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The use of optical televiewer and endoscope imaging methods in TBM tunnels to predict ground conditions

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ABSTRACT: Snowy 2.0 is a 2.2 GW pumped hydro project currently under construction in the Snowy Mountains, New South Wales, Australia. Four shielded TBMs are being used to progress approximately 31.4 km of tunnels through complex alpine ground conditions. Due to the nature of shielded TBMs, obtaining information on ground conditions is extremely challenging compared to D&B tunnelling. Information from probe holes in advance of the TBM is therefore key in risk mitigation; predicting ground conditions and features of concern in advance of the excavation and allowing them to be dealt with appropriately. This paper explores the use of imagery in percussion drilled probe holes ahead of TBM excavation to forecast ground conditions. A comparison between Optical Televiewer (OTV) and Endoscope imaging methods is made, including the observed key benefits and challenges of each method, the outcomes of each method such as key outputs, image quality, time and cost efficiency

1 INTRODUCTION

The Snowy 2.0 Pumped Storage Project (S2.0), currently under construction, represents a significant expansion to the renowned Snowy Mountains Hydroelectric Scheme. The original Scheme, located in New South Wales, Australia, was constructed between 1948 and 1974. It is recognized as one of the world's most impressive civil engineering feats, with a capacity of 4.1 GW, 16 dams, 9 power stations, and a network of 145 km of tunnels. S2.0 will enhance the existing scheme by adding 2.2 GW of power generation capacity with 350,000 MWh of storage, providing deep energy storage to support the growth of Australia's renewable energy generation. S2.0 involves substantial and complex underground works including ~31.4 km of TBM-driven tunnels, ~10 km of drill-and-blast tunnels, three shafts, and a power station complex located ~750 m below surface. This paper will focus on the TBM driven power waterway tunnels, excavated by 4 single-shield TBMs.

Snowy Hydro Limited, the owner, has engaged Future Generation as Principal Contractor for civil works - a consortium comprising Webuild, Clough, and Lane. The design joint venture includes Lombardi, Tractebel, and Coffey, whilst SMEC are engaged to provide technical engineering support to the owner.

The project is situated in a complex alpine geological setting, with 7 geological formations and over 40 lithologies (Figure 1). Rigorous site investigations have been undertaken in many stages throughout the project to date. However, due to the long, linear and deep nature of the project, the complex geological setting, and access limitations from the project sitting within a remote and pristine national park, it was not practically possible to fully define ground conditions along the entire alignment prior to excavation. This is particularly true for the long TBM driven power waterway tunnels, with some sections having up to 2.5 km between boreholes. The tunnels' segmental lining (and the TBM's themselves) are designed to cover the full range of ground conditions considered possible along the alignment. However, understanding when to implement support classes, pre-treatment, or TBM excavation modes requires good understanding of ground conditions directly ahead of the TBM excavation. This can be challenging in a shielded TBM due to minimal opportunities and accessibility to directly view ground conditions.

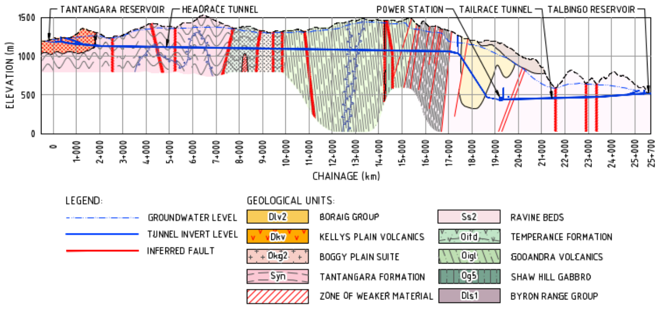


Figure 1. Geological long section of the S2.0 Power Waterways tunnels

To ensure sufficient notice is given on ground conditions directly ahead, each TBM is equipped with a minimum of two drill rigs capable of both percussive and rotary drilling (Figure 2). Percussively drilled probe holes are undertaken in an overlapping fashion. These provide information on conditions ahead through the return of small rock chips, measurements of groundwater inflow, drilling parameters, and, the subject of this paper - imagery in the form of Optical Televiewers (OTV) and Endoscopes. Face mapping is undertaken daily together with photogrammetry, and is combined with information from probing and TBM parameters to assess ground conditions, verify design assumptions, assess whether pre-treatment is required, and select the correct segment support class for installation. This paper will focus on the use of imagery in percussively drilled probe holes, and will discuss what information can be obtained from each imagery type, the advantages and limitations of each and key observations.

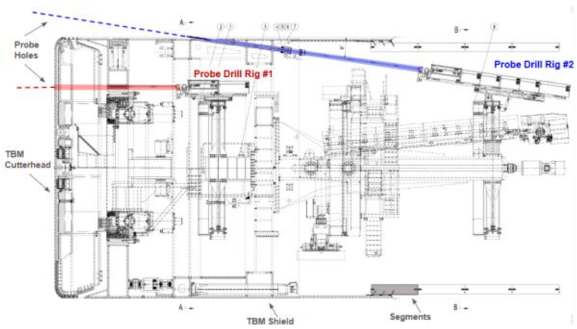


Figure 2. Positioning of drill rigs and probing locations from TBMs

2 METHODOLOGY

Ground conditions ahead of the TBM are defined based on information from multiple sources, including probe drilling, face mapping, and photogrammetry. While geological mapping and photogrammetry is typically undertaken daily, this provides only single spatial snapshot of conditions at the excavation face, and not beyond. To collect information in advance of the excavation and continuously along the drive, probe holes are progressed 60-100 m ahead of the face.

On S2.0, all TBMs are equipped with drills capable of both percussive and rotary drilling. Drilling cored holes from within the TBM is possible and is advantageous in terms of sample recovery. However, depending on hole length and ground conditions, this may take up to several days to complete and is therefore not a time-efficient option as construction is halted during these activities. In contrast, a percussively drilled probe hole of the same length can be progressed in a fraction of the time - as little as a few hours. This provides rock chip return, an assessment of groundwater conditions, drilling parameters, and an opportunity to insert cameras into the hole. However, percussively drilled probe holes can present certain limitations. Sample return is often challenging, as rock chips often become trapped between the rock and the TBM shield. Drilling parameters can be highly variable for reasons other than ground conditions, including factors like drilling technique, machine performance and equipment condition, and are therefore difficult to reliably assess.

OTV and endoscope recordings prove to be extremely valuable in providing direct visual confirmation and aiding in the interpretation of subsurface conditions. This provides key information on lithology, defect spacing, and some aspects of defect condition, whilst taking only two hours.

After completion of drilling and flushing of the hole, the geologists perform the image inspection. Depending on observations during drilling, the geologist on site has the authority to decide if it is necessary to do a preliminary inspection of the hole with the endoscope (to assess the hole condition) or proceed directly with OTV inspection. This is done to minimize risk of damaging the OTV tool, as it is more costly and fragile. The process ends with a groundwater inflow measurement, inserting a packer at 4m depth. Finally, all observations from the endoscopes and OTV, are reported in the probe hole geological assessments, which compiles assessments from all datasets including drilling parameters, cuttings description and water inflow measurements. These are assessed against design assumptions.

2.1 *Optical Televiewer (OTV)*

2.1.1 *Tool*

The OTV QL40 probe line is designed to capture high-resolution, magnetically oriented colour images of borehole walls, enabling detailed logging of rock types and structures. The tool uses a digital camera paired with a conical mirror to produce continuous 360-degree images in both air- and water-filled boreholes.

OTV tools are designed primarily for use in vertical holes and have fragile glass housing for cameras. Scenarios like steeply inclined boreholes, with non-curvilinear geometries, or the presence of residual materials within the borehole that cannot be adequately cleaned, therefore render OTV usage challenging. To mitigate this, on S2.0, a light perspex housing is applied overlying the glass, to reduce glass fractures and/or waterlogging the camera.

2.1.2 *Procedure*

The following outlines the steps of executing imagery using the OTV tool:

- Instrumentation Setup: Connect the OTV, datalogger, and winch to the power source; configure recording and image acquisition settings.
- Tool Insertion: Insert the tool into the probe hole (PH) and set the 0-meter depth reference and start the preliminary record. Push the instrumentation into the PH using 32 mm PVC tubing and maintain a maximum speed of 5m/min to avoid tool crashing. During the pushing in of the tool, the images are checked for quality and equipment setup.
- Tool Retrieval: Upon reaching the end of the hole, stop recording. Begin a new recording during retrieval setting the winch at a maximum of 3 m/min for best image quality. Operators detach PVC tubes as they exit the hole, reducing the speed during this process to avoid interference with the winch and image quality.

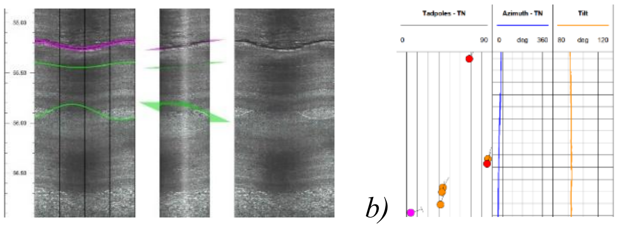
2.1.3 *Data Analysis*

WellCAD is a software by RocScience used for the import, processing, interpretation, and visualization of geophysical and geological data collected in boreholes with OTV. The software allows analysis of geological structures including location, type, and orientation of defects, as well as aperture, infilling, and to some extent waviness.

Images are processed by splitting them along a reference azimuth (typically north), then unrolling and flattening them into a 2D log for interpretation, and borehole irregularities such as breakouts or washouts can be identified. This method transforms raw image data into a precise structural map of the borehole.

Within the S2.0 project, two distinct reports are developed. A preliminary report is produced immediately after drilling and presents an image of the borehole accompanied by azimuth and inclination data of the hole. This provides a quick but effective preview of the status of the rock mass, and permits a quick visualization of whether critical zones are present. Subsequently, the final report is produced, elaborated with WellCAD, involving picking of the geostructures. This report displays the image of the borehole in two forms: an unwrapped 2D image and a 3D core-like view. It presents an overlay of the structure on the borehole image, hole survey information (Figure 3a) and tadpoles illustrating the corrected orientation of the structures, along with azimuth and tilt charts (Figure 3b). It is worth noting that in the TBM environment, the method is limited in Azimuth (TN) accuracy for the first 10m to 15m due to magnetic interference from the shield.

Defect information such as type, orientation, and aperture, and other information such as hole survey, temperature, magnetic field can be easily exported (a sample of extracted defect attributes from WellCAD shown in Figure 4) and used to analyse the rock mass properties in excel sheets and 3D modelling software such as Leapfrog Work, Vulcan and Rhino.

a) 

b)

Figure 3. a) Visual modules in an OTV report and b) tadpoles of structures and hole survey in an OTV report

Depth	Dip	Azimuth	Type	Apertur	Infilling	Shape
m	deg	deg		mm		
0.37	78.74	231.53	JT	0	N	PL
0.43	13.97	123.88	PT	1.27	N	PL
0.79	78.38	289.47	JT	2.49	N	PL
1.26	79.4	216.25	JT	0	N	PL
1.4	82.96	224.85	JT	1.45	N	PL
1.53	21.91	39.3	PT	0	N	PL
1.88	35.98	23.11	JT	0	N	PL
2.06	15.18	102.94	PT	0	N	PL
2.12	86.72	27.58	JT	0	N	PL
2.53	13.39	66.01	PT	0	N	PL
2.74	52.55	200.42	VO	0	H	CU
3.75	44.72	19.22	JT	0	N	CU
3.98	70.11	24.79	JT	0	N	CU
4.2	84.73	109.08	JT	0	N	CU
4.49	49.55	12.38	JT	0	N	CU
4.96	81.31	202.77	JT	7.94	N	UN

Figure 4. Example of extracted information of picked structures from WellCAD

2.2 *Endoscope*

2.2.1 *Tool*

On the S2.0 project, two types of endoscope cameras are used. The DGRT Wireline Digital Camera 360 View provides very good resolution and accurate images, however has similar limitations to the OTV due to its dimensions (1m length and 40mm diameter), weight, and equipment set up requiring a winch. The Ridgid Seesnake is simpler to use due to the 35mm diameter and 42mm length camera, equipped with 11mm push cable and powered by battery.

Both provide a practical and effective method for examining geologic structures and discontinuities in real time. The Ridgid camera has certain limitations, such as a lower resolution and accuracy than the DGRT camera, but is typically sufficient in providing preliminary information for the scale of the tunnels. The Ridgid camera is the preferred method for collecting the endoscope images in S2.0.

The endoscope is an invaluable tool in specific project scenarios where the use of an OTV is hindered by technical challenges, as mentioned in Section 2.1.1. In such cases, the endoscope proves its worth by enabling the acquisition of visual data, playing a crucial role in ensuring that probe hole imagery can still be captured, maintaining the continuity and reliability of the data collection process.

2.2.2 *Procedure*

The following outlines the steps of executing imagery using the endoscope tool:

- Instrumentation Setup: configure recording and image acquisition settings.
- Tool Insertion: Insert the tool into the probe hole (PH) using the self pushing cable (Ridgid) or PVC pipe (DGRT). Set the 0-meter depth reference and start recording.
- During: Real time footage is monitored via screen, with operators targeting certain sections of interest with slower speed if needed, or stop the pushing if the hole is obstructed.
- Footage is captured both inwards and outwards through the hole, giving different quality of images depending on the water flow condition of the hole.

2.2.3 *Data Analysis*

For endoscopic imagery, the first analysis is undertaken simply by watching the video screen as the tool is inserted into the hole. This provides an immediate assessment of conditions, and checks whether it is safe to proceed with the OTV record. Then, the geologists again watch and analyse the endoscope video, where more detailed observations and notes of ground conditions and any potential geohazards are taken and reported in the probe hole geological assessment.

3 RESULTS

3.1 *Geotechnical features interpretation*

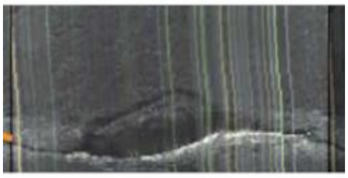
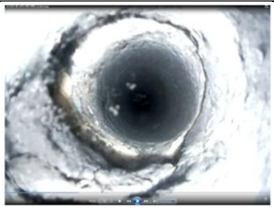
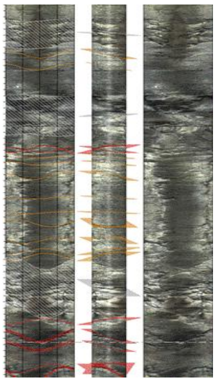
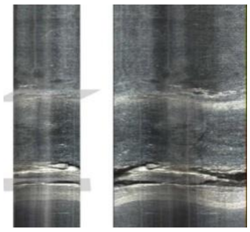
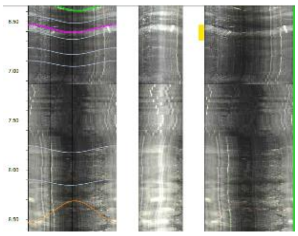
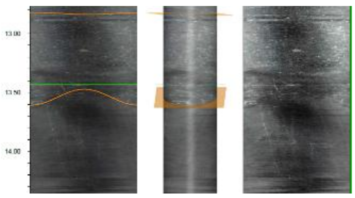
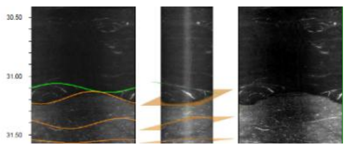
Side-by-side comparison of OTV and endoscope data from the same borehole illustrates the unique perspectives each tool provides for geostructural and geotechnical feature analysis. Table 1 presents examples where OTV and Endoscope imagery was useful in understanding specific geological conditions, and the key differences of OTV and endoscopes in these situations.

Extracts and screenshots from images produced by the OTV and endoscope quickly show that by nature of the camera lens, features typically appear larger in endoscopes, whilst OTV provides a less biased view of the aperture of a feature, see Observation 1 in Table 1. In Observation 2, the high quality image allowed good visibility of the sheared features of concern and ability to easily assess geotechnical attributes which led to timely decision-making by the designer in regards to the suitable excavation support class in that section.

Observation 3 in Table 1 shows endoscope imagery of a geological feature where water flow was observed. This confirmed the exact location of water inflow and visual assessment of the rate and behavior of inflow, which could not be captured precisely either from an OTV or the standard inflow test. On the other hand, OTV provided high-quality images and strong quantitative data of the feature such as defect type, defect orientation, defect location, planarity, infilling and aperture. In addition to the outputs from each tool, the combination of the two sources of information provided complementary benefits and better understanding of the situation.

Changes of geological formations are also effectively presented by the OTV reports in Observation 4 and Observation 5. Notably in Observation 5, the contact is not easily distinguishable in the endoscope videos. In combination with the accurate depth tracking, ability to pick dip and dip direction, planarity and correction based on hole survey, a confirmation of the precise location and direction of the contact was obtained.

Table 1. Key observation findings.

Key Observations	Extract from OTV reports, depth scale of 1:20m	Screenshots from Endoscope videos
Observation 1: Sheared feature observed in a probe hole showing typical ground conditions in Ravine Beds West. Endoscope allows slightly more visibility of defect coating due to the nature of the camera lens.		
Observation 2: Observed sheared features in OTV, excavation support class change was recommended by the designer. The mapping performed on this area later confirmed the presence of these sheared zones.		No endoscope is available for this probe hole.
Observation 3: Geological feature from where water flow was observed in Endoscope video. OTV image does not capture water flow but provides high-quality image of the defect.		
Observation 4: Geological formation Ravine Beds West to Boraig Group, clearly observed in OTV. In the endoscopic image, the contact is not easily distinguishable.		
Observation 5: Intercalated contacts between Kelly's Plain Volcanics Formation and Peppercorn Formation at 13.0m depth and 31.0m depth.		No endoscope is available for this probe hole.
Also, a change in TBM parameters and lack of rhyodacite in the cuttings has confirmed that the excavation has passed through the contact.		

4 DISCUSSION

Table 2 below summarizes key outputs available, and advantages and disadvantages of the two imaging tools.

Overall, whilst OTV generally provides a more technically rigorous output and its information is powerful in assisting design assumptions confirmation, the simplicity and cost advantages of endoscopes spotlight the tool's beneficial practicalities while typically still being able to provide sufficient information to clear that no geological hazards are present along the hole.

Noting the prominent time saving between progressing percussively drilled holes vs. cored holes, the ability to capture imagery in percussive holes allows a similar level of information to be obtained at an overall fraction of the time, offering a significant production advantage with still great information return.

It is important to note that in cases of very poor ground conditions where the drilled hole is collapsing, or where there is a high groundwater inflow at high pressures, the use of either tool would not be physically feasible, and in this case, assessment will rely on drilling parameters and coring, it is also noted that the knowledge that the hole was collapsing is in itself noteworthy and to be considered in the evaluation.

Table 2. Summary of available outputs, pros and cons of OTV and Endoscope

	OTV	Endoscope
Outputs	– Output format as image, or pdf – Quantitative data (defect type, defect orientation, defect location, planarity, infilling, aperture) via WellCAD – Qualitative (observation of grain size, change in lithology, weathering) – High quality imagery – Survey data (orientation of probe hole in the form of Tilt and Azimuth)	– Output format as video – Qualitative assessment (defect relative orientation, estimated defect location, planarity, infilling, aperture, observation of grain size, change in lithology, weathering) – Location of the water sources and estimation of the water inflow observed
Pros	– Accurate quantitative geotechnical parameters obtainable, high quality imagery allowing detailed assessment – Corrected dip/dip direction of picked features based on hole survey – Easy extraction of information allowing straightforward inputs to geological models, and/or calculations – Image output easily accessible and shareable – The ability to adjust the depth scale during viewing and printing	– Local providers with stock available – Specialist software to interpret data is not required – Tool is typically lower cost – Allows observations of water inflow – Versatility due to the small diameter and strong camera – Battery powered
Cons	– Tool is typically higher cost and more fragile – It does not provide images in front of the tool, risking its integrity when it needs to be pushed into the hole – Power connection is required – Cannot easily show locations of water inflow	– Video formats can be inconvenient for sharing/communication or storage consuming, especially in larger scale projects – Geotechnical parameters such as dip/dip direction of the structures can only be inferred from video – Observations both qualitative only and less accurate – Assessment may be more time-consuming due to video format

4.1 *Role of OTV and Endoscope in Clarification of Design Assumptions and Risk Management*

As discussed, the project sits within a complex alpine geological setting, with limited information available along some portions of the alignment, particularly the long TBM driven power waterways. Although there are several predicted areas of higher geological risk, there remains potential for additional unexpected geological hazards to be present in other areas. Unlike a smaller metropolitan project where the ground conditions are heavily investigated and understood, on long, deep and remote alpine projects it is not possible to pre-prescribe support to a certain area. The design is rigorous in being able to cover the full range of conditions which may be encountered. However, there remains a level of uncertainty as to precisely where along the alignment any particular hazard may be encountered, and therefore where a certain pre-treatment, support class, or even TBM excavation mode may be required. Being able to understand the conditions directly ahead of the TBM excavation is therefore vital for risk mitigation, to highlight any hazards present ahead and to act accordingly. This allows the TBM to proceed with confidence, understanding that the risk of encountering unexpected features without advance warning is reduced.

Imagery acts to enhance the information available from percussively drilled holes, which is in particular useful for validating and, if needed, modifying design assumptions. Segmental lining design uses Geological Strength Index (GSI) as one of the key parameters. The use of OTV allows for the estimation of GSI, by providing information on defect spacing/RQD and many properties required to assess defect condition (aperture, infilling, weathering, and to some extent, waviness). This allows for the validation of design assumptions and the appropriate selection of support for installation. Similarly, where larger features (such as shear zones) are encountered, imagery from both OTV and Endoscope can provide more information on the nature and extent of the feature than simple drilling parameters. This provides the designers with the information required to assess whether a feature falls within or outside of design assumptions, and whether any pre- or post-treatment may be required. Should more detailed information be required, the TBMs are equipped with coring capability which can be used to target areas of concern highlighted by the percussive probing and imagery.

5 CONCLUSION

The use of downhole imagery has proven to be exceedingly useful on S2.0, offering an advantage over standard percussively drilled holes, which are more heavily reliant on simple drilling parameters and chip collection. It allows geological information gathered to rival that obtained during core drilling, but at a fraction of the drilling time.

Having these instruments as part of the contractors' toolbox increases the capability to react to encountered conditions quickly and mitigate the always present risks and uncertainties during tunnelling. Observations from S2.0 discussed in this paper have demonstrated the value of advance information from probing, amplified by downhole imagery and the unique benefits that each tool brings, with a specific focus on changes in lithology and geological formation, groundwater inflow, and understanding features of concerns. Both OTV and Endoscopes are useful tools with advantageous practicalities that play an important role in risk mitigation, predicting ground conditions in advance of the TBM excavation and allowing them to be dealt with appropriately and safely.