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Adaptive Risk Management for Soft-Soil Bridge Foundations: Application of a Performance-Based Framework on the Boorloo Bridges Project

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ABSTRACT: This paper presents an adaptive, performance-based risk management framework for geotechnical infrastructure founded on soft soils, integrating principles from established ISO 31000:2018, AGS (2007), and BS EN 1997-1:2004 guidelines into a unified, phase-independent workflow. A five-step workflow was developed and applied to the Boorloo Bridges in Perth, Western Australia – a complex project featuring deep paleochannels, strict performance limits, and cultural constraints. During design, performance-based triggers enabled early adaptation of optimised foundation and ground improvement solutions. During construction, the workflow accommodated sequencing deviations and unexpected subsurface anomalies through real-time verification and targeted model updates. These applications show the framework's ability to support adaptive design and real-time risk treatment across project stages.

KEYWORDS: Adaptive risk management, performance-based design, observational method, soft soil.

1 INTRODUCTION

Major civil infrastructure projects – such as metro tunnels, port expansions, and especially bridges founded on soft soils – are typically constrained by tight cost and schedule targets alongside high geotechnical uncertainties. Designers must satisfy stringent deformation requirements while relying on evolving ground models informed progressively by site investigations, laboratory data, and construction observations. Deviations from assumed ground conditions require real-time reassessment, which – if delayed – can amplify schedule impacts and stakeholder tension.

Conventional geotechnical approaches typically rely on static risk registers, which address known-knowns (measured parameters) and apply conservative assumptions for known-unknowns (e.g., expected ground variability, parameter bounds or ultimate designs) but seldom (and can't) accommodate the unknown-unknowns (unforeseen conditions or latent hazards) that often manifest during construction. As infrastructure is delivered under increasingly compressed timeline and heightened accountability, there is a growing need for risk systems that are not only structured but also dynamic and responsive in nature.

This paper applies an adaptive, performance-based risk management framework that essentially integrates core principles from ISO 31000:2018, AGS (2007), and BS EN 1997-1:2004 into a unified, phase-independent workflow. The framework is structured around five-steps – context definition, hazard identification, acceptance evaluation, and monitoring – supported by performance-based triggers and observational feedback loops to provide a repeatable, auditable process for managing evolving risks and aligning responses with project-specific performance criteria.

2 ADAPTIVE PERFORMANCE-BASED FRAMEWORK

To manage geotechnical risks that evolve throughout a project's lifecycle, this study adopts an adaptive, performance-based risk management framework that integrates principles from ISO 31000:2018, AGS (2007) guidelines, and the Observational Method as defined in BS EN 1997-1:2004. The proposed framework systematically links risk identification, performance criteria, and adaptive controls within a five-step, closed-loop workflow suitable for both design and construction phases.

As illustrated in Figure 1, the five-step workflow comprises:

1. Define Context & Risk Appetite – Establish technical objectives, serviceability and durability requirements (e.g. settlement limits, construction sequencing), stakeholder roles, and tolerable risk levels.
2. Identify, Prioritise & Assess Hazards – Compile a project-specific hazard register informed by desk studies, geotechnical investigations, and interdisciplinary workshops. Each hazard is rated based on likelihood and consequence.
3. Evaluate against Acceptance Criteria – Assess each residual risk against the defined risk appetite and threshold values. If risks are tolerable, no further action is required; otherwise, move to intervention measures.
4. Adapt Controls or Designs – Implement pre-defined mitigation actions, such as design modifications/check, sequencing changes, or enhanced monitoring, as part of a staged or responsive risk treatment framework.
5. Monitor and Verify (adaptive loop) – Use field instrumentation, visual inspections, and Bayesian or observational feedback to track system behaviour. When performance deviates from expectations, the workflow loops back to Step 2 for hazard re-evaluation and iterative refinement.

This structured loop supports evidence-based, real-time decision-making, enabling early interventions, reducing rework, and aligning technical actions with defined performance objectives. Crucially, it avoids rigid adherence to static assumptions and allows risks to be dynamically managed as new data emerge, whether during investigation, detailed design, or construction execution.

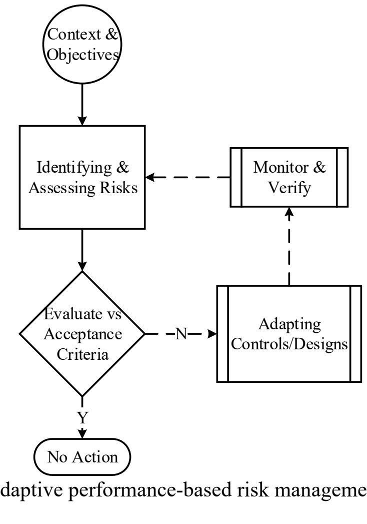

Figure 1. Adaptive performance-based risk management framework.

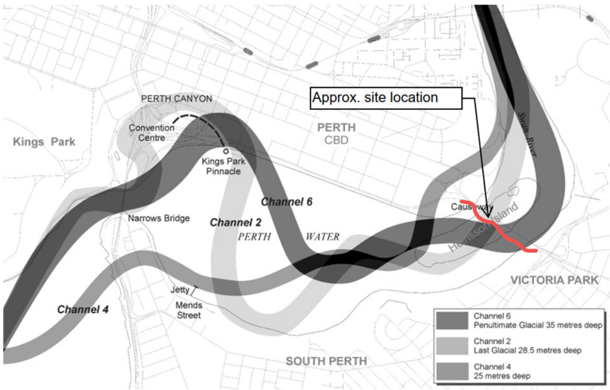

Figure 2. Location of Paleochannels (Gordon, 2003).

3 PROJECT CONTEXT

To evaluate the proposed adaptive, performance-based framework across all stages of geotechnical risk management, the method was applied to the Causeway Pedestrian and Cyclist Bridges (also known as the Boorloo Bridges) – a major infrastructure project completed in December 2024 in Perth, Western Australia. This twin cable-stayed structure provides a segregated pedestrian and cyclist crossing between Point Fraser and McCallum Park, traversing Heirisson Island. The site, of cultural significance to the Whadjuk Noongar people, lies within a dense urban corridor and presents challenges including variable soil conditions, deep paleochannels, cultural constraints, and complex settlement behaviour. These were compounded by stringent performance requirements, particularly limits on post-construction settlement and lateral displacement to ensure the long-term integrity of shared paths and approach embankments.

Stakeholders – including the client, consultants, contractors, and Whadjuk Noongar representatives – were engaged throughout planning, design, and delivery. A shared risk appetite was developed through interdisciplinary workshops and reflected in performance specifications. Project-specific criteria encompassed deformation limits, durability targets for marine-exposed substructures, and construction constraints in culturally sensitive areas. These formed the basis for risk prioritisation, evaluation, and action across the project lifecycle.

3.1 *Geotechnical hazard identification*

The project alignment traverses reclaimed land formed by historical filling activities, situated on the flat topography of the Swan Coastal Plain, with ground surface levels ranging between RL 0.4 m and 3.0 m AHD. Subsurface conditions, however, are governed by a complex stratigraphy comprising unconsolidated Holocene sediments, including the Swan River Alluvium (SRA), underlain by Pleistocene deposits of Perth Formation (PF), and deeper lithified strata such as the Mullaloo Sandstone and Kardinya Shale Members.

A key geotechnical feature is the presence of two major paleochannels – Channel 2 (East Perth) and Channel 6 (Victoria Park), eroded into the Kings Park (KPF) and Osborne Formations (OF) (Figure 2). These channels are infilled with heterogeneous materials from the Swan River and Perth Formations, with thalwegs inferred at ~26 m and ~35 m depth, respectively. Their geometry remains partly speculative due to data limitations.

Consequently, subsurface conditions vary markedly across the alignment. As depicted in Figure 3, at Point Fraser, thick deposits of compressible SRA with interbedded sand, silt, and clay presented challenges in terms of settlement and short-term stability, although no paleochannels were present. Heirisson Island, centrally located above both paleochannels, featured complex stratigraphy and was subject to significant cultural restrictions, precluding intrusive ground improvement. In contrast, McCallum Park exhibited a thinning SRA layer and more abrupt transitions between the Kings Park and Osborne Formations, offering relatively better ground conditions but still requiring location-specific design considerations. These spatial variations in stratigraphy were used to establish the initial hazard register, which underpinned the risk assessment and prioritisation process.

3.2 *Acceptance criteria*

The piling system was designed to address both structural performance and long-term durability in a corrosive marine environment. Hollow steel tubes were utilised as sacrificial formwork to protect the primary reinforced concrete piles from corrosion. Continuous flight auger (CFA) piles were considered for the bridge foundation to comply with project requirements and maintain quality control. The design accounted for subsurface variability, liquefaction potential, construction constraints arising from available pilling rigs, and anticipated lateral soil movements near abutments.

For ground improvement works, the approach embankments were required to meet defined settlement, deformation, and stability limits to ensure long-term serviceability of shared-use paths and bridge approaches. As outlined in the project's Basis of Design and Construction (BDC), vertical settlements were limited to 200 mm at five years and 400 mm at 40 years post-construction. Correspondingly, horizontal displacements were restricted to 100 mm and 200 mm at the same respective timeframes. Differential settlement between piled abutments and adjacent embankments was constrained to a maximum ratio of 1:100. Global stability requirements included minimum factors of safety of 1.25 for temporary conditions under a 10 kPa static live load, 1.35 for permanent load cases, and 1.1 under pseudo-static conditions. These criteria governed both design validation and construction-stage monitoring, forming the basis for compliance assessment and adaptive response as part of the proposed framework.

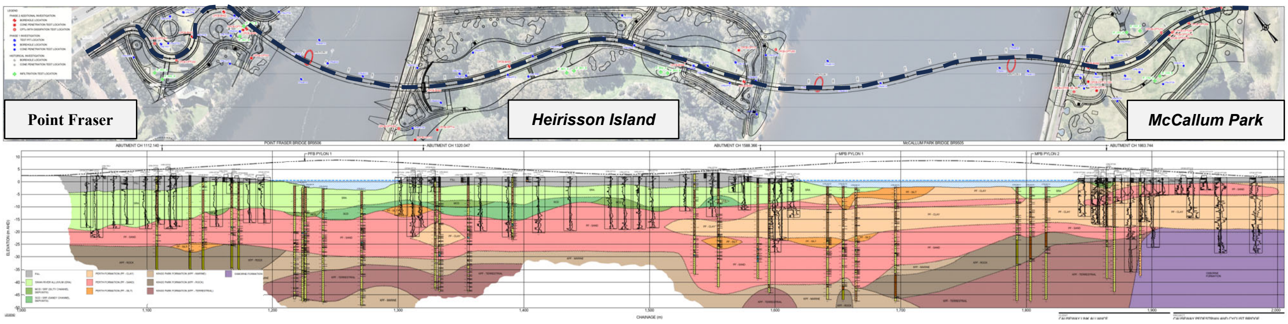

Figure 3. Inferred subsurface profile along bridge centreline (crossing from Point Fraser to McCallum Park over Heirisson Island at midspan).

4 DESIGN-PHASE APPLICATION OF WORKFLOW

Design-phase implementation of the proposed adaptive framework focused on managing two primary risks among others, identified early in the project: (i) variable ground conditions – arising from complex soil profiles, paleochannel geometry, and abrupt formation transitions, and (ii) construction schedule constraints – driven by tight programme requirements and rest-period demands for ground improvement. These risks were addressed through performance-based decision criteria and adaptive design responses, in alignment with the five-step framework.

4.1 *Managing variable ground conditions*

The geotechnical profile across the site exhibited significant variability, including shallow to deep soft compressible soils, interbedded sand–silt–clay layers of varying stiffness, and abrupt transitions between geological formations. These characteristics were identified during Step 2 of the adaptive workflow and evaluated through a structured hazard register.

To address both known heterogeneity and potential unknowns, the foundation and ground improvement design was developed to be robust and adaptable, in line with Step 3 of the workflow. The piling design incorporated fully grouted steel tubes acting as sacrificial formwork to ensure marine durability, and reinforced bored piles sized to accommodate site-specific axial and lateral demands.

Ground improvement behind abutments combined Controlled Modulus Columns (CMCs) with surcharging or preloading techniques, applied with or without Prefabricated Vertical Drains (PVDs), depending on the location and ground response. The final pile configurations (Table 1) and hybrid ground improvement layout (Figure 4) were tailored to site-specific conditions and reflect a performance-based design approach developed through continuous risk evaluation against settlement and lateral movement criteria.

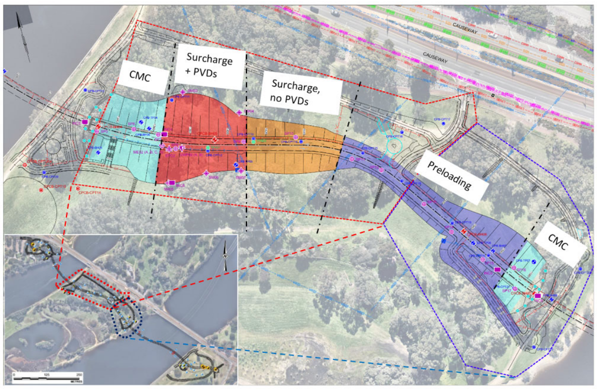

Figure 4. Typical ground improvement layout at Heirisson Island (adapted from Duong and Tan, 2026).

Table 1. Summary of foundation design solutions.

Bridge	Structure	Pile Configuration
Point Fraser (PFB)	Abutment 1	2 x 1200 mm dia. bored piles
	Pier 1	1 x 1200 mm dia. bored pile
	Pier 2	1 x 1200 mm dia. bored pile
	Pier 3	4 x 1200 mm dia. bored piles
	Pylon 1	6 x 1200 mm OD x 20 mm (*)
	Abutment 1	8 x 900 mm diam. Bored piles
	Abutment 2	4 x 1050 mm dia. bored piles & 6 x 900 mm dia. bored piles
McCallum Park (MPB)	Pylon 1	6 x 1200 mm OD x 20 mm wall thickness (*)
	Pylon 2	6 x 1200 mm OD x 20 mm wall thickness (*)
	Abutment 2	8 x 900 mm dia. bored piles

* Close ended steel tubes with concrete infill.

4.2 *Adapting construction schedule constraints*

The construction sequence constraint was identified early in the design phase as a high-risk item. Table 2 summarises the structured risk assessment and the adaptive design strategy implemented in accordance with the proposed five-step framework. The original 'linear' construction sequence developed during the tender stage – requiring fully surcharging prior to CMC installation and piling – posed unacceptable risks to the project timeline. If implemented, critical-path activities would have been delayed by up to three months. Under the adaptive performance-based framework, this schedule risk was identified early (Steps 1–2) and evaluated as exceeding the defined project risk appetite (Step 3).

In response, a Step 4 adaptation was implemented through an innovative parallel construction sequence, allowing surcharge placement to proceed concurrently with foundation works. As a result, CMCs were pre-installed with tolerance for intentional flexural cracking induced by lateral soil movement from surcharging (Duong and Tan, 2026). This approach addressed the schedule risk on the premise that the CMCs would maintain axial stiffness, despite undergoing significant bending deformation, with cracking anticipated at a later stage as a result. The underlying hypothesis of intentionally cracked CMCs could still function as settlement reducers to satisfy total and differential settlement criteria along the alignment – was validated through BM-N envelope checks (Steps 4 and 5). To enhance robustness, selected CMCs were reinforced with a single vertical bar to reduce the risk of column dislocation.

A comparison of the original and optimised sequences is shown in Figure 5, suggesting a construction time saving of approximately 2–3 months achieved through parallel execution and targeted design adaptation. These outcomes, together with structured risk reviews at each gate, demonstrate the practical application of the five-step adaptive workflow introduced in Section 2.

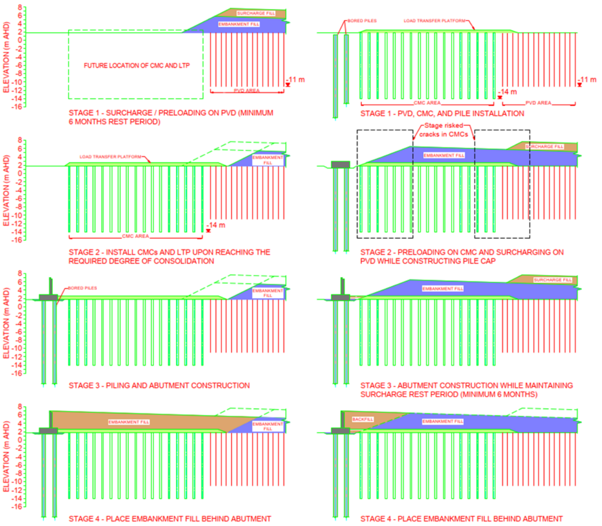

Figure 5. Comparison of the conventional 'linear' installation sequence (Left) and the optimised (Right), parallel sequencing with cracked-CMC tolerance (adapted from Duong and Tan, 2026).

Table 2. Risk assessment and adaptive response for construction sequence constraint – Design and construction phase

Phase	Step	Assessment Element	Details
Design	Step 1 – Context & Criteria	Technical objectives	Ensure construction proceeds within the constrained timeframe while minimising impacts on existing structures.
	Step 2 – Hazard Identification	Hazards	A rigid linear construction sequence incompatible with the varying requirements of preloading/surcharging scheme, ground improvement (CMCs), and piling activities.
	Step 3 – Risk Evaluation	Likelihood: *Possible* Consequence: *Major* Risk Rating: *High*	Linear construction sequence risking critical path delays by up to 6 months.
	Step 4 – Adaptation	Performance-based design	Re-sequencing: A parallel construction strategy was adopted, allowing CMCs to be installed prior to full surcharging. CMCs were allowed to crack under controlled bending while maintaining axial stiffness.
	Step 5 – Verification	FEM modelling	Design verified using BM–N envelope checks and FEM modelling; the intentional cracking scenario was shown to satisfy settlement and structural performance targets.
Construction	Step 1 – Updated Context	Execution constraints	Equipment access and material delays caused divergence from planned sequencing.
	Step 2 – Emerging Hazard	On-site changes	On-site deviations led to out-of-sequence execution of surcharge placement and foundation works.
	Step 3 – Re-evaluation	Likelihood: *Likely* Consequence: *Moderate* Risk Rating: *High*	Changes in the construction sequence may result in loading that exceeds the structural capacity of unreinforced CMCs.
	Step 4 – Responsive Adaptation	Live model update	Revised PLAXIS 3D model implemented with updated loading and construction stages.
	Step 5 – Real-Time Monitoring	Envelope check and instrumentation	Some unreinforced CMCs (e.g., L7 to L12) exceeded BM–N capacities but retained axial stiffness. Instrumentation confirmed total and differential settlements remained within allowable thresholds.

5 CONSTRUCTION-PHASE ADAPTATION AND MONITORING

Although key geotechnical risks were identified and 'partially' mitigated during design, the construction phase introduced additional constraints and unforeseen changes, necessitating real-time reassessment. These developments highlighted the practical value of the proposed adaptive workflow, most notably in relation to Step 4 (responsive adaptation) and Step 5 (real-time verification and feedback).

5.1 *Responding to construction sequence changes*

During construction, previously unforeseen site constraints necessitated a deviation from the optimised sequence established during the design phase (Section 4.2). Table 2 summarises the structured reassessment and corresponding adaptive response, illustrating the full-cycle implementation of the proposed five-step framework under 'live' site conditions. Specifically, delays in material delivery and limited equipment access at Point Fraser Abutment 2 (Heirisson Island) disrupted the planned sequence of surcharge placement and foundation installation (Figure 6). In accordance with Step 1, this change prompted a revised contextual understanding of site conditions, including construction logistics and timeline impacts.

As part of Step 2, this revised sequence introduced a new hazard: out-of-sequence loading on pre-installed, unreinforced CMCs, exposing them to axial and flexural stresses beyond their original design envelope. In Step 3, this emerging risk was re-evaluated and classified as high, considering its likely occurrence and moderate consequence. The evaluation focused on BM–N interaction behaviour of CMCs during construction, as well as predicted settlement at both 5-year and 40-year post-construction stages.

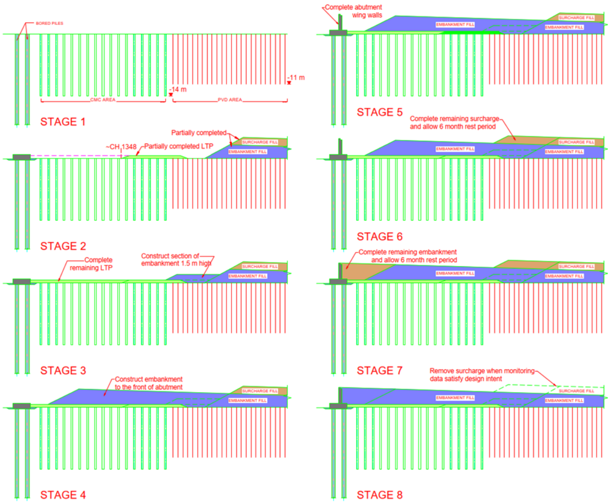

Figure 6. Actual construction sequence.

To address the revised risk scenario, Step 4 involved a real-time design adaptation, carried out in parallel with ongoing construction works. The actual staging was re-modelled in PLAXIS 3D, incorporating updated loading histories at key construction milestones (Stages 3, 4, 6, and 8). These simulations enabled direct assessment of compliance with axial load capacity and serviceability-based settlement criteria. As shown in Figure 7, recalculated BM–N envelopes confirmed that several unreinforced CMCs (e.g., CMCs L7 to L12) exceeded their original structural bounds while the predicted post-construction settlements remained within the prescribed tolerances (Figure 8).

These findings underscore the effectiveness of the cracked CMC design principles, which are embedded within the parallel construction approach, and further reinforce the flexibility of the proposed adaptive framework in managing construction-phase uncertainties through real-time model updates, performance verification, and iterative feedback between design and field execution. One key insight emerging from this experience is the critical role of proactive communication between design and construction teams. Timely exchange of field updates ensured that deviations were not passively assumed to align with the original design intent but were instead actively re-evaluated and incorporated into the adaptive process. Without this feedback loop, on-site decisions risked divergence from validated performance pathways.

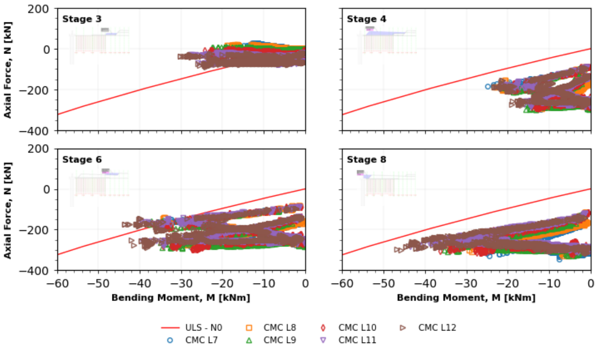

Figure 7. Predicted BM-N interaction plots for Stages 3, 4, 6 and 8.

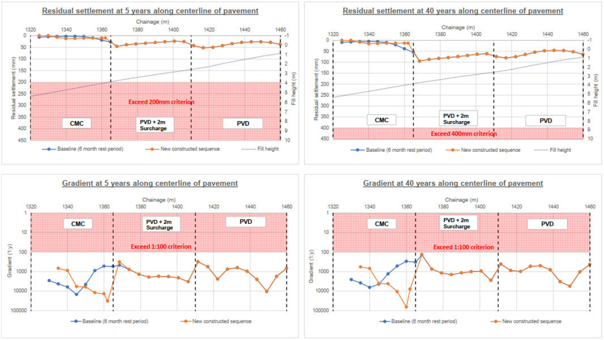

Figure 8. Predicted settlement and differential settlement profiles at 5- and 40-years post-construction.

5.2 *Reacting to unexpected ground conditions*

As introduced in Section 4.1, the project faced a recurring geotechnical challenge related to highly variable subsurface conditions. This variability became critical during pile construction at Point Fraser, where a localised anomaly in the inferred depth of the Kings Park Formation (KPF) was encountered – an unforeseen condition not indicated by adjacent borehole records. While most piles within the vicinity terminated at the expected KPF surface between RL –25 m and –28 m AHD, pile P2-1 encountered a sudden and significant drop in founding level, with KPF not encountered until RL –43 m AHD (Figure 9).

Initial drilling to RL –28.5 m resulted in uncontrolled sinkage of the Kelly bar to RL –36 m, followed by signs of cavity formation and backfill collapse at the pile base. As an immediate safety measure, the pile shaft was temporarily stabilised using cement-stabilised sand and later redrilled after sufficient curing to achieve the required embedment into the formation. The steep, cliff-like subsurface geometry was suspected to result from abrupt paleo-erosional features, possibly related to incision effects of the nearby paleochannel system (Figure 2), although the precise origin remains inconclusive due to sparse investigation data in the affected zone.

This event reflects a classic unknown–unknown scenario – a latent geotechnical hazard not predicted during design – which triggered a real-time reassessment process consistent with Step 5 of the proposed adaptive framework. In response, construction methods were adapted on site, incorporating stabilisation and staged re-drilling to mitigate immediate geotechnical risks. Additionally, the risk profile for nearby piles was revised, with contingency measures developed for zones potentially affected by similar undetected anomalies. This included targeted review of borehole data, incorporation of geological interpretation updates into the ground model, and proactive monitoring during subsequent pile installations.

To verify that the amended foundation meets geotechnical performance objectives, high-strain dynamic load testing was conducted post-construction. The results confirmed satisfactory load transfer and pile integrity, indicating that the reactive measures were effective in achieving design functionality.

This case highlights the resilience of the adaptive framework when applied under high uncertainty, particularly when unexpected geological features emerge during construction. The ability to respond rapidly, modify construction methods in the field, re-evaluate design assumptions, and validate performance through testing underscores the framework's value not only in addressing known risks, but also in managing unknowns as they emerge during construction.

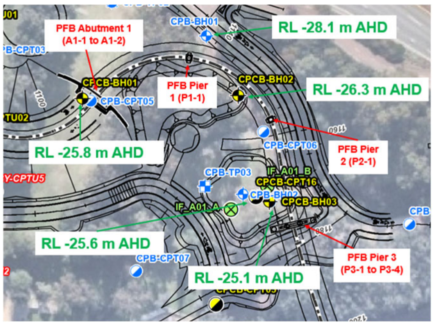

Figure 9. Inferred top of KPF level at Point Fraser bored piles.

6 DISCUSSION

6.1 *Effectiveness of the adaptive framework*

This project demonstrated how cost and schedule pressures, coupled with evolving geotechnical uncertainty, intensified at key milestones. The adaptive, performance-based risk framework applied in the Boorloo Bridges project proved effective in managing both anticipated and unforeseen conditions. Grounded in ISO 31000:2018, AGS (2007), and BS EN 1997-1:2004, the framework enabled structured yet flexible decision-making across the project lifecycle.

During design, the framework facilitated early risk identification and adaptive planning – such as the adoption of parallel construction sequencing and the design of CMCs to tolerate flexural cracking – accommodating variability without compromising performance.

During construction, the framework (with an emphasis on real-time model updates and feedback) supported effective responses to unanticipated conditions, such as deeper than expected KPF interface at Point Fraser. The ability to re-model foundation behaviour, revise sequencing, and validate through monitoring data illustrates how observational feedback was translated into engineering response. This aligns with the design-update principles of Finno and Calvello (2005) and Spross and Johansson (2017), who advocate for continual design updating based on observed performance as a means to reduce uncertainty and enhance resilience in ground engineering.

The effectiveness of the framework is further synthesised in Table 3, which generalises adaptive responses across the design and construction phases, providing a reference model for application in similarly constrained infrastructure projects.

Table 3. Generalised framework for applying adaptive, performance-based risk management across infrastructure project phases.

Scenario	Cost/Schedule Pressure	Geotechnical Uncertainty	Triggering Observation	Adaptive Response
Pre-design	Budgets fixed, limited investigation	Incomplete data/stratigraphy	Early lab data reveal unexpected variability	Step 1–2: Revise context and design basis
Design	Cost escalation, design freeze vs. value engineering	Existence of Paleochannels High compressibility	CPT / oedometer deviation BM-N envelope integration	Step 3–4: Reassess parameters, allow controlled deformation
Construction	Delay penalties, limited access, safety concerns	Cavity formation, rock 'cliff'	Drilling collapse, casing sinkage	Step 4–5: Field adaptation, model update, load testing
Post-construction	Maintenance liability, performance guarantees	Long-term settlement, creep, consolidation lag	Instrumentation shows deviation from predicted trend	Step 5: Feedback into model validation, maintenance planning, future designs

Note: Diagnostic signals and example responses are based on the Boorloo Bridges case study but structured for broader applications.

6.2 *Robustness and conditional limitations*

It is obvious that the framework's robustness lies in its structured five-step process, which links performance criteria to looped risk response. Its success in this project reflects its ability to accommodate uncertainties and variability through timely adaptation, model recalibration, and field verification.

However, several enabling conditions are essential:

- Timely risk identification: Adaptive responses rely on timely recognition of potential hazards during investigation and early design phases or construction. Delays in recognising emerging risks may close the window for low-impact interventions.
- Stakeholder collaboration: Rapid adaptation requires efficient and timely communication between design, construction, and client teams. Mechanisms such as RFIs/TQs must be supported by a shared understanding of performance criteria and risk tolerance.
- Monitoring infrastructure: Real-time or near-real-time instrumentation is essential for triggering Steps 4 and 5 of the framework. Without monitoring, the looped verification process becomes speculative.
- Analytical capability and readiness: The framework presumes the ability to update models and interpret field data within a tight delivery timeline. This requires adequate design resources and integrated digital workflows.

These conditions suggest that while the framework is technically sound, its effectiveness depends on project readiness and risk culture. Table 3 illustrates how triggers and responses can be systematised for future projects.

6.3 *Transferability and adaptation potential*

Although developed in a geotechnical infrastructure context, the framework's structure is transferable to other domains where subsurface conditions are uncertain, and design assumptions must be verified dynamically. Its staged, evidence-based nature makes it suitable for tunnelling, deep excavation, coastal works, and soft soil infrastructure projects.

In the mining sector, similar adaptive methodologies have demonstrated potential. Rice (2021) highlighted how staged risk modelling and design iteration improve value outcomes and response agility under geological uncertainty. While adaptive frameworks are also used in areas such as flood management and climate-sensitive infrastructure (Hochrainer-Stigler et al., 2021), they often remain strategic in nature. In contrast, the proposed framework offers operational clarity – specifying trigger conditions, modelling procedures, and field verification steps.

The Boorloo case illustrates that adaptive risk management need not remain theoretical or strategic. It can be embedded into routine project delivery, provided that performance criteria, response triggers, and verification protocols are clearly defined.

7 CONCLUSIONS

The adaptive, performance-based risk management framework presented in this study offers a structured yet flexible method for managing both anticipated and unforeseen geotechnical risks. Its application to a bridge project demonstrated how integrating design criteria, observational thresholds, and real-time verification supports timely, evidence-based decisions. The framework enabled adaptive design, construction-phase response, and compliance with performance targets under evolving site conditions. Its staged and operational nature makes it transferable to other complex infrastructure projects facing ground variability and delivery constraints, offering a robust pathway for risk-informed decision-making across project phases.

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