Integrated Ground Risk Management and Observational Design Approach for the Exploratory Tunnels of the Borumba Pumped Hydroelectric Energy Storage (PHES) Project

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Abstract

The Borumba Pumped Hydroelectric Energy Storage (PHES) project's Exploratory Tunnels face challenges due to limited geotechnical information and ground subsurface uncertainties. To manage these challenges, Queensland Hydro (QH) adopted a flexible and collaborative contractual framework for tunnel procurement and delivery. The contract, based on the NEC4 Engineering and Construction Contract (ECC) with use of a Bill of Quantities (BoQ) to facilitate effective risk management and equitable allocation of geotechnical risks between the Client and Contractor. This paper outlines the integrated ground risk management process developed to support the technical and contractual delivery of these tunnels, incorporating an observational geotechnical design approach.

Keywords: Pump storage hydro, Geotechnical risk allocation, Observational method, Ground risk management, NEC4 ECC.

1.0 Project Overview and Context

The Borumba PHES is a proposed 2000 MW pumped hydro energy storage system to be located at Lake Borumba, south-west of Gympie in Queensland, Australia. The project, owned and developed by Queensland Hydro (QH), entails the construction of two reservoirs and major underground works, including shafts and waterway tunnels to link the two reservoirs, as well as the construction of a 440m deep powerhouse complex.

The project area encompasses a National Park, State Forest, and farmland. The terrain is difficult with limited existing access track development. Elevation varies from 105 to 600 mAHD and the landform is also heavily vegetated. The limited geotechnical information available and difficulties encountered in conducting intrusive investigations were key in the decision to develop two parallel exploratory tunnels and an exploratory adit to investigate the ground conditions along their alignment and at the location of the powerhouse complex (Figure 1 and 2). Results from these investigations will form the basis for the development of the engineering geological model that will inform the design of the project's main underground works and be used for the preparation of the Geotechnical Baseline Report (GBR). Additionally, the exploratory tunnels will be repurposed to function as the Emergency Cable and Ventilation Tunnels (ECVT) during the project operation, provided the powerhouse location is confirmed.

Inferred ground conditions have been based on desktop studies, remote data collection (LiDAR and airborne geophysics), some surface lithological mapping and a very limited number of cored boreholes. The inferred ground model is shown in Figure 3. The alignment of the exploratory tunnels is anticipated to run mainly through slightly weathered to fresh rock masses with very high rock strength. The use of the 'drill and blast' (D&B) excavation method is envisaged, with rippers and rock breakers potentially being used in areas of poorer ground.

Figure 1: Plan view of the current power scheme layout showing the alignment of the Exploratory Tunnels (ECVT 1 and ECVT 2) and the exploratory adit (blue).

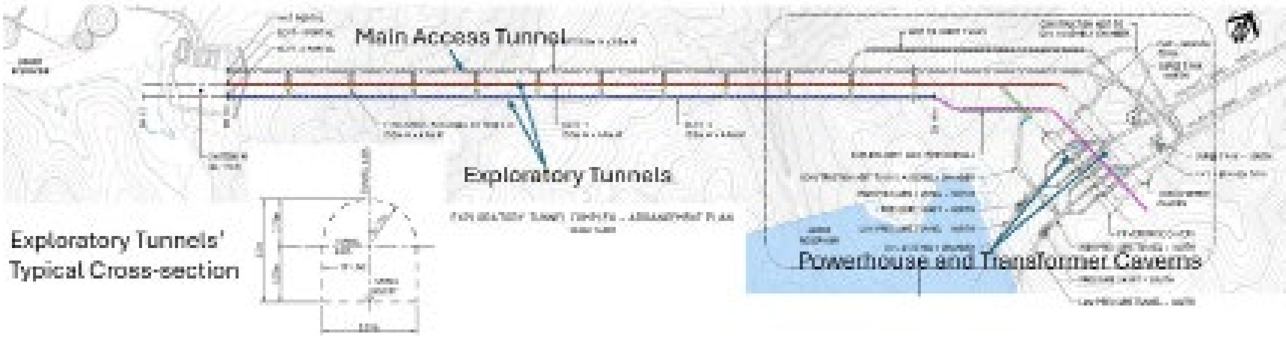


Figure 2: Isometric view of the proposed Powerhouse station area showing the Exploratory Tunnels (ECVT 1 and ECVT 2) and other ancillary underground works.

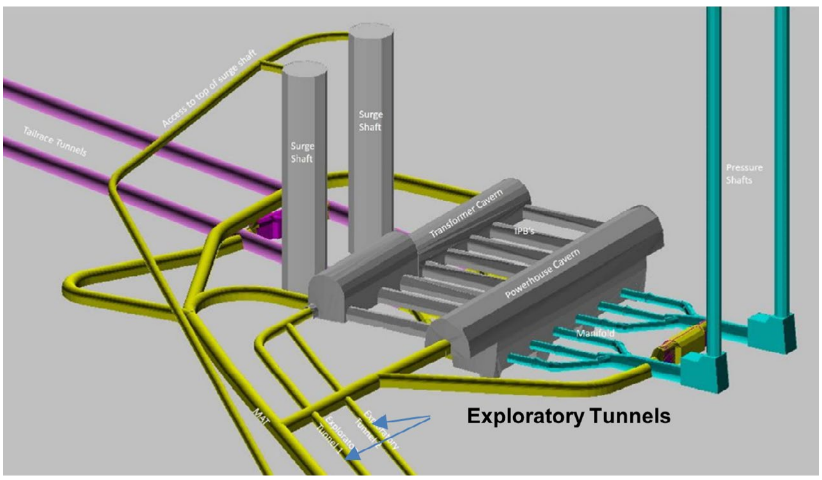
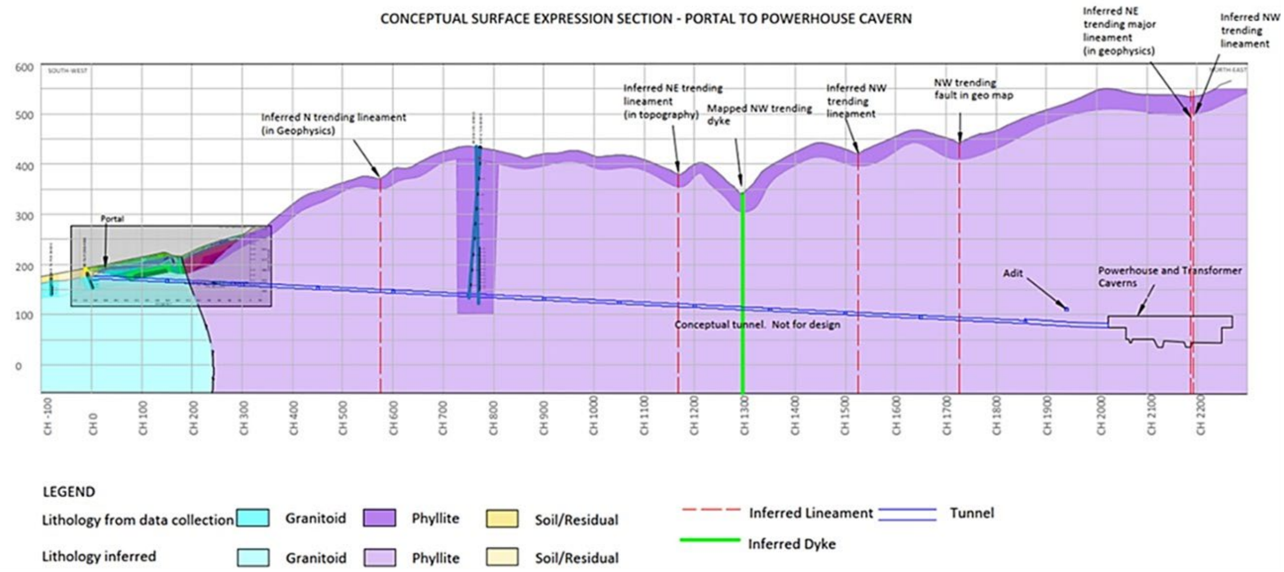


Figure 3: Exploratory Tunnels (ECVT 1 and ECVT 2) Longitudinal profile and conceptual ground model inferred from surface mapping and preliminary intrusive investigations.



In response to the geotechnical uncertainties associated with tunnel construction, QH adopted a flexible and collaborative contractual framework, utilizing the NEC4 Engineering and Construction Contract (ICE, 2017) Option B – priced contract with a bill of quantities (BoQ). Geotechnical risks will be primarily allocated between the Client and Contractor through the remeasurement of executed quantities (BoQ), which form the basis for both payments and schedule adjustments. A Geohazard Risk Allocation Matrix (GRAM) was also developed to identify specific geotechnical Exploratory Tunnels risks and conditions and assign their ownership to either the Contractor (to be factored in into the pricing schedule) or to the Client, effectively functioning as a Geotechnical Baseline Report (GBR).

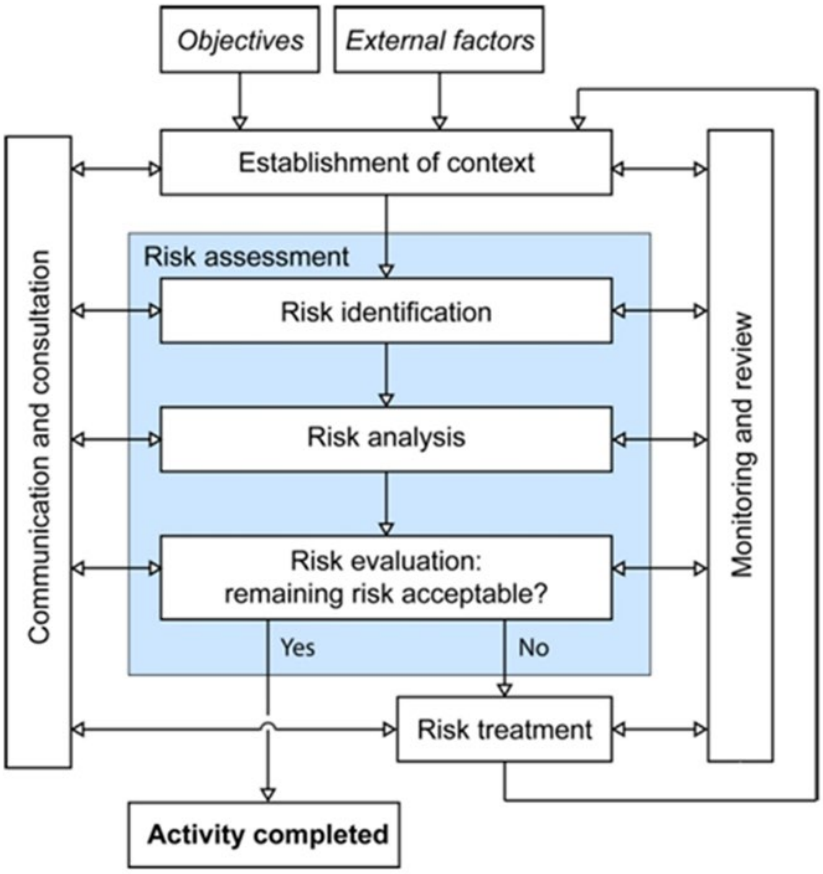
The following sections outline the Ground Risk Management (GRM) process developed to support the technical and contractual delivery of the exploratory tunnels, which integrates an observational geotechnical design approach.

2.0 Generic Risk Management Framework

ISO 31000, "Risk Management – Principles and Guidelines (ISO, 2018)," offers a framework for conducting comprehensive risk assessments applicable to diverse projects. It defines risk as the "effect of uncertainty on objectives". This definition broadens the scope of risk management beyond mere risk mitigation to include opportunity exploitation, aligning it with the principles of collaborative contractual framework.

The ISO 31000 risk management process consists of six interconnected steps designed to systematically identify, analyze, and treat risks within an organization or project, as illustrated in Figure 4. The process begins with communication and consultation, which occurs throughout all stages to ensure stakeholder engagement. Next, the scope, context, and criteria are established to define objectives and parameters. The core of the process is risk assessment, which includes risk identification, analysis, and evaluation. This is followed by risk treatment, where strategies are developed and implemented to mitigate risk. Throughout the process, monitoring and review activities are conducted to ensure the effectiveness of all stages. Finally, recording and reporting ensures that the results of the risk management process are documented and communicated to relevant stakeholders. This iterative process is designed to be integrated into an organization's overall management system, promoting a culture of proactive risk management.

Figure 4: The ISO 31000 cyclic work process for risk management. (ISO 2018, CC-BY 4.0).



3.0 Integrated Ground Risk Management (GRM) Framework

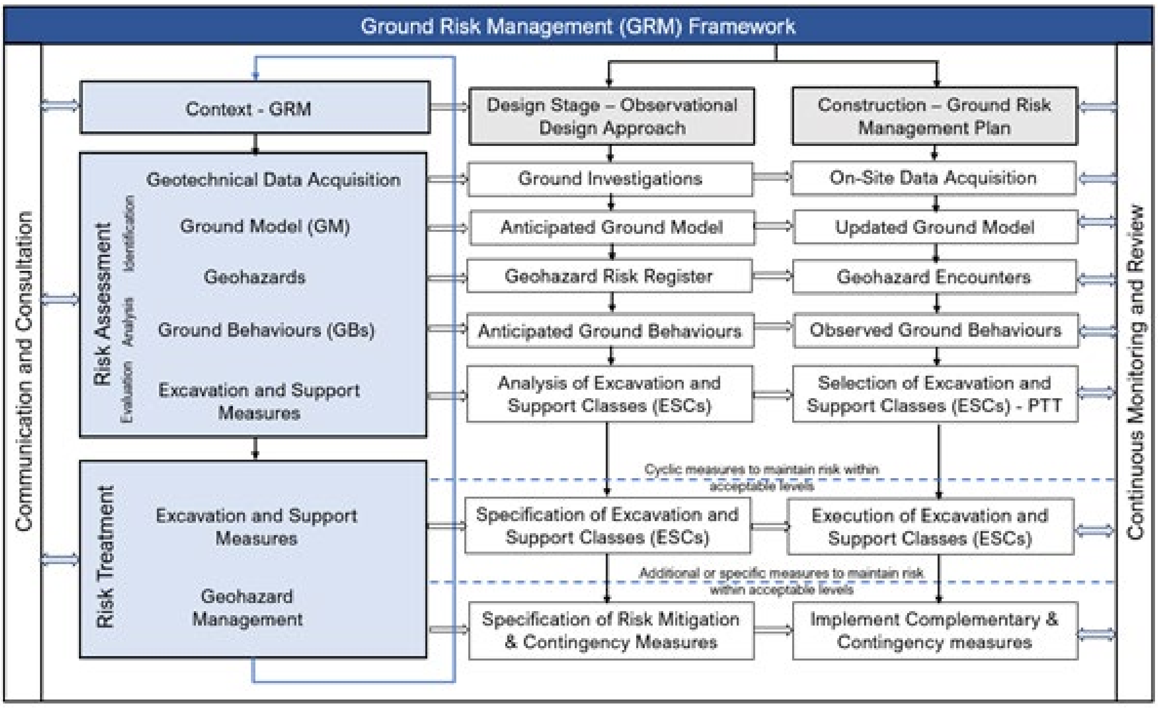
3.1 Project Specific Gound Risk Management Framework

Given the geotechnical uncertainties inherent in tunnel design and construction, the generic methodology proposed by ISO 31000 has been adapted into a ground risk management (GRM)

framework, which integrates an observational geotechnical design approach, as illustrated in Figure 5 and outlined in the following sections.

At Borumba PHES, the GRM framework is established within the overall project context, encompassing both the design and construction stages of the exploratory tunnels. For each stage, the GRM framework defines the steps involved in the risk assessment —identification, analysis, and evaluation— as well as risk treatment components of the risk management process. In line with ISO 31000, the framework emphasizes effective communication and consultation among stakeholders, as well as continuous monitoring and review throughout the process.

Figure 5: Adaptation of the ISO 31000 risk management process into a Ground Risk Management (GRM) Framework that integrates an observational geotechnical design approach.



The observational geotechnical design approach is an essential component in the proposed GRM framework. The approach fosters an adaptable, iterative process, allowing for the selection and implementation of "pre-designed" solutions tailored to deal with a specified range of ground conditions and behaviours. Additionally, the approach assists in the validation of design assumptions, verification of safety margins, and identification of opportunities for either design optimization or the need of implementing contingency measures during construction.

It is notable that, since its introduction by Terzaghi (1943) and formalization by Peck (1969), the observational method (OM), which is the basis of the proposed observational geotechnical design approach, has evolved from a "design-as-you-go" philosophy based on simple visual observations and basic measurements into a comprehensive approach of continuous, managed, and integrated process of design, construction control, monitoring and review (Nicholson et al, 1999). The OM is often integrated into tunnel design and construction practices worldwide and has also been recognised by the Eurocode 7 (2004) as a valid approach for verifying limit states in geotechnical design.

In Australia, the OM has been integrated into multiple tunnel projects by employing a process known as the Permit to Tunnel (PTT). The PTT process utilises the principles of the OM to manage geotechnical risk during construction, requiring designers and constructors to formally review observations and monitoring data to select appropriate ground support solutions based on the encountered conditions (Clark, 2021 and 2023).

The process outlined in the following sections were incorporated into the Client's reference design and shall be followed in the preparation of the Ground Risk Management Plan (GRMP) by the Contractor during the detailed design and construction phases.

3.2 Design Stage – Observational Geotechnical Design Approach

3.2.1 Ground Investigations

The geotechnical investigations for the reference design primarily comprised desktop studies and surface mapping. Two pre-tender phase cored borehole was completed, penetrating the rock formation which the exploratory tunnels are expected to encounter. Other exploration campaigns, including deep core drilling and in situ testing, have been scheduled to extend through the tender and pre-construction phases. These additional investigations are designed to yield supplementary data crucial for informing the detailed tunnel design, which will be executed by the Contractor.

3.2.2 Ground Model (GM)

Due to the limited available geotechnical information, the reference design ground model may be categorized as a "Conceptual Ground Model", in accordance with the IAEG guidelines (Baynes et al, 2023). Data obtained from the planned geotechnical investigations should enable the preparation of a more comprehensive Geotechnical Data Report (GDR) and an enhanced Geotechnical Interpretative Report (GIR), which shall underpin the development of enhanced Engineering Geological Models to inform the detailed design and construction phases. The Ground Model (GM) will be recorded and maintained using a robust Digital Ground Model (DGM), which will be continuously updated during construction, ensuring a dynamic understanding of the site's geotechnical conditions.

3.2.3 Identification and Assessment of Geohazards

Despite the limited site-specific borehole data along the exploratory tunnel alignment, and the significant uncertainty regarding the subsurface conditions, typical geotechnical risks associated with deep rock tunnelling with use of the D&B method can be anticipated (at least on a conceptual level). Typical geohazards include but are not limited to the presence of soil and highly weathered rock in shallow areas; excess overbreak, large deformations and ground instability associated with high in-situ stress; anisotropic behavior; and high water-inflow, among others. Identified risks have been included in the Geohazard Risk Register (GRR) for risk management and selected risks included by the Client in the GRAM for risk allocation purposes.

For the project specific conditions, a low likelihood of occurrence of serpentinite rock in fault zones has been identified and requires further investigation. These rocks may contain naturally occurring fibrous minerals and pose tunneling excavation and waste rock reuse/storage challenges.

Another key consideration is the potential for water inflow during tunneling, which could affect construction and impact the environmentally sensitive area. For that, acceptable impact limits on environment impact, as well treatment requirements, such as the need to pre-grout and/or post-grout the rock mass to control water inflow and unstable ground, have been established.

Data from additional geotechnical investigations, inclusive of surface investigations and in-tunnel probing ahead of the excavation face, will allow a more detailed assessment of geohazards during construction.

3.2.4 Assessment of Ground Behaviors (GBs)

This stage involves evaluating how the anticipated ground conditions are expected to respond to the proposed excavation and support methods. This ground response is referred to as 'Ground Behavior'. For the project, ground behaviors have been categorized into Ground Behavior Types (GBs) based on key controlling rock mass failure mechanisms, following the methodology recommended by the Austrian Society for Geomechanics Guidelines (2010). Examples of such key controlling mechanisms are also provided in Gomes et al (2023).

The assessment of ground behaviors informs strategy decisions and requirements for the design and is later used on site to identify ground conditions and determine the suitability of 'pre-designed' solutions and measures (construction toolbox) to address the encountered subsurface conditions. For that, ground classification systems coupled with measurable parameters, along with use of heuristic engineering judgement will be required, since not all GBs can be directly measured in a timely manner. For instance, brittle failure may only become apparent after the tunnel has been excavated and supported, potentially requiring post-treatment measures.

3.2.5 Excavation and Support Classes (ESCs) and Risk Mitigation and Contingency Measures

Construction is anticipated to be carried out with the D&B excavation method. The permanent ground support consists mainly of a shotcrete lining with patterns of corrosion-protected rock bolts, together with other auxiliary support elements, such as lattice and steel girders, fore poling, canopy tubes, face bolting, and pre and post ground-treatment, among others. The ground support has been subdivided into several ESCs, which represent ascending levels of difficulty in terms of restrictions for the excavation and quantity of support elements and measures required, forming the basis for the items included in the bill of quantities. Due to the existing geotechnical uncertainty, ESCs have been developed to provide a comprehensive toolbox that enables excavation through a broad range of ground and groundwater conditions, including potential adverse conditions with low probability of occurrence. In addition, forward probing will be used to assess conditions ahead of the excavation face and allow for changes in the excavation and support, as needed.

For the detailed design, when more geotechnical information will be available, the reference design shall be improved and refined based on the contractor's specific construction methodologies.

3.2.6 Risk Management during the Design Stage

As an integral part of the design stage, risk assessments must be carried out to inform strategic design decisions, mitigate risks to acceptable levels and leverage potential opportunities. During the design stage, Safety in Design Risk Assessment (SiD) and Construction Risk Assessment (CRA) shall therefore be conducted to ensure risks have been properly addressed, documented and communicated.

3.3 Construction Stage

3.3.1 Ground Risk Management Plan (GRMP)

Aiming at a proactive risk management approach, the Contractor shall develop a comprehensive GRMP for the construction stage. This GRMP is designed to be an evolving document to systematically identify, assess, and mitigate risks associated with the ground throughout the tunnel design and construction project (modified from Clark, 2023).

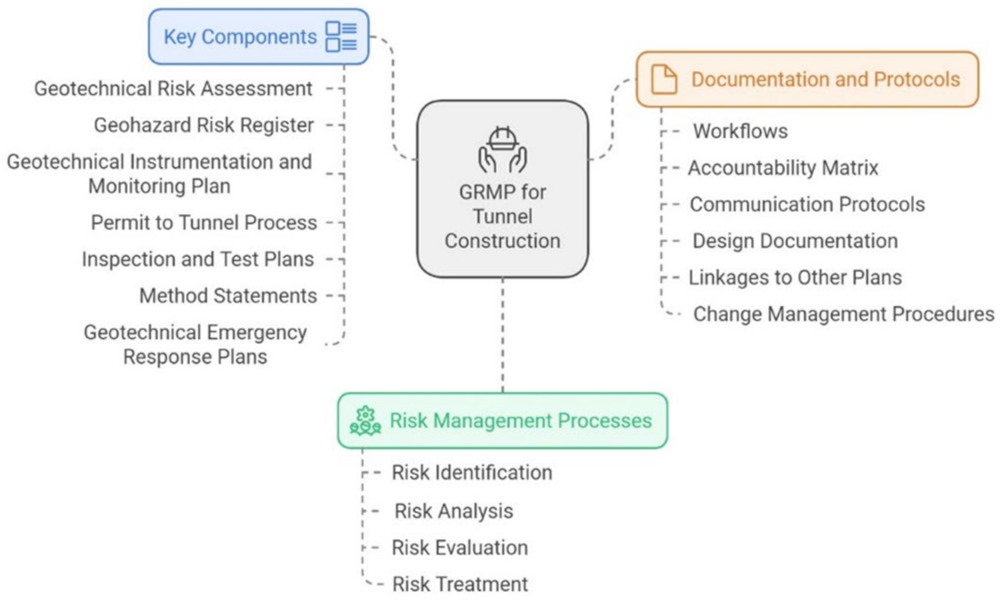
The GRMP is an integral part of the Contractor's global construction Risk Management Plan, Figure 6, which shall be developed in accordance with the Code of Practice for Risk Management of Tunnel Works (ITIG-ITA, 2023) and the Safe Work Australia Guide for Tunnelling Work (2013) (Safe Work Australia, 2013).

Relevant information that shall be documented in the GRMP include, but it not limited to, workflows for geotechnical and hydrogeological processes; accountability and responsibility matrix; communication protocols; design and construction documentation; linkages to other project plans; risk assessment, mitigation strategies, and contingency measures; as well as procedures for managing changes in conditions.

The GRMP also includes key documents and processes, which include but are not limited to:

- Geotechnical Emergency Response Plans (GERPs): Predefined procedures and actions to effectively manage and mitigate adverse ground-related incidents, addressing potential impacts on construction, safety, and project progress.
- Construction Stage Geotechnical Risk Assessment: Anticipated ground-related risks during construction, considering residual design risks and specific GERPs for risk mitigation.
- Geohazard Risk Register (GRR): live document recording and tracking geohazard risks throughout the project.
- Geotechnical Instrumentation and Monitoring Plan (GIMP): describing monitoring details, frequency and associated trigger levels.
- Permit to Tunnel (PTT) process: A collaborative process ensuring safe and documented tunnel advancement, involving Contractor and Client to review the Contractor's decisions on suitable construction measures based on ground conditions and monitoring data, as part of the implementation of the observational geotechnical design approach.
- Inspection and Test Plans (ITPs): Detail inspection, checking, and certification procedures for construction works, specifying hold points and referencing relevant GIMP sections.
- Method statements: Contractor's methods and resources for relevant construction works, demonstrating compliance with best practices and standards.

Figure 6: Key Components of a Ground Risk Management Plan (GRMP) for Tunnel Construction



3.3.2 Risk Assessment Components of the Construction Stage

Both the ground risk management process and the observational geotechnical design approach require the continuous gathering and interpretation of geotechnical data during construction to identify, analyse and evaluate risks. During construction, relevant data shall be collected, recorded, and evaluated on-site at each excavation cycle, excavation round or construction stage.

Typical geotechnical information collected, assessed, and interpreted during construction includes face mapping; results of forward probe drilling and sample testing, as well as drilling operational data, such as thrust/torque and penetration rates; groundwater measurements, including inflows; monitoring of stress, strain, and displacements (as per the GIMP); geophysical measurements (if applicable); in-situ and laboratory testing; and back analysis to validate design assumptions based on observed behavior (e.g., in-situ stress conditions).

The GRR, the GM and the DGM must be continuously updated as new knowledge is gained from new data, testing, and back analysis to inform ground and system behaviours, and the need to implement contingency measures.

The design implementation on site follows the PTT process, which shall ensure safety, quality documentation, and proper communication across the stakeholders. The PTT process involves regular meetings attended by designated representatives from both the Contractor and the Client to review the Contractor's decisions on applicable engineering solutions. The PTT process formalizes the observational design approach and states the conditions for which the proceeding tunnel advance(s) may occur, including the Client's 'no-objection' in relation to the selected measures to be implemented, stating the distance for which the permit is valid as well as the need of additional measures, like more frequent and localised monitoring.

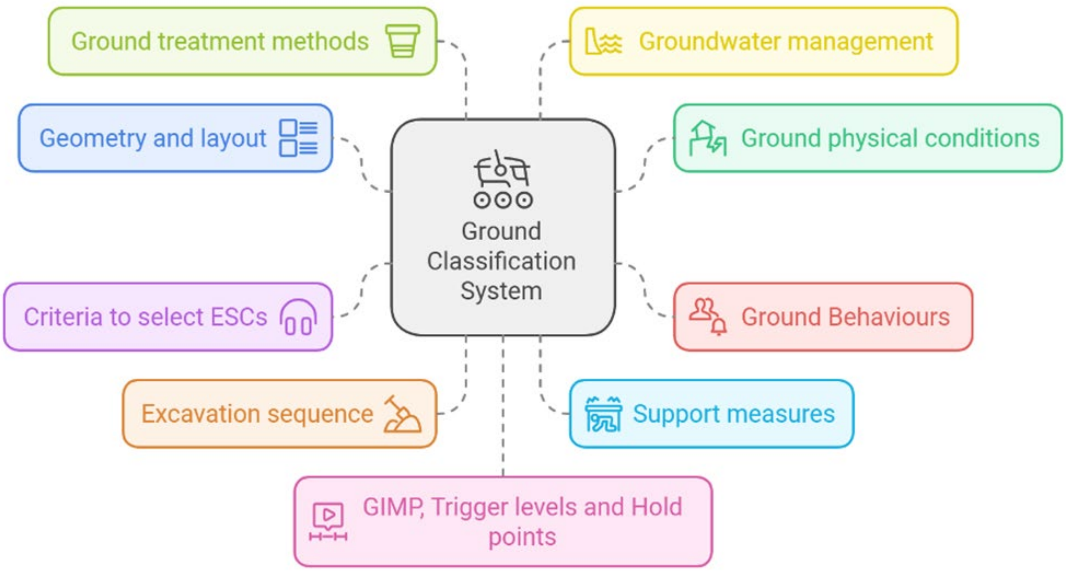
The ground classification system provides quantitative, qualitative and observational criterion and workflows to assist the PTT process in identification of GBs and selection of suitable construction measures or the need of contingency measures, under the given encountered subsurface conditions. The ground classification system is established for each specific work area, work type and construction method, including the aspects shown in Figure 7, including geotechnical "Hold Points" relative to locations and conditions where the PTT needs to be reviewed in detail due to lack of information, high risk zones, or where further investigation or analysis is required.

3.3.3 Risk Treatment Components of the Construction Stage

The design implementation must be carried out in accordance with the PTT process and in compliance with the project technical requirements and approved method statements. Design assumptions must be verified and validated during construction through the observation of performance

limits established as part of the detailed design, covering all technical requirements, as well as accepted level of impact on environment, in accordance with the respective ITPs.

Figure 7: Key Components of a Ground Classification System



Conclusions

This paper outlined the ground risk management process developed to support the technical and contractual delivery of the Exploratory Tunnels of the Borumba Pumped Hydroelectric Energy Storage (PHES) project in Queensland, Australia, which integrates an observational geotechnical design approach as a key component of the process. By embracing a collaborative contractual framework considering this integrated approach to design and ground risk management, the Bo-rumba PHES project demonstrates a commitment to achieving safe, efficient, and cost-effective tunnel construction, despite uncertainties regarding the geological subsurface conditions. The pa-per presents the key considerations for managing ground risk in complex tunnelling projects in line with international best practices, emphasizing the importance of continuous monitoring, data interpretation, and collaborative communication and decision-making to ensure successful project outcomes.

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