Observational method for the deep powerhouse cavern construction of Snowy 2.0 project

I. Ching
SMEC Pty. Ltd., Sydney, NSW, Australia

M. Diederichs
Queen's University, Kingston, Ontario, Canada

B. Chapman
Snowy hydro Limited, Cooma, Australia

K. Thermann
Tractebel Engineering, Germany

K. Acharya
Future Generation Joint Venture, Cooma, NSW, Australia

ABSTRACT: The Observational Approach for geotechnical design and construction was discussed by Bjerrum and Terzaghi in the early 1960's as a means to cope with the uncertainty of working with Earth materials. In 1999, CIRIA R185 suggested "The Observational Method in ground engineering is a continuous, managed, integrated, process of design, construction control, monitoring and review…" This paper highlights the application of observational method for the design and construction of the deep powerhouse caverns of Snowy 2.0 project which is a 2200MW pumped storage expansion to the existing Snowy Hydroelectric Scheme. From establishing the design assumptions and acceptance criteria; to support performance prediction and construction control monitoring; and finally, the review and back-analysis based on the observed ground responses and ground conditions, the complete cycle of observational method with design, monitoring, re-analysis and response has been demonstrated.

1 BACKGROUND

The Observational Approach for geotechnical design and construction was discussed by Bjerrum and Terzaghi in the early 1960's as a means to cope with the uncertainty of working with Earth materials. Rather than defining, a priori, all underground conditions, the project team conducts exploration to define the nature, pattern and range of properties, assess the most probable deviation from these conditions, establish a design based on most probable condition, with a toolbox of modifications to the design should there be a foreseeable deviation. Measurable quantities during construction are to be determined and monitored. The as-built design is then verified or modified to suit actual conditions. Similarly, CIRIA R185 "Broadly speaking, the Observational Method (OM) is a process in which acceptable limits of structural and geotechnical behavior are established. In addition, performance predictions, monitoring, review and modification plans, and emergency plans, are fully prepared." This method served geotechnical engineering well, but as Peck observes, "“It is essential that the quantities to be observed should reflect the phenomena that will actually govern the behavior of the works to be constructed....A mistaken preconception of the nature of the problem may lead to omission of observations of types that would have disclosed the real reasons for concern." Rather than utilizing a codified classification scheme for conditions, or relying on standard measurements such as closure, conditions to be recorded, quantities to be observed, and triggers for response, must be relevant to the instability mechanisms anticipated. The application of OM for the powerhouse cavern construction of Snowy 2.0 project has been agreed in the early stage of the project due to its complexity. Both ground conditions as well as ground performance are integrated into an observational design cycle with design, monitoring, re-analysis and response tailored to specific deformation and instability modes identified during investigation and pre-construction modelling.

2 SNOWY 2.0 PROJECT

Snowy 2.0 is a major renewable energy infrastructure project located in the Kosciusko National Park (KNP) in southern NSW Australia, currently under construction. Upon completion, the project will increase the generating capacity of the existing Snowy Hydroelectric Scheme by 2200 MW. The project links two existing reservoirs, Tantangara (elevation 1231 m) and Talbingo (elevation 546 m), through 27 km of waterway tunnels and an underground power station equipped with 6 Francis pump-turbine units. The project also includes more than 10 km of access tunnels. The project is owned and operated by the Snowy Hydro Limited (SHL). The design and build contract has been awarded in 2019 to the principal contractor Future Generation Joint Venture (FGJV) and a Design Joint Venture (DJV) has been appointed by the contractor to carry out the engineering design for civil and mechanical and electrical works. The project has introduced new contract arrangements following a major project reset in 2023.

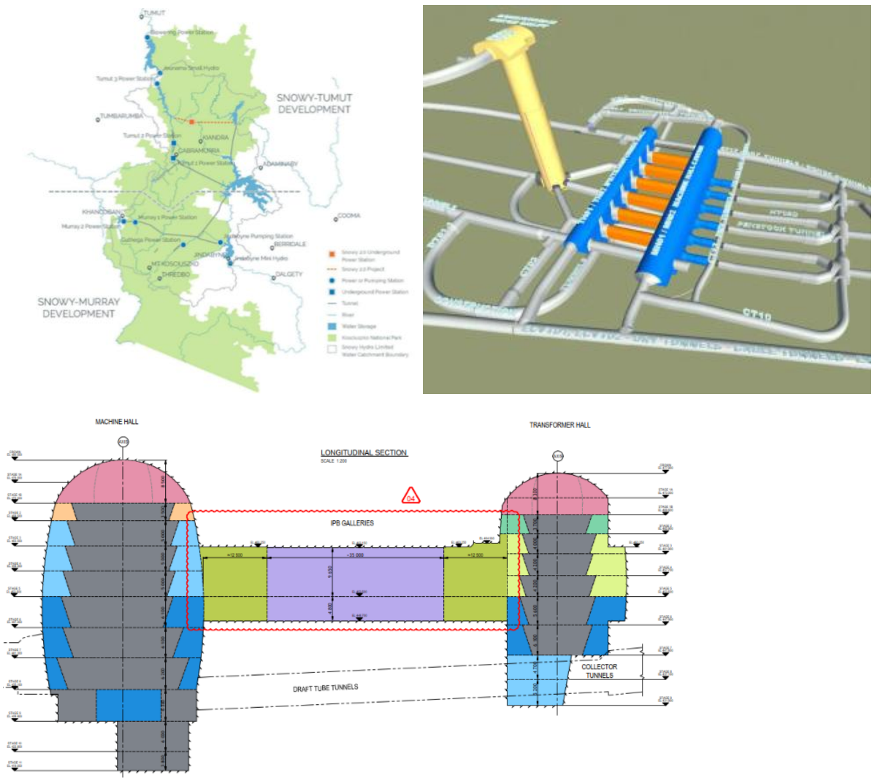

Figure 1. Snowy 2.0 project location (top left); Power station complex isometric view (top right); Cross-section of PSC and excavation stages (bottom)

3 THE POWERHOUSE CAVERNS

The Power Station Complex (PSC) is within the Ravine Beds West (RBW) formation at about 750m below ground in sedimentary rocks (predominated by interlaminated and interbedded siltstone and sandstone) with two main caverns, the Machine Hall (MH) and the Transformer Hall (TH) connected by the axillary tunnels. The 251m long, 32m wide and 52m height Machine Hall will host six units of pump-turbines, motor-generators, main in-let valves. The TH where the six main transformers, draft tube valves and cooling water equipment are located, is 217m long, 20m wide and 46m height. The distance between the two main caverns is 60m. There are two Main Access Tunnels (MAT and ECVT) and six Isolated Phase Busbar (IPB) tunnels which house the electrical equipment required between the motor-generators and the main transformers. The IPB tunnels are 10m wide and 14.5m high. The pillar width between IPB tunnels are 18m to 19m. The caverns have been excavated by conventional Drill and Blast (D&B) method with heading, benching and side-slashing excavation sequence. The design has considered 11 and 9 stages excavation for the MH and TH respectively (Refer to Figure 1).

4 DEFINITION OF ACCEPTANCE CRITERIA

4.1 *Global stability criteria*

According to the Employer's Requirements (ER) of the project, the general design criteria of PSC must achieve functionality, stability, and safety along the entire design life of the Project. The design shall ensure safety during construction and operation, considering uncertainties known and unknown (local variability of rock behavior and unexpected conditions). For the functionality requirement, the design must fulfill the space proofing requirement to host the facilities in the IPB gallery tunnels connecting the generators in the MH to the transformers in the TH, as well as various other important electrical equipment related to the reversible pump-turbines units. Stability was referring to the design must provide a sufficient margin against the state of failure without excessive deformation and/or progressive failure over the design life.

The design requirement of rock pillars between IPB was the critical criteria for the global stability of the caverns. It also affected the overall PSC layout and excavation volume, and eventually had the cost and programme impact. One of the challenges of the design was due to the significancy of the in-situ stress resulted in a relative low ratio of the sigma_ci/sigma_1 such that the rock mass could reach post-yield state upon excavation.

To develop the acceptance criteria for the IPB rock pillar performance with optimized pillar sizes, rock pillar stability assessment using different design approaches were performed and investigated. Empirical approach using Lunder and Pakalnis plot was performed to determine the rock pillar size ratio W/H (width/Height) at a specific average pillar vertical stress and the intact strength of rock mass. The W/H ratio provided an indication of the pillar stability based on the statistic of historical database mainly from mining industry with interpreted trend. The database and trend lines were reviewed and modified to exclude the data from irrelevant ground condition or ground behavior to improve the estimation.

Numerical approach was adopted to determine the spare capacity/margin (Factor-Of-Safety) of the pillars. This margin was important to cover uncertainties related to material, long term behavior, design modelling. The assessment using both Shear Strength Reduction (SSR) and Strength/stress method (SSM) methods were performed. The SSR method was the measure of the reduction of rock mass capacity (shear strength) until full pillar plasticized in the model occurs. This was equivalent to decreasing the failure envelope in a similar fashion until the rock mass softening happens. The FOS was the ratio between the actual strength of the material to the minimum required strength to prevent the full plasticity of pillars.

The SSM applied vertical displacement to the pillars in the model at the end of caverns excavation stage to increase the rock pillars stress. Considering the central 1/3 area of the pillar cross section as the central core which to be loaded until yielding (softening occurred) to determine the pillar strength. The pillar stress was the pillar core stress at caverns excavation completion. The FOS was defined as the pillar strength divided by the pillar stress (Strength/Stress). Both assessments provided a similar result achieving FOS=1.3 with an elastic core surrounded by different degree of yielded rock mass.

4.2 *Rock reinforcement acceptance criteria*

The Double Corrosion Protection (DCP) rock bolts were used for the cavern excavations. Based on the predicted failure mechanisms and durability requirements of the rock reinforcement at different stage of the project, acceptance criteria were established and verified by specific preproduction testing. Under the action of shear displacement of rock defects, the protective sheathing of the installed DCP bolts could be compromised. In order to quantify and correlate the shear displacement of the rock discontinuity to the damage of rock bolts, double shear tests were carried to confirm the bolt performance under the acceptance criteria of 20mm and 35mm shear displacement for durability and structural integrity respectively. Besides, a strain-based acceptance criteria was established based on the result from the design analysis to reflect the combined action of pull and shear on the bolt section across the sheared features. Double embedment elongation tests were carried out to confirm the performance of bolts under the 1.5% and 2.5% bolt strain limits for secondary and primary bolts respectively. Figure 2 below presents the shear test setup and the results from the three tests (DSI CT26WR).

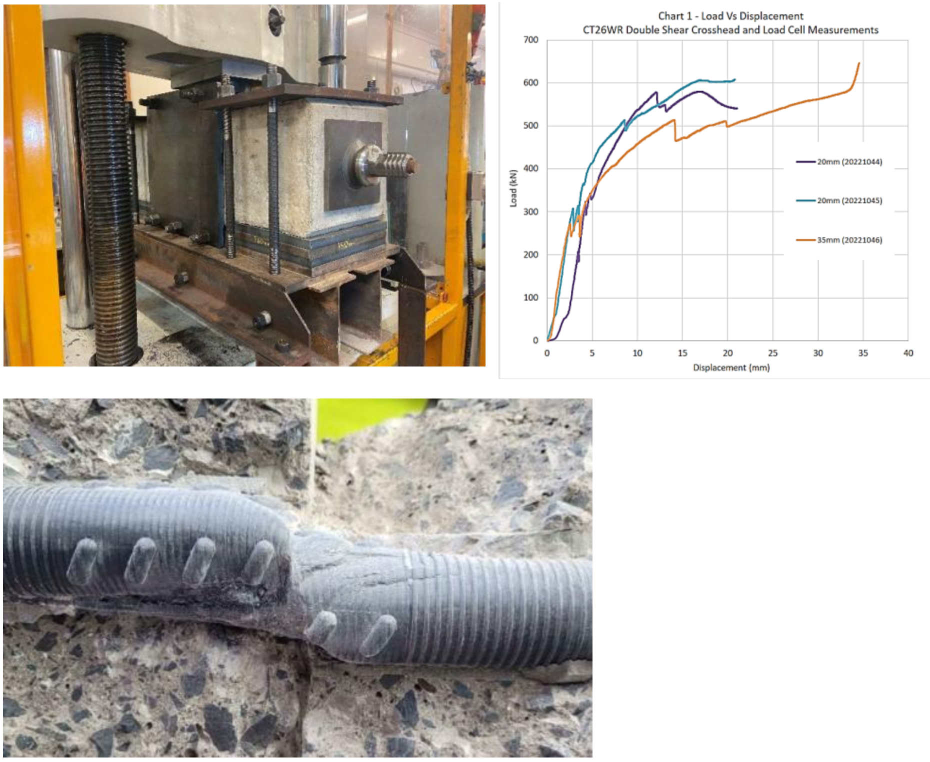

Figure 2. Double shear test of bolt (left); Load-displacement curves of CT26WR double shear tests for 20mm and 35mm limits (right); CT26WR after 35mm shear displacement (bottom)

5 PREDICTED GROUND BEHAVIOUR AND SUPPORT PERFORMANCE

5.1 *Predicted rock mass behavior*

The ground behavior assessment for the PSC excavation corresponded to an evaluation of potential failure mechanisms that would control the behavior of the unsupported excavation. The assessment considered relevant influencing factors, such as ground type (geotechnical units and ground parameters), excavation profile and span, in situ stress, over-burden, etc. According to the GBR, the potential controlling failure mechanisms for underground excavations could be categorized as per Table 1 below.

Table 1. Major controlling failure mechanism

Failure mechanism	Description
Discontinuities and Gravity	Failure controlled by the rock mass discontinuities, including overbreak, fall of wedges or blocks, friable ground, up to unravelling ground and chimney failure conditions. Ground majorly in elastic domain and/or with lack of confinement.
Ground Overstress	Failure controlled mainly by rock mass overstress, which can occur with or without association with existing ground structures. Ground damage in form of shear and brittle (tensile) failure with increasing depths of damage into the surrounding rock mass. When rock is massive and hard, rock failure will tend to be controlled by brittle (extension)

	failure, whereas shear tends be dominant in weak and fractured ground. Combination of both type of failures occurs over a broad range of conditions.
Groundwater	Rock mass deterioration and instability due to groundwater presence, flow or pressure. Hazards includes wash of fines flowing ground or slaking/swelling phenomena.
Frequently Changing Conditions	This overarching category is meant to capture the situation where ground conditions are very complex and frequently changing. This includes highly heterogeneous and anisotropic rock mass with frequently changing strength and deformation conditions.

The strength and deformability of rock mass depended on the strength and deformability of the intact rock, the discontinuities, and the geo-environmental conditions such as natural stresses and hydrogeological conditions. The primary criteria for the determination of the ground behavior included: the rock mass fabric expressed with the parameter Geological Strength Index (GSI); the compressive strength of intact rock (UCS) and of rock mass; and the initial stress state and maximum stress around the excavation opening. Based on the strength and stress parameters obtained from the SI, it was estimated that the failure mechanism of the excavation could be controlled by plastic behaviors at locations with stress concentration such as the IPB rock pillars. Wedge instability or geological overbreak, resulting from deconfinement and the presence of structural discontinuities within the cavern crown and sidewalls, could represent the predominant mechanism. This mechanism could be enhanced by the blasting activities. At locations where main sheared features were encountered, shear displacement mechanism was expected.

5.2 *Predicted support performance*

Following the predicted ground behavior, a dedicated flexible support system comprising rock bolts and shotcrete lining (Figure 3) was designed to address the failure mechanisms and design life requirement. The support system allowed the ground to deform as per prediction and provided necessary confinement to maintain the local and global stability during construction and the design life. The long-term global stability was maintained by the systematic secondary rock bolts to from a reinforced rock arch around the excavation. The primary rock bolts were installed after each round of excavation to maintain the stability during excavation and provided a “supported” ground for personnel entry. The shotcrete lining was designed to hold the rock mass (any damage/plastic zone) between rock bolts. The use of stainless-steel wire mesh within the shotcrete was to increase the lining ductility to meet the ground deformation and durability requirement. Due to the depth of the caverns and the observed pre-sheared features within the rock mass, it was expected that the combination of the elevated in-situ stress and the shear displacement failure mechanism of rock reinforcement could be the main driver of potential instability in the caverns. The displacement of rock blocks along sheared joints due to ground deformation could yield a grouted bolt locally where it crossed the rock joints. The bolt could be loaded by a combined action of tensile and shear forces induced by the shear displacement. The ultimate load depended on the inclination of the rock bolt crossing the rock joint. To assess the interaction between the rock blocks and the bolts, discrete element analysis (Figure 3) coupling the interaction between the rock discontinuities and the rock bolt structural elements was performed to allow quantitative assessment of this failure mechanism.

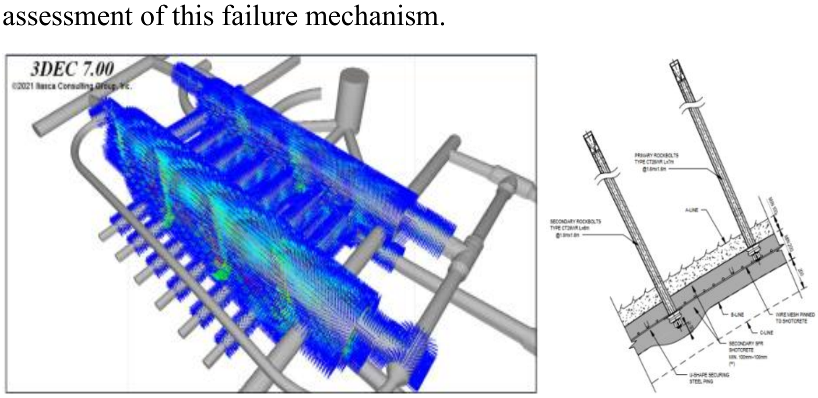

Figure 3. 3DEC analysis with rock bolt and sheared features modelled explicitly (left); PSC cavern rock support system (right)

6 CONSTRUCTION CONTROL AND MONITORING

Under the Employer's Requirements and the framework of Geotechnical Baseline Report (GBR), major construction control activities were developed to fulfill the requirement, such as Geological data acquisition plan; PSC caverns geotechnical instrumentation and monitoring plan; Excavation performance review process etc. The geotechnical information and monitoring data collected during construction were processed and reviewed in the regular meeting such as the daily geotechnical monitoring meetings and weekly geo-hazard meetings. The outcomes from these meetings such as the confirmation of ground behavior and ground support were conveyed to the frontline of construction for execution via the Permit-To-Tunnel (PTT) process where the details and requirements for the next round cavern excavation such as supports and monitoring, advance length and sequencing were confirmed.

The construction control activities also formed a linkage between the design assumed conditions and the actual conditions encountered. The probe hole drilling estimated the rock mass quality and the groundwater inflow rate ahead the excavation face. The geological face mapping assessed the actual rock mass classification GSI/RMR and identified the defects of the exposed ground. Other construction requirements such as blast control underneath the support of crane beam for stage 3 (Figure 4) excavation. With the construction control activities in place, the design assumptions and limits could be confirmed and validated. Contingency measures shall be applied when the encountered conditions outside the design limits or predictions. The instrumentation and monitoring plan was developed, and the instrument adopted could be classified as two groups: 1) ground response monitoring such as Displacement Measuring Point (DMP); Multi-Rod Extensometers (MRE); and Piezometer. 2) support performance monitoring such as shear monitoring holes; load cells; and strain gauges. The monitoring strategy has provided sufficient information for the intended purposes.

Figure 4. Stage 3 excavation of TH (left); Stage 3 excavation of MH (right)

7 REVIEW AND BACK-ANALYSIS

In general, the review and back-analysis is a process of using observed or measured data during construction to refine and calibrate the initial design assumptions, models, or parameters bridging the gap between theoretical design and actual performance, ensuring safer and more efficient construction activities. In the PSC cavern construction, this continuous review process has been formalized by adopting design hold points (HPs) and witness points (WPs) system. HPs or WPs have been established for each critical stage of construction, such as:

- HP0: End of central heading excavation prior to side slashing, to confirm the wedge analysis.
- HP1: End of cavern crown (stage 1) excavation, to confirm the pre-sheared features in the crown.
- HP1a: End of central heading excavation, to confirm the design for the intersection between the cavern and the MAT01 TBM tunnel underneath.
- HP2: End of stage 3 excavation, to confirm the design for IPB tunnels and intersections.
- HP3/HP4: End of IPB excavation and end of caverns excavation respectively, to confirm the rock pillars behavior and support performance.
- WP1/WP2: End of stage 2 and stage 5 respectively, to review and update the design with obtained data.

The sheared features/surfaces were identified by geological mapping and the data from 3D Lidar scans after the Stage 1 excavation of the crowns. These features were then confirmed by drilling of dedicated shear monitoring holes with endoscope inspection to record the details of the shear features. Endoscope inspections in systematic drainage also played an important role to confirm the extent of the sheared features and determine the "critical zones" for shear displacement monitoring. The baseline condition of each shear holes was established and compared with subsequent inspection. The endoscope inspection was a direct and quantitative measurement for shear displacement. A combination of qualitative monitoring measures was adopted to monitor the "critical zones" identified. Figure 5 presents the identified sheared features at the crowns of MH and TH with the endoscope images of the targeted features.

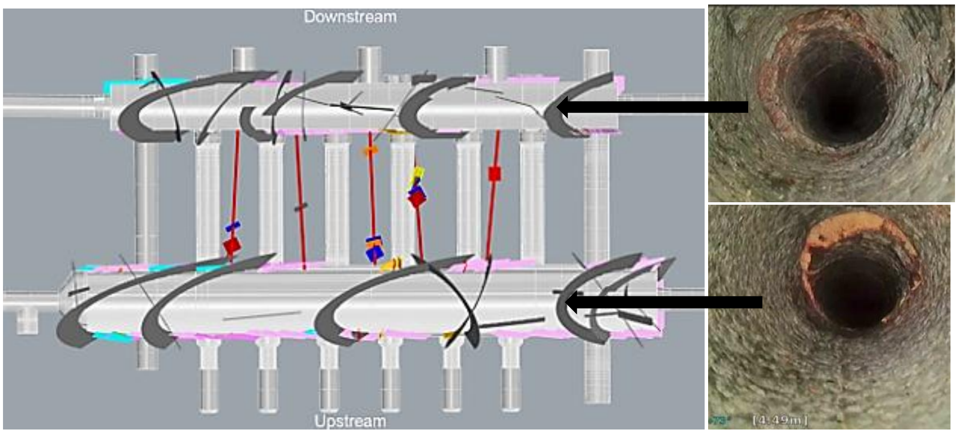

Figure 5. Plan view of 3D geological model with sheared features identified at the crowns of cavern (left); endoscope images of targeted features (right).

The back-analysis was conducted utilizing the 3DEC discontinuum analysis. A critical input for this analysis was the interpreted ground structural model, as illustrated in Figure 5. Other essential rock mass parameters, such as a GSI of 72 and a UCS of 58, were derived from actual ground conditions identified through comprehensive mapping data. The 3D geological model underwent significant refinement, incorporating the actual main sheared features identified within the crowns of the excavations. This update was further supplemented by initial findings from five inclined boreholes drilled specifically for pillar investigation. Subsequently, this refined 3D geological model was imported into the 3DEC numerical model to simulate the excavation and support installation sequence. The performance of the rock support, encompassing both primary and secondary bolts, was then assessed based on the numerical analysis results and corroborated with site monitoring data to determine any triggers for re-bolting. The numerical analysis was calibrated against actual ground response data obtained from field monitoring. Figure 6 shows the comparison between the measured MRE readings (at 2m, 5m, 10m, 15m, and 20m anchor lengths) and the corresponding output from the 3DEC model at Chainage 0+116 of the MH. Displacements from the extensometer initiated during Stage 1 excavation, exhibiting a notable increase upon the side-slashing (full span) was opened. During the Stage 2 excavation, a general increasing trend with a relatively mild slope was observed. After the entire span of Stage 2 was opened, the displacements increased, stabilizing at a final cumulative displacement of approximately 13mm. This observation aligns with the result from the 3DEC model.

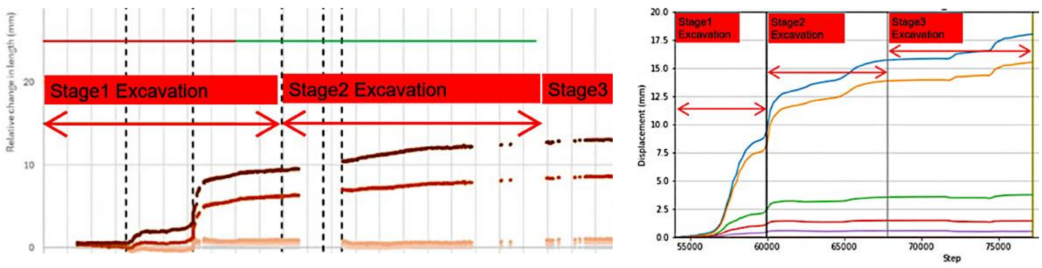

Figure 6. the measured MRE readings (at 2m, 5m, 10m, 15m, and 20m anchor lengths) at Chainage 0+116 of the MH crown (left); The corresponding output from the 3dec model (right).

8 CONCLUSION

The implementation of the observational method for the construction of the Snowy 2.0 powerhouse caverns has effectively mitigated the complexities associated with geological uncertainties. By establishing predefined acceptable limits derived from design predictions, performance was systematically measured and evaluated through construction control procedures. The primary instability mechanism was identified based on anticipated ground behavior, informing the development and application of targeted monitoring strategies and trigger values during construction. The actual conditions and site data observed throughout construction were integrated into a continuous review process, enabling iterative design updates and modifications to accommodate actual conditions. This comprehensive application of the observational method has yielded tangible benefits in terms of risk mitigation and optimization opportunities.

9 ACKNOWLEDGEMENTS

The authors acknowledge the permission granted by SHL to publish this paper. The authors also acknowledge the joint effort and the contribution of the colleagues from SHL, FGJV, Design Joint Venture (Lombardi, Tractebel and Coffey) and SMEC on the project.

10 REFERENCES

Chapman B. Yee M., Gomes A.R.A. 2019. Engineering challenges of the Snowy 2.0 pumped storage project. ITA-AITES World Tunnel Congress WTC2019, Naples, Italy - Tunnels and Underground Cities: Engineering and Innovation meet Archaeology, Architecture and Art – Peila, Viggiani & Celestino (Eds), Taylor & Francis Group

Ching, I., Diederichs, M., Chapman, B. & Cardone G. 2024. Deep powerhouse caverns design development and challenges – Snowy 2.0 experience. ITA-AITES World Tunnel Congress WTC2024, Shenzhen, China - Tunnelling for a Better Life – Yan, Celestino, Thewes & Eberhardt (Eds), Taylor & Francis Group

Diederichs, M., Miller, D., Chapman, B., Ching, I. & Gomes, A. 2022. Snowy 2.0 Pumped Storage Scheme: Rock Engineering Challenges in Tunnelling and Cavern Construction, Proceedings of the 2022 Tunnelling Association of Canada Conference, Vancouver, B.C., Canada

Gomes, A.R.A, Chapman, B., Diederichs, M. & Ching, I. 2023. Conceptual Framework of the Snowy 2.0 Pumped Storage Project (PSP) Geotechnical Baseline Report (GBR) for underground works. ITA-AITES World Tunnel Congress WTC2023, Athens, Greece - Expanding Underground - Knowledge and Passion to Make a Positive Impact on the World – Anagnostou, Benardos & Marinos (Eds), Taylor & Francis Group

Gomes, A.R.A, Chapman, B., Chapman N. and Cortes, F. 2021. Development of the Geotechnical Baseline Report for the Snowy 2.0 Pumped Storage Project, ATS 2020+1 Tunnel conference, Melbourne.

Hoek, E. 2006. Practical rock engineering.

Nicholson, D., TSE, C. & Penny, C. 1999. The observational method in ground engineering – principles and applications. Report 185. CIRIA. London. 214p.