and psychological barriers.

First, contractual, and procedural rigidity prevents flexible design updates during construction. Public projects require certified designs before construction begins, and any changes must pass through formal approval gates. The design change process is lengthy and slow (weeks to months) for modest changes. This structure is fundamentally at odds with OM's core requirement: the ability to adapt the design based on monitored performance.

Second, the OM suffers from misconceptions. It is often misunderstood as a reactive or improvised method, used only when a project has gone wrong (Liew et al 2023). This leads to resistance from stakeholders who perceive it as less rigorous than conventional design. There is also an unfair association between the OM and higher levels of risk (Powderham 2002).

Third, there is a strong desire for certainty, particularly among client organisations. As discussed by Machiels et al. (2021) and Powderham and O'Brien (2020) uncertainty avoidance is a deeply rooted behavioural bias. Kahneman and Tversky's (1974) Prospect Theory explains why individuals prefer fixed, deterministic designs, even when flexible alternatives may offer better outcomes. In this context, OM's adaptive nature is often seen as a risk rather than an advantage.

Finally, there is a perception that OM relies on engineering judgement more than conventional design, which some view as subjective or fallible (HSE, 1996). This discomfort, coupled with a lack of clear guidance on when and how OM should be applied, often leads to its exclusion from the design process altogether. Together, these factors create a systemic bias against the OM, not because it is ineffective, but because it challenges entrenched norms in project delivery.

2.3 *Progressive modification*

Progressive modification refers to making design improvements, typically by relaxing initial conservatism, as uncertainty is reduced through observations. As shown in Figure 1, current practice often involves setting traffic-light style thresholds to detect when behaviour deviates from expectations, enabling intervention via contingency actions. However, the reverse is rarely performed: when monitored behaviour confirms conditions to be better than the conservative assumptions, the design is seldom adjusted to be more efficient. This is a missed opportunity for economic optimisation, noting that early applications of progressive modification can lead to safe, staged relaxation of support schemes during construction based on actual performance.

2.4 *The impact on structural safety*

A central challenge in applying the OM is how to transparently demonstrate its impact on structural safety. How does the 'factor of safety' or probability of failure of a structure change during an application of the OM? Recent research has explored this question through the lens of reliability-based design, with contributions from Johansson et al. (2016), Spross and Johansson (2017), Bjureland et al. (2017), and Spross and Gasch (2019). In geotechnical engineering, as in other structural domains, design adequacy is typically justified through the inclusion of safety margins, usually quantified via deterministic approaches. However, as noted by Lacasse and Nadim (1998), and Duncan and Sleep (2015), when uncertainty is significant, deterministic methods can obscure the actual level of safety being achieved, making them a poor medium for communicating risk.

As demonstrated in Roper et al (2024) when framed probabilistically, sceptics might incorrectly interpret the OM as narrowing the margin between load and capacity, thereby increasing the probability of failure (Figure 2A). OM enhances safety through two distinct mechanisms.

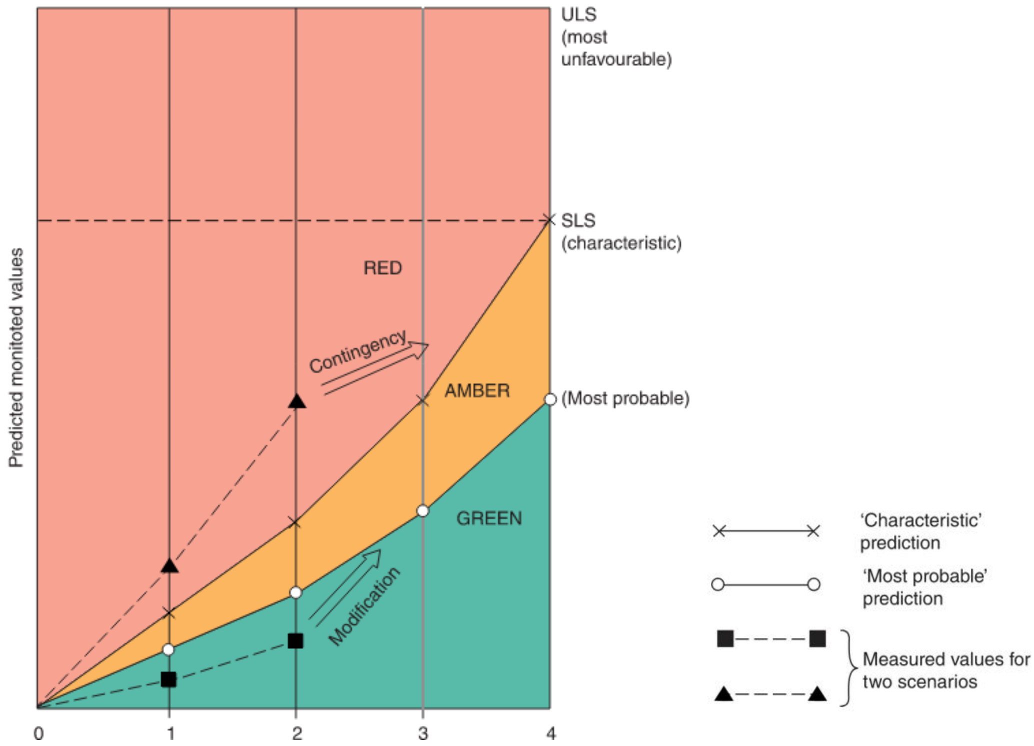

Figure 1 Multi-stage construction trigger values and modification (after Patel 2023)

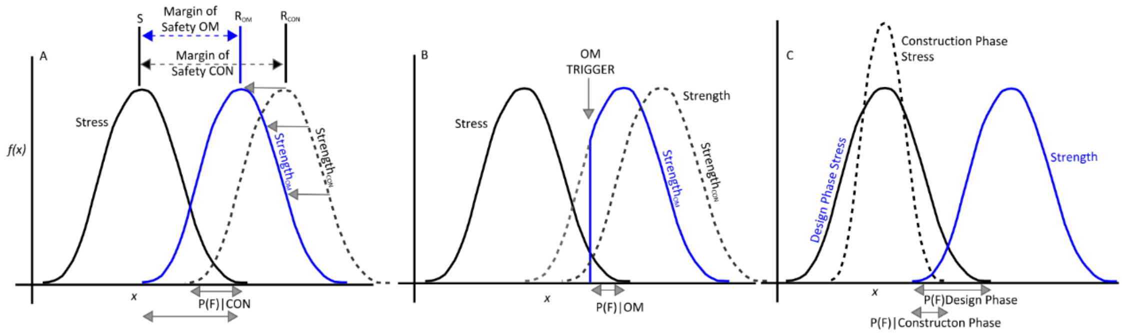

Figure 2 The impact of the observational method using strength-stress-interference (after Roper et al., 2024) where CON= Conventional approach, OM = Observational method approach.

First, the use of monitoring 'triggers' introduces predefined interventions (Figure 2B), which effectively remove the lower tail of possible outcomes by activating contingency measures as needed. Second, uncertainty itself is progressively reduced during construction, as field observations and monitoring refine the understanding of geotechnical conditions (Figure 2C).

2.5 *Aim of this paper*

Construction in Australia has a productivity crisis and geotechnical engineers must explore new strategies to help address this challenge. Unlocking the potential of the OM is one such strategy, but doing so requires more than sound design. It demands appropriate contractual frameworks, a clear communication of its impact on structural safety, cultural shifts within the industry, and tools that enable rapid, evidence-based decision-making. This article contributes to this challenge by demonstrating how modern digital technologies, specifically DAARWIN, can enable timely design optimisation as uncertainty is progressively reduced. A recently constructed station box on the Sydney Metro West project is used as the vehicle for this investigation, specifically, the analysis focuses on the progressive modification of the design (Fig 1), taking advantage of the reduced uncertainty through construction phase data.

3 RETROSPECTIVE CASE STUDY

3.1 *Geological and design context*

The retrospective case study presented in this paper is based on the excavation of The Bays Station Box, one of five new metro stations constructed as part of the Sydney Metro West – Central Tunnelling Package. The excavation is substantial in both scale and complexity, measuring approximately 230 metres long, 25 metres wide, and 32 metres deep (Figure 3). The site is in a low-lying area approximately 4 to 5 metres above sea level, with challenging geological and hydrogeological conditions. The ground profile consists of approximately 4 metres of reclaimed landfill, underlain by up to 20 metres of Holocene and Pleistocene alluvium, comprising interbedded clays and sands. Beneath this, the excavation intercepts Hawkesbury Sandstone.

Figure 3 The Bays Station Box looking west.

In the original design, characteristic soil parameters were selected to conservatively represent the ground conditions, typically corresponding to the lower bound of tested values—around the 80-90th percentile for strength and stiffness. This approach is standard practice in geotechnical engineering to manage uncertainty during early design phases.

The high groundwater table imposed significant hydrostatic loading on the excavation support system, necessitating robust structural and waterproofing measures. The temporary retention system adopted was an anchored secant pile wall (SPW) with toe embedment into the underlying sandstone. The SPW was supported by multiple rows of active ground anchors, ranging from five rows at the deeper western end to two rows at the shallower eastern extent. At the western end, the anchors comprised 19-strand post-tensioned systems, with the longest anchors extending up to 60 metres in length to achieve the required rock embedment. Detailed design description can be found in Okumusoglu and Sentry (2025). The wall was monitored with inclinometers, wells, survey prisms, and load cells on select anchors.

Following installation of the piles, capping beam, and the first row of anchors, excavation progressed in stages, pausing at each level to install the next anchor row. This staged approach (excavate > install > repeat with continuous monitoring) provided natural intervals to compare observed behaviour against design expectations (Figure 4).

3.2 *DAARWIN as tool for progressive modification during construction*

DAARWIN is a cloud-based geotechnical back analysis platform that automates the inverse modelling process by combining high-performance computing with machine learning optimisation.

Specifically, it integrates field monitoring data (e.g., inclinometers, strain gauges, prisms) with numerical simulations in Plaxis to iteratively calibrate soil parameters through genetic algorithms. The core of the process is the minimisation of an objective function, defined as the discrepancy between predicted and observed ground behaviour. By systematically adjusting parameters such as stiffness modulus, cohesion, friction angle etc, DAARWIN identifies best-fit soil models that replicate site behaviour with high fidelity. A complete description of the methodology can be found in de Santos (2015).

Each back analysis run deploys up to 200 parallel simulations in a cloud environment, enabling the rapid evaluation of thousands of models in a fraction of the time traditional methods require. This functionality enables the OM to be applied proactively during construction, supporting real-time decisions and progressive optimisation of design. This approach that has been successfully demonstrated in deep excavation case studies; Cordoni et al (2024) and Liew et al (2023).

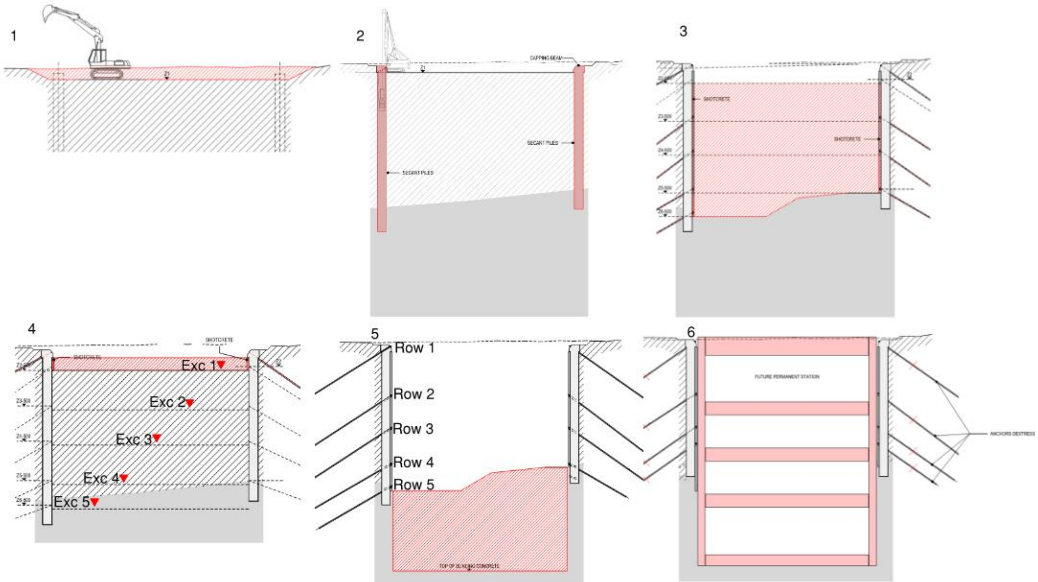

Figure 4 The Bays Station Box construction sequence.

3.3 *Methodology - Implementation of Back-Analysis Framework*

The methodology was as follows,

1. Construction and monitoring: Following the excavation down to anchor row 3, prior to installation of the anchors, inclinometer data are used to show the response of the retaining wall. We then simulate how the OM could have been used to optimise the following rows of anchors.
2. Data selection and model calibration: Using monitoring data from inclinometers at excavation stage 3, we performed a back-analysis of soil behaviour. Thousands of Plaxis models were generated in DAARWIN and soil parameters calibrated to match observation.
3. Design parameter testing: Using the best-matching calibrated model, key design variables (anchor stiffness and spacing) were systematically adjusted to assess the feasibility and impact of progressive optimisation. A simplified design criteria was selected, max horizontal deflection ($U_{x,max}$) of 40mm to ensure the outcome does not exceed that of the original design.
4. Quantification of outcomes: Translate the design optimisation in to cost, program, and carbon savings.

The analysis centred on a back analysis of monitoring data collected during excavation Stage 3. Figure 5A shows the difference between the original design model outcome for horizontal deflection and the inclinometer data. Over 3,000 Plaxis models were generated in parallel across cloud computing environments to iteratively calibrate soil parameters—including stiffness modulus (E') and cohesion (c')—to best match the observed ground movements.

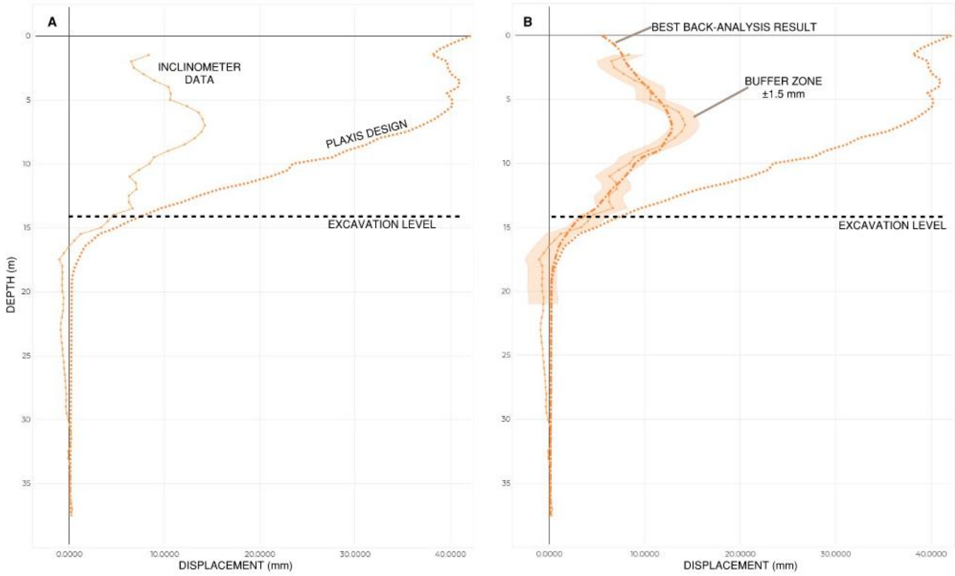

Figure 5 – Inclinometer data versus design. Figure 5A shows the comparison between the inclinometer data (solid line with points) and the original Plaxis model response (dashed line) at Excavation 3. Figure 5B shows the best individual model iteration (dashed line with points) can match the inclinometer data. The buffer indicates the data selected for the analysis. In this case, we defined the buffer width as ±1.5 mm around the monitoring data. The buffer width defines the “good” simulated cases, that is, simulations that match at least 80% of their response within the buffer.

The back-analysis confirmed that the original soil parameters adopted in the design could be improved with the benefit of new information. Specifically, the clayey sand layers, which had been modelled as loose to medium dense, were found through inverse analysis to behave as medium dense to dense granular materials, exhibiting significantly higher stiffness moduli (E') than previously assumed. Similarly, the loose clayey sand layers, initially assumed to be cohesionless, displayed behaviour consistent with dense, partially cemented sands, with apparent cohesion values reaching up to 30 kPa. The back-analysis, calibrated using monitoring data within DAARWIN, provided a more representative picture of actual ground behaviour, revealing that the soils were denser and stiffer than assumed. This refined understanding offers clear justification for design optimisation, where parameters can be updated during construction as uncertainty is progressively reduced. The implications of these adjustments are explored in the sensitivity analysis shown in Figure 6.

Following calibration, we conducted a sensitivity analysis to evaluate the influence of different anchor design parameters on wall displacements, with particular focus on row 3 (S3) and row 4 (S4) anchors as these were significant for consumable quantities. Design variables tested included anchor stiffness and spacing. The model used for this assessment was based on averaged parameters from the top 20 best-matching simulations. Only one parameter was modified at a time to preserve clarity around its individual influence. The results are shown in Figure 6.

3.4 *Results and implementation of optimisation*

The back-analysis conducted using DAARWIN identified several feasible optimisation opportunities for the ground anchor system in The Bays Station Box, without compromising the original deflection performance criteria. The scenarios explored were:

- Reducing anchor capacity in either Row 3 or Row 4 by lowering the number of strands per anchor.
- Doubling the anchor spacing in Row 3 from 1.5 m to 3 m.

In contrast, increasing the anchor spacing in Row 4 was found to have a significant negative impact on wall deflection and was therefore deemed non-viable (Figure 6D). Row 3 presented the greatest opportunity for optimisation. With over 200 anchors, each up to 30m long and originally designed with 15 strands, even modest changes led to substantial material, cost, program, and carbon saving. These scenarios, optimisation options, are summarised below. Table 1 presents a summary of the outcomes, including material savings, carbon emissions, and direct/indirect costs.

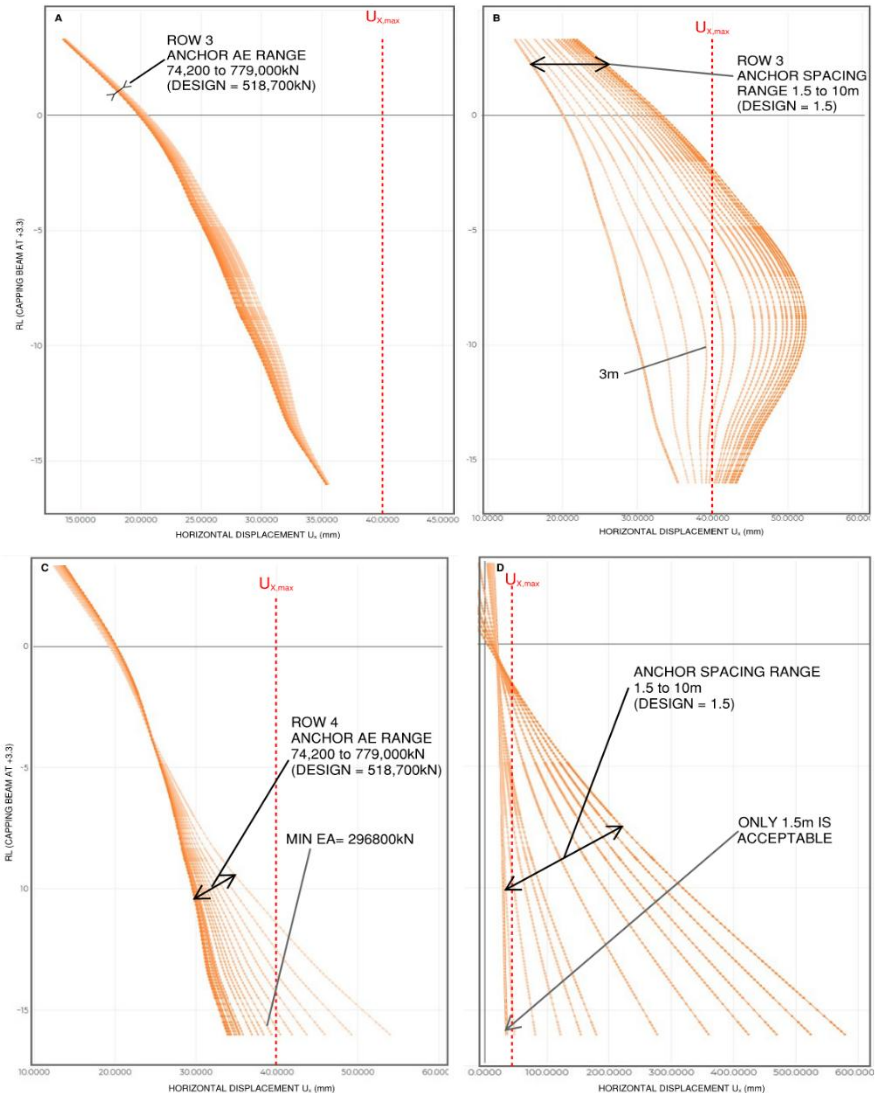

Figure 6 Horizontal displacement of the retaining wall at the final excavation stage, showing results from a sensitivity analysis of ground anchor parameters. Each plot illustrates the influence of a single variable on wall performance, with the red dashed line indicating the design displacement limit ($U_{x,max}$), set at 40mm. (A) Variation in axial stiffness (EA) of Row 3 anchors. (B) Variation in spacing of Row 3 anchors, demonstrating that up to 3 m spacing remains acceptable. (C) Variation in axial stiffness (EA) of Row 4 anchors, with a feasible minimum of 296,800kN (~10 strands). (D) Variation in spacing of Row 4 anchors, showing that only the original 1.5 m spacing satisfies deflection criteria.

1. Row 3 – Strand Reduction: Anchors reduced from 15 to 4 strands, leading to smaller drill holes (from Ø150 mm to Ø90 mm) and reduced bond length in rock (from 5 m to 3 m).
2. Row 4 – Strand Reduction: Anchors reduced from 19 to 10 strands, with drill hole diameter reduced to Ø130 mm and bond length to 4 m.
3. Row 3 – Spacing Increase: Anchor spacing increased from 1.5 m to 3 m (while keeping strand count constant), halving the total number of anchors.

Table 1 Ground anchor quantities in the original design and revised design and the impact of cost, carbon, and program.

OPTION	ROW	NO. ANCHORS	SUM OF TOTAL STRAND LENGTH (KM)	TOTAL STEEL (T)	GROUT (T)	CO_2 SAVING (T)*	DIRECT COST SAVING **	INDIRECT COST**	PROGRAM
1	3	213	65.7 → 14.5 **(Δ = -51.2)**	91 → 20 **(Δ = -71)**	49 → 16 **(Δ = -33)**	120	~$0.35 M	~$1.7 M	~3-4 days
2	4	162	32.6 → 15.2 **(Δ = -17.4)**	44 → 20 **(Δ = -24)**	20 → 14 **(Δ = -6)**	41.4	~$0.15 M	~0.6 M	~2 days
3	3	**213 → 107 (Δ = -106)**	65.7 → 33.3 **(Δ = -32.7)**	91 → 45.5 **(Δ = -45.5)**	49 → 24 **(Δ = -25)**	79.9	$~1.3 M	> 6.5 M	~2 weeks

*CO_2 savings calculated using emission factors of 1.7 tCO_2/t steel and 0.1 tCO_2/t grout.

** The cost figures ($AUD 2024) are indicative only and were developed with input from industry professionals.

While the material cost of post-tensioned strand is modest (~$3.30/m), the most significant benefits of optimisation stem from indirect efficiencies. Lighter and shorter anchors are easier to handle, allowing multiple units to be transported on a single reel and installed with less manual effort. Smaller drill holes reduce grout consumption and spoil volumes, while faster drilling and grouting cycles improve installation productivity. Collectively, these improvements help to streamline construction sequencing and reduce the likelihood of delays caused by bottlenecks in anchor installation.

Option 3, doubling the spacing of Row 3 anchors, offers the most substantial potential savings across all metrics ($1.3M direct + $6.5M indirect). However, this scenario would require more extensive structural verification. Reducing the number of ground anchors places greater reliance on the stiffness and capacity of the secant pile wall, which may necessitate supplementary support such as temporary walers. While walers are quicker to install than long ground anchors, the trade-off between material costs, installation speed, and constructability would need to be evaluated.

From a delivery perspective, program gains are particularly valuable. On major public infrastructure projects, delays can attract liquidated damages in the order of AUD$1 million per day. A modest reduction in ground anchors can translate into 1–2 weeks of program savings, representing a significant financial benefit well beyond the material cost savings alone. Moreover, the embedded carbon savings are meaningful, 120t with option 1 is an outcome to be proud of.

4 DISCUSSION AND CONCLUSIONS

Limitations of the study: It is important to acknowledge that the modelling conducted for this study is deliberately limited in scope. For example, changes to anchor capacity were assessed within the bounds of the Plaxis model only and were not followed by detailed structural checks on pile behaviour, reinforcement design, or load redistribution.

Practical considerations and constraints: Chief among the practical considerations is the sequencing of construction and procurement activities. For example, ground anchors are typically pre-ordered with long lead times, sometimes weeks in advance, even in major cities where local production may be available. Practitioners must weigh these practical 'nuisance costs' (as defined in Roper and Karlovšek, 2023) specific to their project when deciding whether and how to implement the OM.

The economics of the OM: One of the prerequisites when deciding to use the OM is that there must be a business case (Powderham and O'Brien 2020). Roper and Karlovšek (2023) and Roper et al. (2024) explore the nuance of this economical decision and proposed a structured decision-making framework grounded in Expected Utility (EU) theory, which provides a rational economic basis for adopting the OM before construction begins. Crucially, this economic framing enables stakeholder to understand the benefit of the OM: it allows for estimation of potential savings under different ground conditions before construction starts. Instead of hoping that value will emerge reactively, the framework enables design teams to assess—ex ante—the expected value of adaptability. This not only strengthens the business case for OM but also provides a means of navigating contractual discussions, where value engineering or early contractor involvement mechanisms might be needed to realise shared benefits. By embedding the OM within a rational economic model, engineers can better align it with project goals, client preferences, and broader sustainability objectives.

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