

CASE STUDY ON SNOWY 2.0, AUSTRALIA: USE OF LIDAR AND ENDOSCOPY FOR ASSESSING AND MODELLING GEOLOGICAL FEATURES IN UNDERGROUND CAVERNS

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ABSTRACT

Snowy 2.0 is a major pumped hydropower project currently under construction in Australia that will complement the existing Snowy Mountains hydroelectric system, adding an additional 2200 MW to the national energy grid. The Power Station Complex (PSC) for the project comprises 3 caverns, a shaft, and some 10 km of Drill and Blast excavated tunnels, at a depth of over 750m. The Machine and Transformer halls within the PSC are excavated using an observational approach to excavation, requiring a thorough understanding of encountered conditions and excavation behaviour.

Traditional mapping techniques in tunnels face challenges due to limited accessibility and visibility. This case study describes the use of survey controlled Light Detection and Ranging (LiDAR) scans of the excavated face to augment traditional mapping, used together with downhole endoscopy and optical televiewer (OTV) to identify and project major defects in 3D modelling softwares. Integrating these technologies has allowed for comprehensive defect detection, persistence and waviness assessments on the cavern scale, and accurate orientation measurements which can be combined with defect conditions assessed in traditional mapping. This is key in the observational approach to excavation, providing a highly accurate geological model which allows a verification of design assumptions, comparison of geological features to monitoring, highlighting areas where bolt shear may be of concern, and ensuring a comprehensive and accurate owners model for the operations phase of the scheme.

1 INTRODUCTION

The Snowy 2.0 project is a major pumped-storage expansion of the iconic Snowy Mountains Hydroelectric Scheme, which forms a vital part of Australia's energy transition towards a low-emissions future. The existing Snowy Hydro Scheme is a major hydroelectricity and irrigation system located in the Snowy Mountains, New South Wales, Australia. Built between 1949 and 1974 it is considered one of the civil engineering wonders of the world, with a 4.1 GW capacity. The existing scheme comprises 16 dams, 8 hydropower stations, and 145 km of tunnels.

Snowy 2.0 is an augmentation of the existing scheme, and is currently under construction. It will add 2,200 MW of energy generation capacity, with storage of 350,000 MW hours. At full capacity Snowy 2.0 will be able to generate for almost one week without pumping.

The Snowy 2.0 project is led by Snowy Hydro Limited as the owner, with SMEC providing technical engineering support to the owner for the geotechnical and tunnelling scopes in particular. The principal contractor for the civil works is Future Generation Joint Venture, a consortium comprising Webuild, Clough, and Lane, responsible for the civil construction works. The design joint venture is composed of Lombardi, Tractebel, and Coffey, with cavern design specifically falling under Tractebel's scope within the joint venture.

Similar to the existing scheme, Snowy 2.0 involves extensive underground works, both in terms of scale and intricacy, and is situated within a complex and highly variable alpine geological and hydrogeological setting. The underground works comprise ~33 km of TBM driven tunnels, ~10 km of drill and blast tunnels, three deep shafts, and a large power station complex located ~750 m underground. Of particular note within the power station complex are the Machine Hall (MHA) and Transformer Hall (THA), which are amongst the largest, widest and deepest caverns in the world. The MHA and THA are approximately 310,000 m³ and 160,000 m³ volume, 33 and 20m span and 61.5 and 46m height respectively.

2 METHODOLOGY

2.1 DATA SOURCES

The geological model for the MHA and THA is fed with several data sources, as follows:

1. Site investigations, comprising cored holes and in-situ testing - both from the surface and underground
2. Downhole imagery in percussion-drilled probe holes - both exploratory holes directly ahead of the excavation, and holes in the cavern crown for drainage and shear displacement monitoring. Imagery is collected using Optical Televiewer (OTV) and/or Endoscope camera inspection, and drilling parameters are also recorded.
3. Geotechnical mapping is undertaken at each advance, as per ASTM D4879-08.
4. LiDAR scanning of the exposed rock face is undertaken at each advance.

2.1.1 Site Investigations

The Machine and Transformer Halls have been targeted with several phases of geotechnical investigations throughout the design phase of Snowy 2.0. A total of 7 cored boreholes were progressed from the surface into the Power Station Complex area, up to 1057 m in length. Given the cavern's depth of up to 750 meters below ground, and access constraints on the surface, geotechnical drilling from the surface is time-consuming and costly. To enhance geological understanding and confirm design assumptions, additional cored boreholes have been drilled from adjacent excavations as they progressed close to MHA and THA, and from within the caverns themselves. These have included multiple oriented cores into the pillars between the caverns, and a 250-meter-long horizontal core along the axis of the THA crown. Oriented core, and Optical Televiewer (OTV) and/or Acoustic Televiewer (ATV) imagery in these holes allowed for an understanding of defect frequency, orientation and condition prior to cavern excavations commencing.

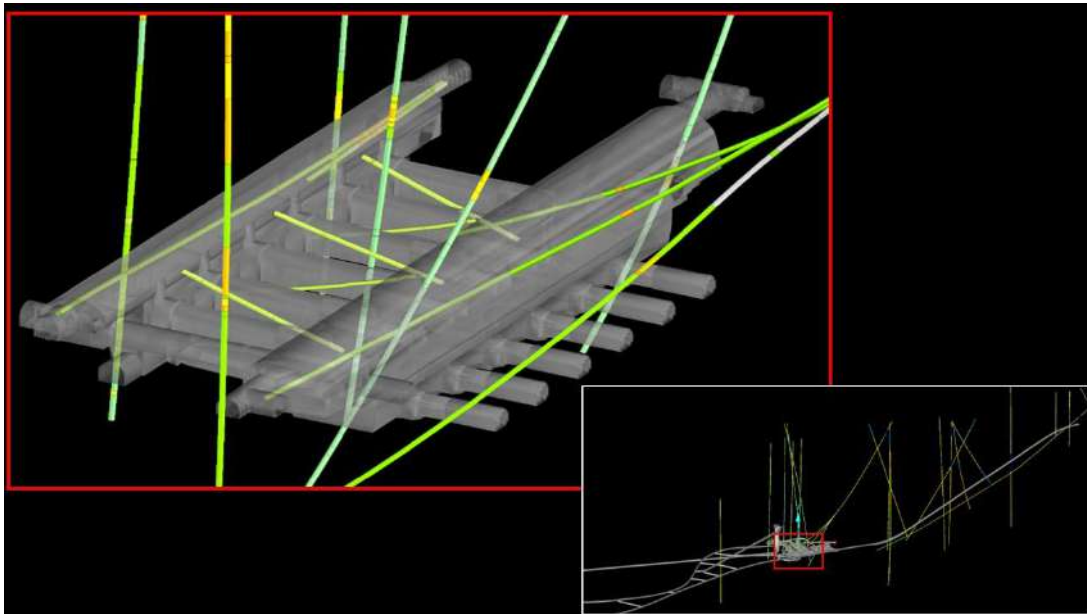


Figure 3: Cored holes undertaken from the surface (refer to inset) and underground at power station cavern (main figure), looking north-north-west. Colours indicate lithology, adjacent tunnels removed for clarity.

2.1.2 Downhole Imagery

Endoscope camera and Optical Televiewer (OTV) are performed in probe holes ahead of the excavation face, and also at the perimeter of the excavation (drainage holes, multi-strand anchors for corbels, and shear displacement monitoring holes) to gain advanced understanding and characterisation of joint set orientations in the rock mass around the excavation periphery. Downhole imagery allows (1) to detect major joints or shear planes which might have not yet been encountered ahead of the cavern excavation, i.e., joints striking out only later in the excavation at the lower part of the cavern, and (2) to follow the evolution of a critical discontinuity at different stages.

To capture endoscope footage, the project utilises a DGRT Wireline Digital Camera 360 View Model 003169, or a SeeSnake CS6X. These capture a forward-facing video of the hole as the tool is inserted or extracted. Contractor's geologists analyse endoscope videos, and note the depth and description of major defects. Endoscope is typically used in place of OTV, where the latter cannot be attained due to physical constraints.

To capture OTV, the project utilises a QL40 OBI-2G Optical Borehole Imager which implements a high-resolution CMOS digital sensor combined with a fisheye lens. This produces a clear 360° continuous-unwrapped digital picture of the borehole walls. OTV images are processed and interpreted using the software WELLCAD (v5.6). Features are classified by type and aperture (such as bedding, parting, closed joint, open joint, seam, etc), and the Rock Quality Designation is calculated. Data can be exported with orientation and categories of the picked features in .csv format.

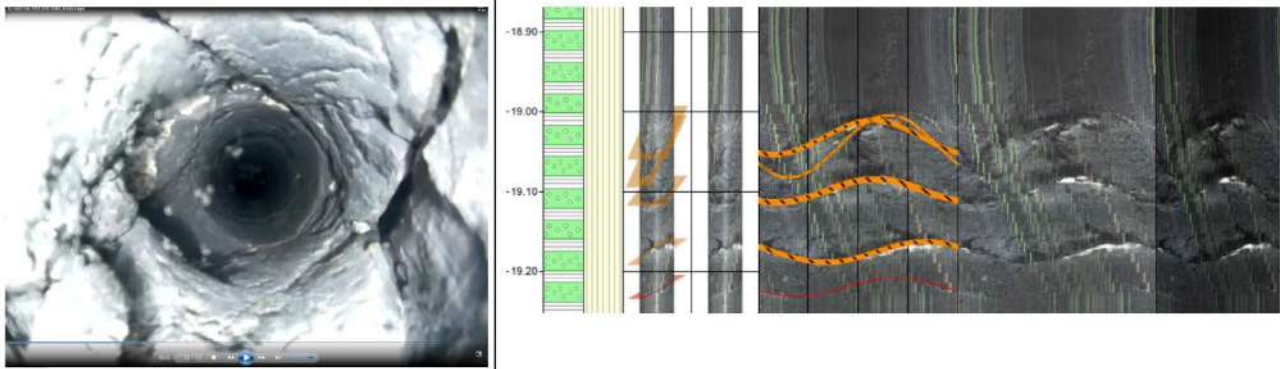


Figure 4: Discontinuity detected in an endoscope (left) vs data available from interpreted OTV (right)

2.1.3 Face Mapping

Geotechnical mapping is undertaken at each advance, as per standard ASTM D4879-08. The face is mapped by the contractor’s geologists, who document detailed descriptions of the discontinuities and defect sets encountered. They also assign a suite of geotechnical parameters which are used as the basis for geomechanical classifications such as the Geological Strength Index (Hoek, Carter, Diederich 2013), Q-system (Barton et al. 1974) and Rock Mass Rating (Beniawski 1989) as well as assigning project-specific Ground Types and Ground Behaviours. These all inform the support class required for the tunnel advance as well confirming the ground conditions remain within the design limitations. A new digital acquisition system is currently being implemented for geotechnical mapping through TUGIS software. This software will streamline the import process of mapping data and pictures into a database which will simplify the modelling of geological features both in TUGIS and other modelling softwares.

2.1.4 LiDAR

During the course of survey and geotechnical inspections of freshly excavated faces, LiDAR scans are collected by the contractor’s survey team using a Leica RTC360 at millimetric accuracy as a part of the project’s employer’s requirements. These LiDAR scans allow for survey and colour accurate ‘point clouds’ of the excavated advance. The point cloud effectively captures the surfaces of discontinuities and lineaments, as the face is scanned from a single origin, capturing shadows cast by protruding surfaces. Thus, by importing these scans, discontinuities can be identified and traced without having to georeference and extensively interpret mapping records. This allows for continuous tracking of defects across multiple advances and headings. Note that this paper focuses exclusively on LiDAR scans on rock surfaces, although the project also utilises LiDAR scans of shotcrete surfaces for as-built records and long-term monitoring.

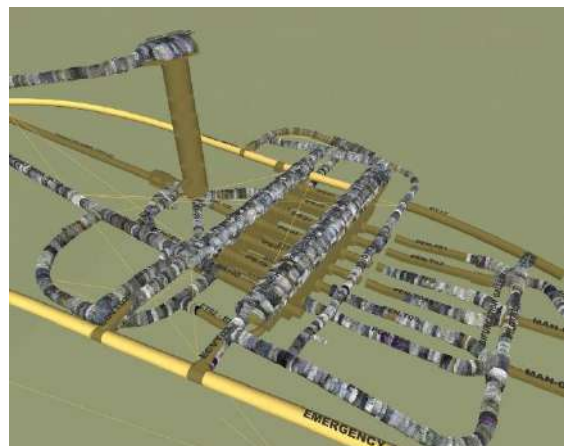


Figure 5: Revizto model of LiDAR scans captured through the excavation of D&B tunnels in the PSC area.

2.2 INTEGRATION AND MODELLING

Collected geological data is integrated into 3D geological models maintained by the designer, contractor, and employer as follows:

- The Designer maintains a geological model in Rhino 6, which is used to feed a digital twin in 3DEC, (Tonioni et al 2024), (Hernandes et al 2025), supporting the observational approach to excavation and informing Witness and Hold Points throughout the cavern excavations. Encountered geological conditions are modelled to assess predicted excavation behaviour and resulting support adequacy.

- The Contractor maintains a geological model in Leapfrog Works, which is a factual summary of major structures encountered in excavation. This provides insight into whether any features may be expected within the remainder of works, and whether this will have an impact upon construction. This will also form the basis of an as-built record.
- The Employer maintains a geological model in the Vulcan package for verification and risk mitigation. This provides an additional layer of rigour, helping to enhance geological insights and ensure that the Owner’s model for operations will contain a comprehensive understanding of encountered conditions and any features requiring monitoring. This approach mitigates operational risks by ensuring potential geological challenges are identified and managed proactively.

The outcomes of the probe holes and explorative investigations are corroborated by the advancements in geotechnical mapping. The table in Figure 6 summarises the diagram flow to process the Geomodel used by the Contractor - starting from the input process, followed by the tools and techniques used to generate finally the model output. The different data sources, and how they are integrated into each model, is tabulated below in Table 1.

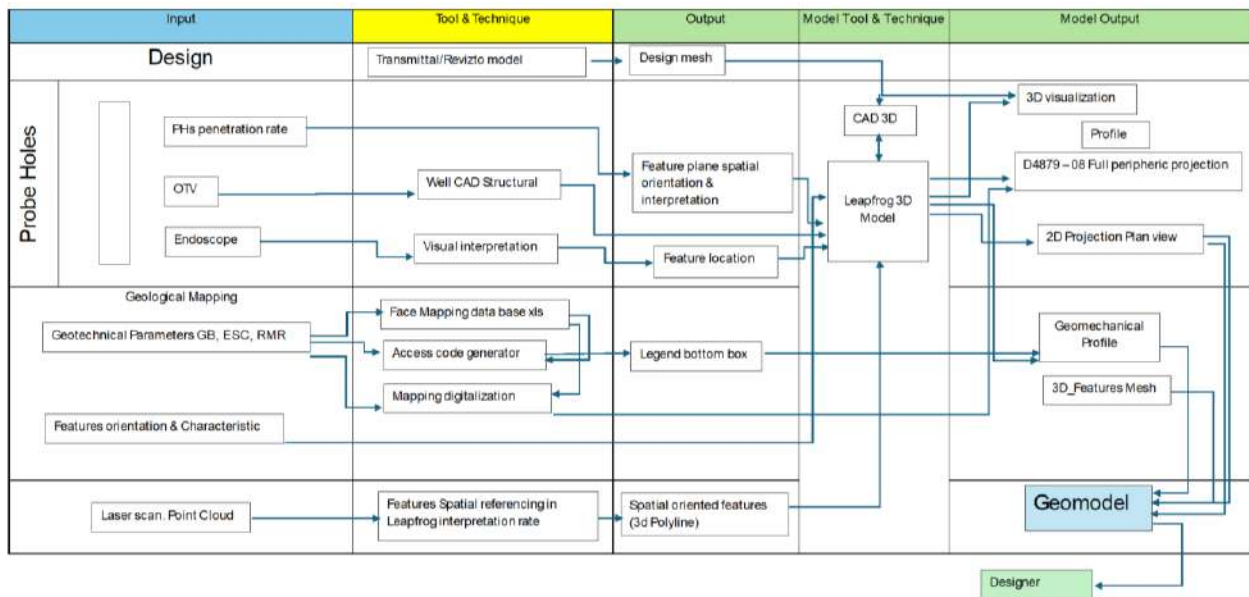
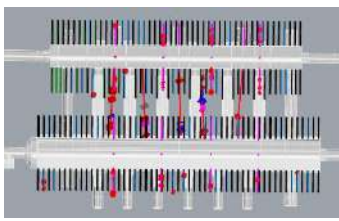
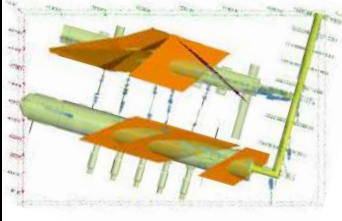
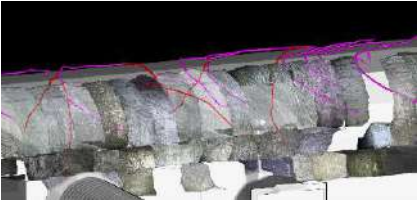
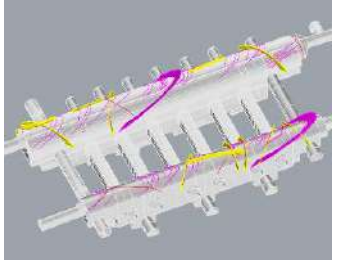
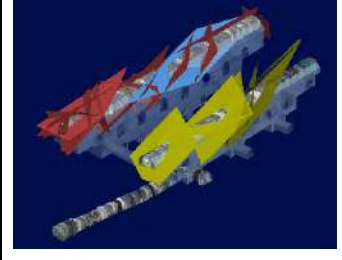
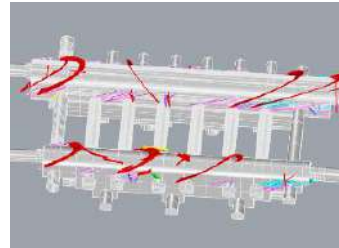
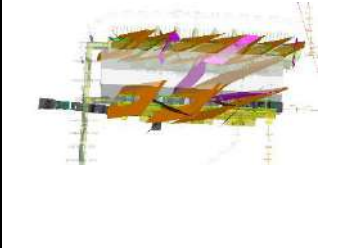


Figure 6: Conceptual map for the development of Geomodels - in use on Snowy 2.0 by the Contractor

Table 1: Methodology for modelling various data sources in each software package

Data Source	Vulcan Package	Rhino 6	Leapfrog Works
Endo-scope	Depths of defects encountered in each hole are recorded by geologists, imported as point data, and plotted as a point along the drill hole.		
OTV	OTV data is exported from the WellCAD .tfd file and saved as a .csv, which can then be imported and displayed as structurally orientated planes.		

	The OTV image itself can also be imported, but relies either on a license extension not available on the project, or a georeferenced image.		
LiDAR	Imported as las or laz files. Discontinuities are traced by creating lines between selected points. A simple projection to a plane can then be made using these points, or using the 'Fault Manager' to account for waviness.	Import of LiDAR is limited, this model relies on export of lines and surfaces of defects picked in the Vulcan Package with cross-checking of traditional mapping.	Processing and interpretation of true colour LiDAR is challenging, therefore this model imports defects as traces or projections
			
Traditional Mapping	Each map has a coordinate assigned, to which the data from mapping (defect type, orientation, properties, etc) is aligned.		Mapped features are traced into a geomechanical profile in AutoCAD 3D, and then integrated into Leapfrog.
	This data is then imported into the Vulcan database, with features typically displayed as structurally oriented discs.		

2.3 DESIGN VERIFICATION

The observational method is currently implemented for the excavation of the PSC. This is supported by the Rhino 6 geomodel and associated 3DEC digital twin (Tonioni et al 2024, Hernandez et al 2025), which are used to inform design control points (Witness Points and Hold Points) defined along the excavation of the PSC. The main objectives of the observational method for design verification are:

- To confirm (or update) the geological conditions and model,
- To confirm the validity of the design (for the actual geological conditions and model),
- To provide design adjustments if the actual conditions differ from the expected design scenarios.

The digital twin model is based on 2 levels of analyses:

- The first level of analyses is the investigation of main discontinuities that can be potential critical areas for the PSC in terms of compliancy of the rock support with the acceptance criteria. The geomodel is continuously updated with the data collected, developed in Sections 2.1 and 2.2 above. Identified potential critical discontinuities are plotted in Rhino 6 geomodel.
- The second level of analyses is developed with 3DEC to carry out “back analyses” identifying the rockbolts exceeding the design criteria based on updated parameters. Georeferenced discontinuities from Rhino 6 geomodel are one of the updated parameters that are inputs of the 3DEC model.

3 RESULTS

3.1 DATA INTEGRATION AND COMPILED MODEL

The integration of LiDAR scans, face mapping, cored holes, downhole endoscopy, and OTV imaging enabled precise identification and tracking of geological features throughout and between the adjacent MHA and THA. This allowed for a detailed understanding of feature orientation and location, which is particularly critical in areas such as intersections with IPB galleries and access tunnels. See below Figure 7 to Figure 9 displaying the final locations of defects tracked in each software, up to the current state of excavation.

Tracing features across multiple datasets also allowed the spatial extent of individual features to be interpreted. Accurate tracing of major features encountered in the sidewalls of the excavations (from LiDAR and mapping), combined with investigative data between and above the caverns (imagery in perimeter holes and cored holes), allowed for a significantly improved understanding of persistence as compared to traditional face maps alone, which are by their nature limited to the field of view. Projecting features between caverns allowed for alignment with information from cored pillar holes and imagery in perimeter holes, showing where features are expected to intersect the pillars. Shears aligned with bedding exhibited significant persistence, typically extending beyond the cavern span, whereas non-bedding-aligned features displayed variable continuity. Additionally, LiDAR scan traces verified that shears exhibited waviness across all orientations, at scales which were much clearer from adjacent LiDAR scans than from individual maps. This allowed for the verification of design assumptions on dilation angle.

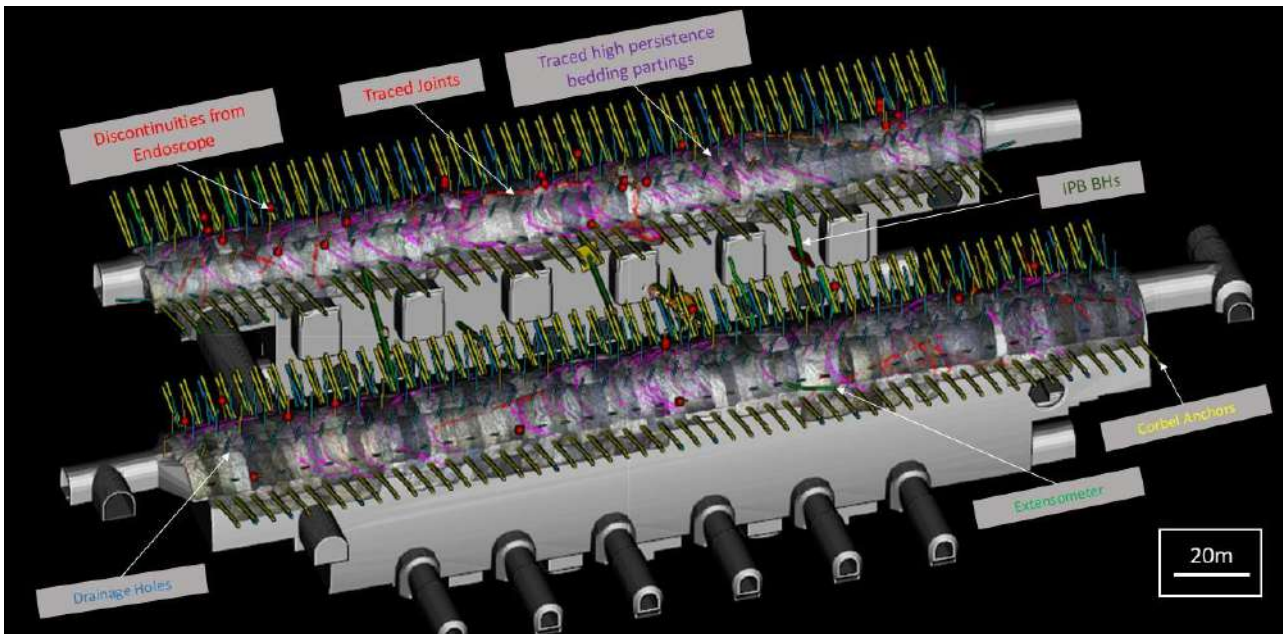


Figure 7: Vulcan package complete geomodel up to current state of excavation, looking north-west

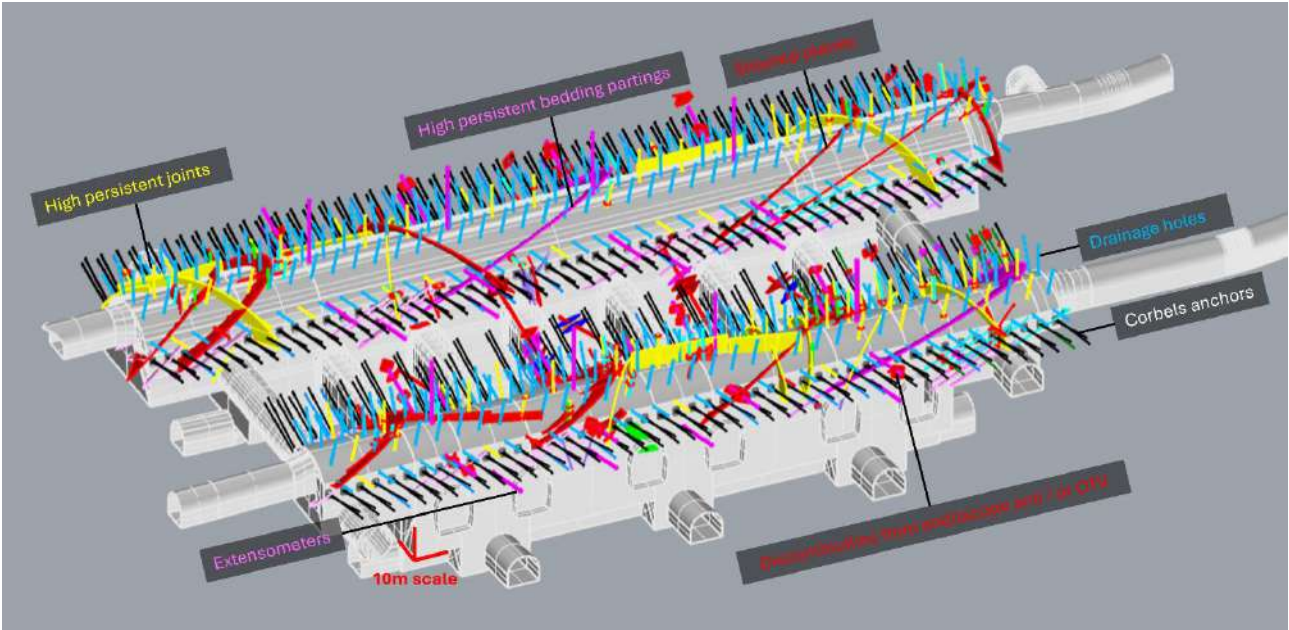


Figure 8: Rhino 6 complete geomodel up to current state of excavation, looking north-west

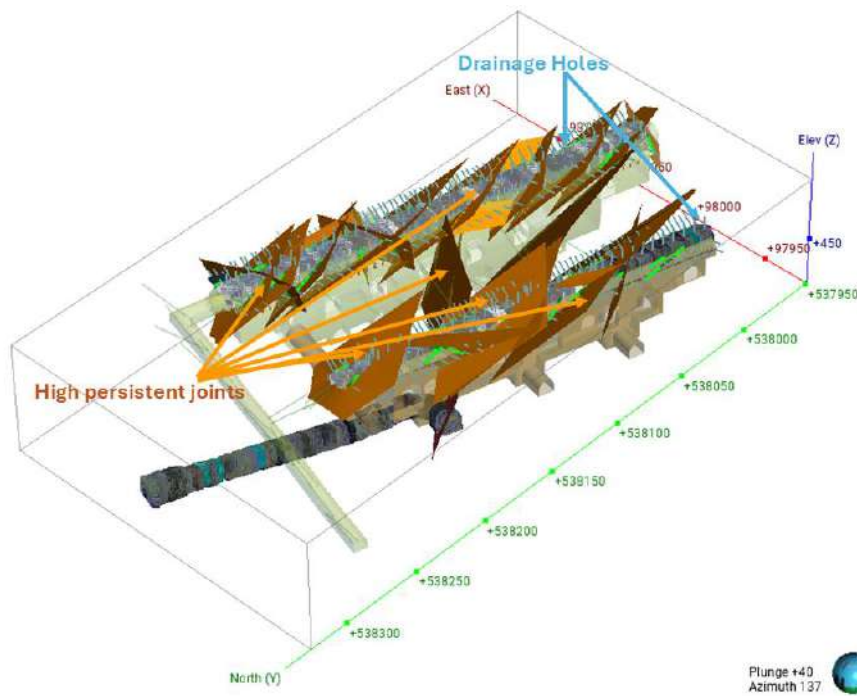


Figure 9: Leapfrog geomodel up to current state of excavation, looking north-west

3.2 CASE STUDY: OVERBREAK IN THA/IPB INTERSECTION

The case study below shows the importance of tracking the location and orientation of features proximal to sensitive locations, in this case, the intersection of the THA and an Isolated Phase Busbar (IPB) gallery. During the geological mapping of each excavation, geological overbreak (GOB) may be identified by the site geologist, occurring when intersecting defects result in the excavation profile exceeding that of design. One such event was identified in the sidewall of the THA, at the future location of the crown of a tunnel immediately adjoining the cavern, as demonstrated in Figure 10 below.



Figure 10: Mapping TH upstream Ch. 132.3 to 144.0

By importing the LiDAR scans of this advance and those neighbouring, the same discontinuity was able to be identified across multiple advances and even benches. This meant it could then be traced directly using the LiDAR scan as demonstrated in Figure 11 below. The orientation of this defect was consistent between both traditional mapping and LiDAR; dip 70 to 80°, dip direction 280 to 290°.

In the construction phase boreholes so far undertaken, this defect has not been detected, thus suggesting that it has a relatively low persistence. However, as construction continues benching down, it allows for additional support to be installed if required, boreholes to be conducted to refine the interpretation of the persistence of the feature, and the targeting defects for shear displacement monitoring should there be a concern it poses a geotechnical risk, such as shearing of installed support.

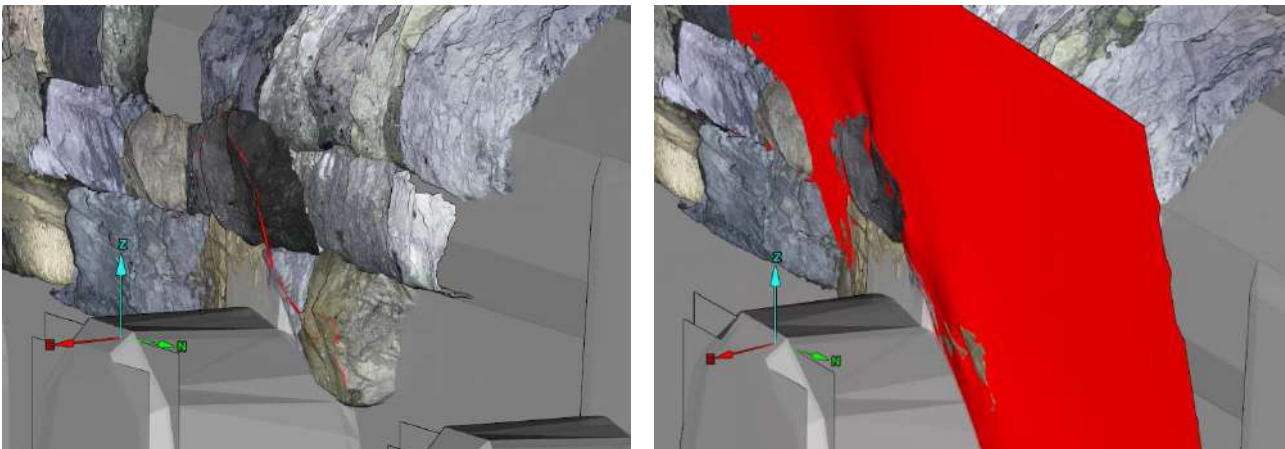


Figure 11: a) Combinations of multiple advances' LiDAR scans, with defect described above traced (red line), looking south-west; b) Projection of trace in 11a, looking south-west

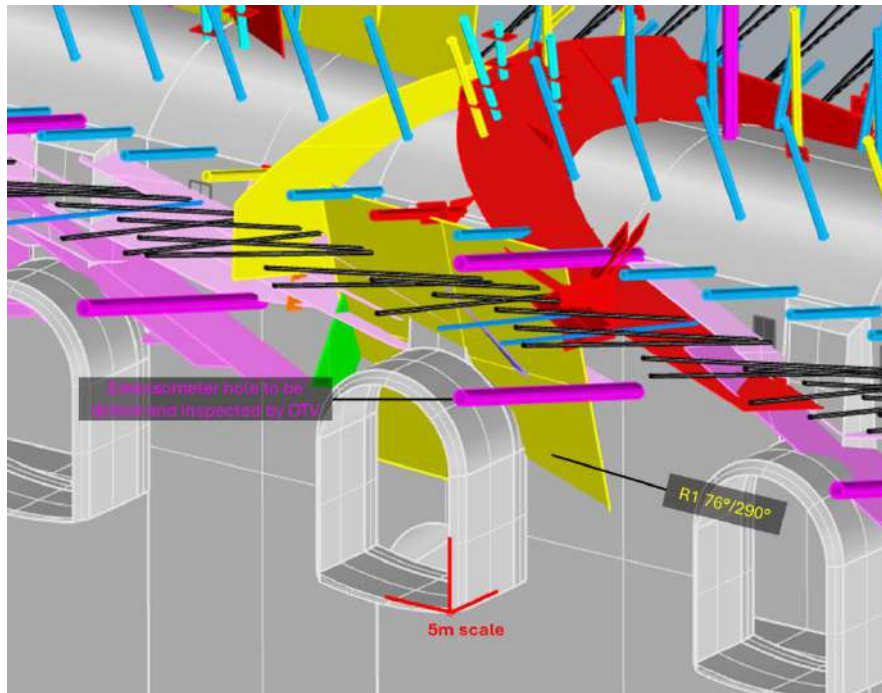


Figure 12: Rhino 6 model, Zoom on TH upstream Ch. 132 to 136, showing all data available in the surrounding of IPB 3. ‘R1’ represents the joint identified in Figure 11.

4 DISCUSSION

The adoption of 3D geological models has proved to be a success on Snowy 2.0, with each model presenting benefits specific to the targeted use and adopted software package. In general, the adoption of 3D modelling softwares has been found to have the following advantages over traditional mapping compilation methods, as follows:

- Allow the rapid visualisation of the main geological features from multiple data sources, with a higher precision resulting from spatially accurate sources such as LiDAR and OTV. Improved understanding of the nature of features, including persistence, waviness etc.
- Comparison of engineering designs within the model - allows for verification of design assumptions, and highlights areas where amendments to design or construction activities, sequencing and monitoring are required.
- Allows features to be projected to future advances to ensure the geologists target the features of interest for more rigorous assessment as they become visible.
- It is fast and simple to add new data and amend interpretations.
- Export of interpretations to 3D BIM models, such as Revizto, for a project wide audience

Table 2: Benefits and limitations specific to each software package used on Snowy 2.0

	Vulcan Package	Rhino 6	Leapfrog Works
Benefit	<ul style="list-style-type: none"> - Rapid visualisation of as-built geology by ease of import of LiDAR scans. - Ability to create defect surfaces that demonstrate the exhibited waviness of the defect, rather than just planar discs or projections. 	<ul style="list-style-type: none"> - Easy extract of the Rhino 6 geomodel for 3DEC model input - Less costly 	<ul style="list-style-type: none"> - Cross sections can be easily cut from anywhere in the 3D model on demand and are automatically regenerated when the model is updated. - The interpolant function can easily provide extended interpretations of features, such as bedding. - User-friendly, easy to learn and common to industry.
Limitation	<ul style="list-style-type: none"> - Cost (more expensive than competitors) 	<ul style="list-style-type: none"> - LiDAR scans limitation due to the big-size data set that is time- 	<ul style="list-style-type: none"> - Leapfrog Works has some limitations for geotechnical modelling, including processing

	<ul style="list-style-type: none"> - Software is targeted towards mining use cases, rather than tunnelling or civil. - The modelling process can be very complex and rigorous compared to other software, though it is improving noticeably in development of the newer ‘Vulcan GeologyCore’. 	<ul style="list-style-type: none"> consuming for import into Rhino 6 model - Planar features modelled in Rhino 6, simplified visualisation that does not show waviness. One single orientation is defining the planar visualisation. - Specific geological modelling tools are not available, requires manual coding 	<ul style="list-style-type: none"> time and the need to adjust model extents. - The importation of LiDAR Data inside the model is not a direct process. It requires an elaboration. In addition, importing big-size datasets is time-consuming. - LiDAR data import requires a high-performance computer.
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Table 3: Benefits and limitations of each data source

Data Source	Benefit	Limitation
Endoscope	<ul style="list-style-type: none"> - Real-time image of the entire holes. - Observation of groundwater inflow - Shear displacement in the hole can be captured - Provides detail of rock colour, weathering condition (when image is clear) - Inexpensive 	<ul style="list-style-type: none"> - Downhole depth in records can be inexact - Captures only a forward-facing view of the hole, meaning defect size and aperture (etc.) can appear distorted or exaggerated. - The camera orientation is not recorded, likewise identified defects cannot be oriented (like they can be in OTV). - Difficult to correlate the features observed with other endoscopes if not interpolated with OTV. - Visual point data, unable to interpret large scale waviness, roughness, persistence or provide a quantified measure of rock quality.
OTV	<ul style="list-style-type: none"> - Features type can be categorised - Feature orientation can be accurately captured - Feature aperture can be accurately captured. - Attains accurate downhole survey of the hole, capturing any deviation 	<ul style="list-style-type: none"> - Cannot be performed when the hole dips > +15° from horizontal (Project specific safety condition). - Visual point data, unable to interpret large scale waviness, roughness or persistence. - Captures only the sidewalls of the hole - Specialised software is required to view and interpret the data file
Lidar Data	<ul style="list-style-type: none"> - Create the most accurate as built geological record possible with high density, spatially accurate point clouds. - Defects can be accurately traced and modelled without the need of georeferencing maps etc. providing an accurate representation of orientation, persistence, and waviness. 	<ul style="list-style-type: none"> - Data-heavy point cloud files can be difficult to store, import and utilise without specialised software and advanced hardware. - Variable underground lighting conditions result in variations in the quality of colour in the scan. - Ensuring appropriate data quality can be challenging. Projects should specify the requirements of LiDAR scans to be not only accurate, but of consistent point densities and lighting. Although it can be difficult to achieve good lighting in a tunnel under construction, poor and inconsistent tunnel lighting results in the colour of scans ranging from black to white, resulting in a “zebra” effect, discernible in figures above.
Geotechnical (traditional) mapping	<ul style="list-style-type: none"> - Detailed geotechnical analysis of each feature, including roughness and infilling. - Overview of waviness that cannot be detected by an OTV related to the difference in scale - Stress (i.e. audible, spalling) and water (i.e. damp, dripping) conditions can be observed and documented 	<ul style="list-style-type: none"> - Human error/typos. - Less accuracy of defect orientations as the geologist cannot physically measure the surface (personnel must remain ~2 to 4 meters behind the face due to unsupported ground restrictions) - Subjective assessments based on experience of geologist

In addition to the points above, geomodels developed by both the Contractor and Designer have allowed the targeting the placement of shear displacement monitoring holes according to identified discontinuities observed in-situ. The objective of this monitoring is to check for any shear displacement along features which may impact the integrity of installed support. The contractor undertook the monitoring at the completion of excavation of each bench, using endoscope camera inspections to check the feature conditions and the absence of movement. Beyond the first three benches, ongoing shear displacement monitoring has been refined based on the shear potential observed in previous records and geo models.

The designer has successfully utilised the Rhino 6 geological model to inform the 3DEC model for several Hold and Witness points in the cavern excavations to date. Figure 13 shows the geological model from Rhino 6 developed for Hold Point 2, and the 3DEC twin numerical model refined taking the Rhino 6 geomodel as input. The reassessment of the design at this control point resulted in the prediction of a lower number of rock bolts exceeding the design criteria at the end of the excavation than what was foreseen during the original design. This has allowed for the adjustment of excavation sequencing and the installation of the rock support, and has also given room to updating the re-bolting strategy.

The Owners geological model has in particular been successful in identifying highly persistent features from LiDAR scanning across multiple advances, including several features which were not clear from traditional mapping methods. This has been used to not only feed the Contractors and Designers models of major structures, but to ensure that the owner’s model for Operations and Maintenance will contain an accurate representation of encountered conditions. This will assist in understanding any unexpected excavation behaviours across the 150-year design life of the structure, and allow for targeted and efficient treatment as required.

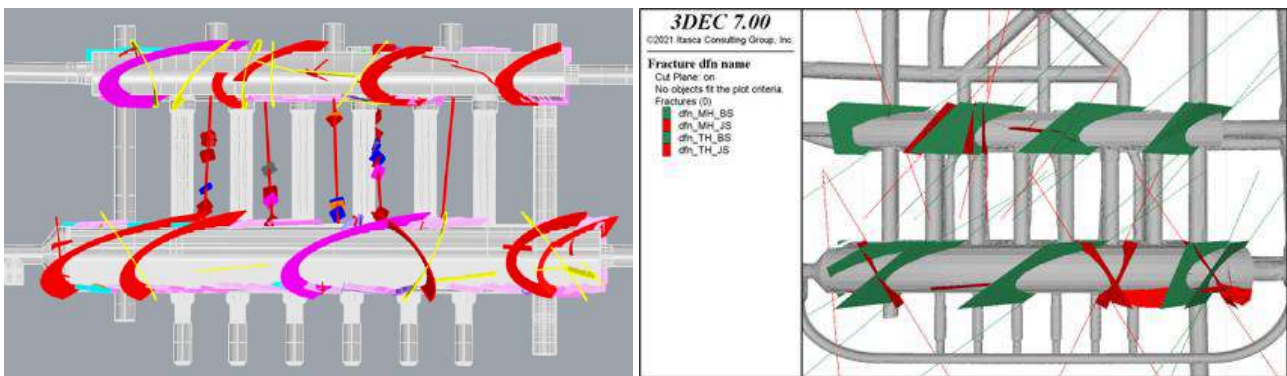


Figure 13: Comparison of models developed for Hold Point 2; a) Rhino 6 Geomodel; and b) 3DEC numerical model

5 CONCLUSION

The Snowy 2.0 project presents significant geotechnical challenges due to the complexity and scale of its underground excavation works, including some uncertainty in ground conditions even within key structures such as the Machine and Transformer Halls. To address these challenges, an observational approach to excavation has been adopted, leveraging the use of multiple models and numerous sources of data to continuously refine geological models and compare expected conditions and excavation behaviour to design assumptions.

This study has demonstrated how integrating multiple data sources - such as LiDAR scanning, traditional mapping, downhole endoscopy, and Optical Televiewer (OTV) imaging together with early-stage site investigations - enhances geological modelling. Accurate tracing of major features using LiDAR and mapping, combined with investigative data from perimeter and cored holes, significantly improved the understanding of feature location and persistence beyond the limitations of traditional face maps, including above and between the caverns. LiDAR scan traces verified feature waviness. The case study of the THA/IPB intersection showed how LiDAR scans can be used to trace a feature beyond the extent which would be noted in traditional mapping, and how this has allowed the feature to be tracked and investigated at a key location where it may impact excavation and support.

By integrating multiple data sources within multiple 3D geomodels, the project has strengthened design verification and improved geotechnical risk management both for during the construction and operation phases of the power station. This integrated approach not only supports safe and efficient excavation, but also provides a valuable and robust framework for future underground projects.

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