A Geophysical Investigation of Near Vertical Boreholes in the Roof of an Underground Tunnel in a Coal Mine

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ABSTRACT
As part of a tunnel roof reinforcement feasibility study, five vertical boreholes were drilled in the roof of an underground tunnel and were logged using unconventional wireless geophysical instruments specifically designed for challenging operational environments. The program was completed in conjunction with a broader drilling program to understand the overlying lithology and bedrock structure as a basis for reinforcement against future planned close proximity mining activities. The tunnel serves as the only corridor for raw coal conveyance from the mine operations to the process plant. The geotechnical investigation was conducted without disruption to the processing plant and conveyance infrastructure.

The geophysical investigation was crucial in supporting the assessment of the jointing and bedding characteristics of the rock mass as well as the lithology. This data was used to evaluate basic tunnel support requirements through closed form analytical solutions to estimate maximum support capacities for the general types of support systems, and to allow for the estimation and evaluation of mining impacts using a series of 2-D finite element numerical models in the PLAXIS™ software suite. The operational challenges encountered in the geotechnical investigation were helpful to highlight potential constructability issues for future tunnel reinforcement works.

RÉSUMÉ
Dans le cadre d'une étude de faisabilité du renforcement du toit du tunnel, cinq forages verticaux ont été forés dans le toit d'un tunnel souterrain et ont été exploités à l'aide d'instruments géophysiques sans fil non conventionnels spécialement conçus pour les environnements opérationnels difficiles. Le programme a été complété en conjonction avec un programme de forage plus vaste visant à comprendre la structure lithologique sus-jacente et la structure du socle rocheux comme base pour le renforcement des futures activités minières prévues à proximité. Le tunnel sert de seul corridor pour le transport du charbon brut entre les opérations de la mine et l'usine de traitement. L'étude géotechnique a été menée sans perturber l'infrastructure de traitement et de transport.

L'étude géophysique a été cruciale pour soutenir l'évaluation des caractéristiques d'assemblage et de stratification de la masse rocheuse ainsi que de la lithologie. Ces données ont été utilisées pour évaluer les besoins de base du tunnel par des solutions analytiques fermées pour estimer les capacités de support maximales des types généraux de systèmes de support, et pour estimer et évaluer les impacts miniers à l'aide d'une série de modèles numériques 2D. Dans la suite logicielle PLAXIS ™. Les défis opérationnels rencontrés dans l'étude géotechnique ont été utiles pour mettre en évidence les problèmes potentiels de constructibilité pour les futurs travaux de renforcement des tunnels.

1 INTRODUCTION

The Raw Coal Conveyance Tunnel at Teck Coal's Elkview Mine was constructed in 1968-1969 and serves as a critical corridor for raw coal conveyance and houses critical infrastructure for the operation. As the Elkview Mining Operations (EVO) advances to the Baldy Ridge Extension (BRE) component of the project, upgrading the existing conveyance tunnel to withstand the planned mining area expansion, which will have mining operations in close proximity to the tunnel, is essential to extending the mines life.

A geophysical borehole program was completed in conjunction with a broader drilling program to understand the lithology and bedrock structure overlying the tunnel.

Three (3) wireless geophysical instruments were used:

- Optical Televiewer
- Natural Gamma
- Deviation

2 GEOLOGY

Geology is based on regional studies performed by various groups in the last 11 years. The Elkview mine is situated in southeast British Columbia, Canada. The region is underlain by the Fernie Formation and Kootenay Group, which includes the Morrissey Formation and economically significant Mist Mountain Formation. Geology overlying the tunnel is presented in Figure 1.

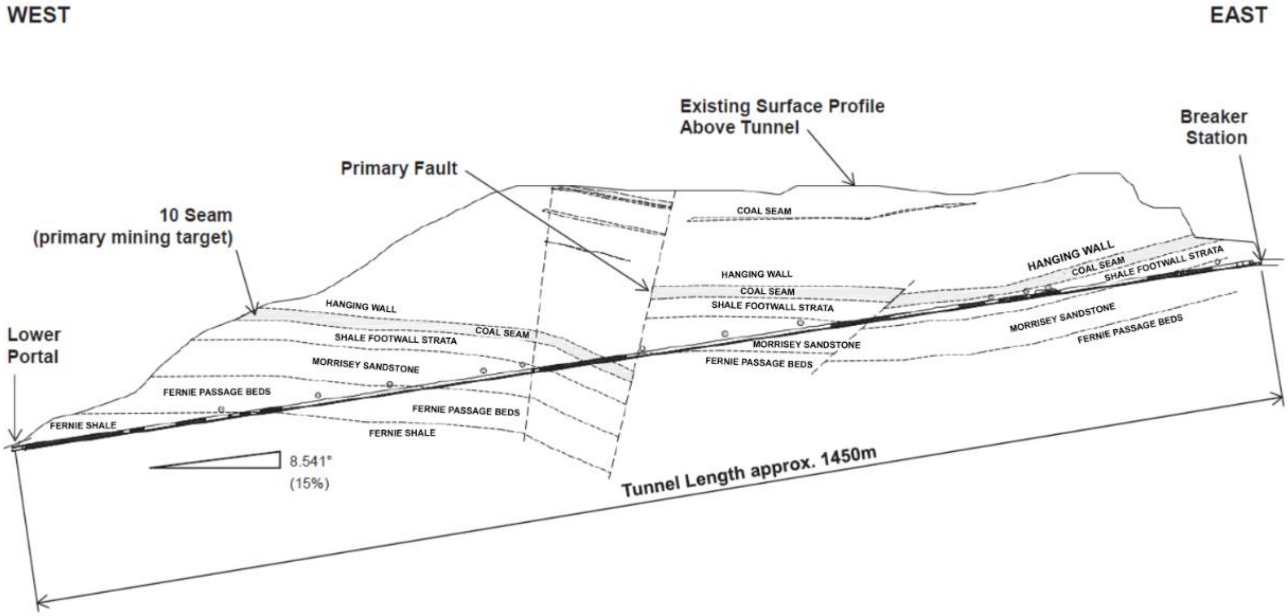

Figure 1: Cross-sectional view of lithology overlying the tunnel.

The Fernie Formation is comprised of the Upper Fernie (a massive-bedded shale) and the Passage Beds (a composition of interbedded shale, siltstone, and sandstone with thin coal seams and carbonaceous partings)

The Morrissey Formation is a sandstone unit that ranges between 20-80 meters in thickness regionally. Over the area of the tunnel, the Morrissey Formation is estimated to be 40m.

The Mist Mountain Formation overlies the Morrissey Formation and is comprised of interbedded sandstones, thin conglomerates, shales, siltstones, mudstones, and seams of minable bituminous coal (the primary mining target being labeled 10-Seam).

The Elkview Mine is located in the Rocky Mountain foreland fold-and thrust belt and is situated on the eastern limb of the north trending, south plunging Sparwood syncline. North trending, west dipping thrust faults and north trending, east and west dipping normal faults are prevalent in the area.

3 GEOPHYSICAL INVESTIGATION

A surficial and tunnel geophysics program was carried out in conjunction with a broad drilling program to gain detailed insight into lithology and bedrock structure overlying the tunnel.

Borehole conditions for the surficial holes were not favorable to acquire optical televiewer data at the time of drilling due to poor borehole wall integrity; however, natural gamma logs were acquired through steel casing.

Five (5) of ten (10) near vertical boreholes were logged into the roof of the tunnel. The holes varied in length from 21.60m to 78.50m.

3.1 Equipment

A combination of commercially available equipment and proprietary equipment was required to meet the survey objectives.

A 2PGA Mount Sopris natural gamma probe along with a winch and acquisition system was used to take geophysical measurements of surficial holes.

Wireless geophysical shuttles were specifically designed by DMT (Germany) for challenging survey environments in which wireline logging is not feasible. DMT's HQ Optic Dip Shuttle, NQ Gamma Shuttle, and EMFaG Deviation Shuttle were used.

3.1.1 HQ Optic Shuttle

The HQ Optic Dip Shuttle is equipped with an optical digital scanner and a gravimetric dip sensor. The shuttle probe is equipped with an integrated battery, memory and LED lighting. The tool is built to fit into a HQ inner core barrel. After mounting it to the core barrel and installing into the outer barrel, the optical head protrudes the core a few centimeters, allowing view of the borehole wall (see **Error! Reference source not found.**); the instruments electrical components are protected by the drill rods. The probe is slowly advanced into the hole by the drill to take the scan. Measurements are collected in time instead of depth (as is done in traditional surface logging). When advancing the instrument, data must be collected at a constant speed for each rod (1.5 m) interval and without rotation.

The optical scanner takes continuously 360° digital pictures of the borehole wall. Depending on lighting conditions, the acquisition frequency can range between 10 and 50 Hertz. Measurements were taken at approximately 25 pictures per second. During each revolution, more than 510 pixels are acquired, which leads to a circumferential resolution of 0.6 mm in the HQ size holes. The optic shuttle can be used in dry or in clear water-filled holes of any deflection angle (see Figure 2).

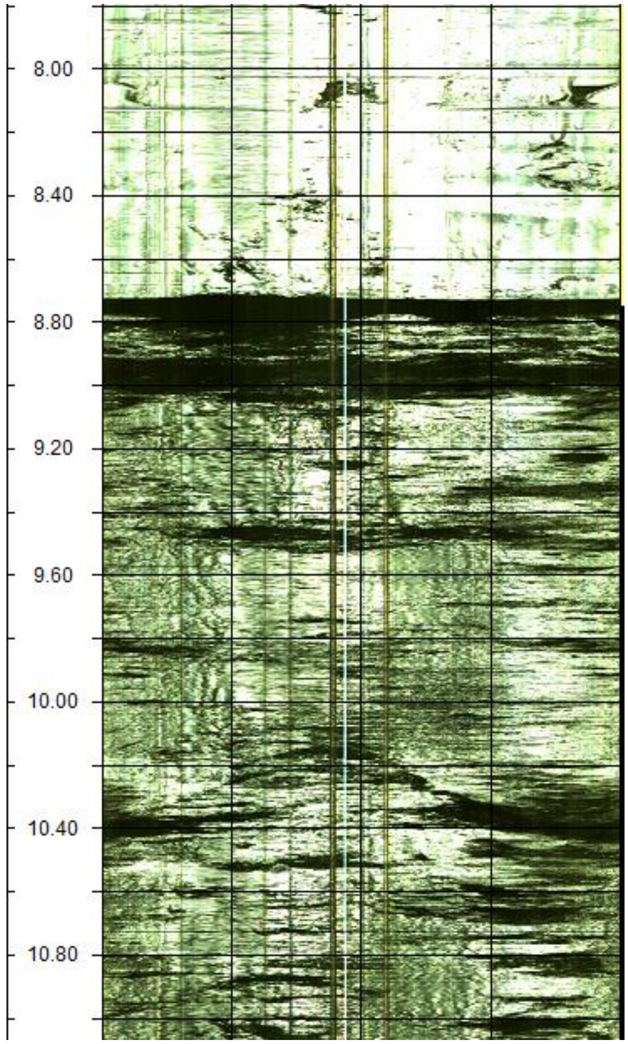

Figure 2: Example image of HQ Optic Shuttle data showing lithology and structure; transition from sand to coal approximately at 8.40m.

3.1.2 NQ Gamma Shuttle

The tool is equipped with a high-resolution detector to measure the emission of natural gamma radiation from the surrounding rock within a borehole. Radiation is detected by a sodium iodide crystal optically coupled to a photo-multiplier and logged as counts-per-second (this value was then converted to API units during processing). Since radiation is of a statistical nature, it is necessary to average the measurement of radiation over a selectable time period in order to derive a representative sample of the amount of radiation being emitted.

Natural gamma radiation is the result of decay of radioactive isotopes potassium (K40), uranium (U), and thorium (Th). For this particular investigation, natural gamma radiation is likely due to the presence of K40 in clay rich strata. Coal seams and sandstone layers can be distinguished from claystone and/or mudstone layers by determining where low and high natural gamma readings occur.

3.1.3 EMFaG Shuttle

The EMFaG (electromagnetic field and gravity) shuttle records the strength and dip of the X, Y, and Z-components of the local magnetic field. Local gravimetric and temperature data are recorded as well. Together, the inclinometer and magnetic data provides information on borehole deviation.

3.2 Results and Interpretation

Strike and dip of geological features, such as bedding and fractures/joints, interface between geological units, and condition of borehole wall were determined by combining data from the optical and .deviation probe. Features were categorized into the following list (see Table 1)

Table 1: Classification chart for features identified in optical shuttle logs.

Code	Tadpole	Sine Wave	Name
1			Major Open Joint / Fracture
2			Minor Open Joint / Fracture
4			Filled Fracture / Joint
5			Bedding / Banding / Foliation

Geological structures were analyzed and separated into two different categories depending on whether structure was in a coal seam or roof strata. The geological structures identified in the optical shuttle logs were used to refine the results of core logs and improve future modeling parameters. Structure identified on core logs, but not optical shuttle logs were likely induced by drilling and handling of core.

Published information about in-situ stresses in south-east British Columbia indicate that maximum horizontal stresses are roughly oriented in the East-West direction (Bell et al, 2012). Two of the optical shuttle logs showed possible east-west break-outs in weak coal strata. This was interpreted as a possible indicator of maximum horizontal stress in a north-south direction, which is contradictory to the literature. While it is possible that previous mining activities within close proximity the tunnel could cause a localized change in stress direction, the optical shuttle logs suggest the break-outs were not stress induced.

Natural gamma log were used in conjunction with core logs to determine lithology and identify zones of coal.

4 MODELING OF INTERPRETED RESULTS

The initial modeling parameters were informed by existing surface drilling information, targeted surface drilling information, field observations, and Teck's resource model for the area. These parameters provided the baseline for stratigraphic condition and to define zones of interest for the underground drilling program.

The underground drilling and geophysics program provided high quality information that confirmed and refined the lithology. The information from the underground drilling and geophysics program was also used to establish adjusted parameters for subsequent modeling efforts. Figures 3 through 7 present initial models centered over the tunnel of pre-mining topography, current topography, post –mining topography, and completion of mining with backfill.

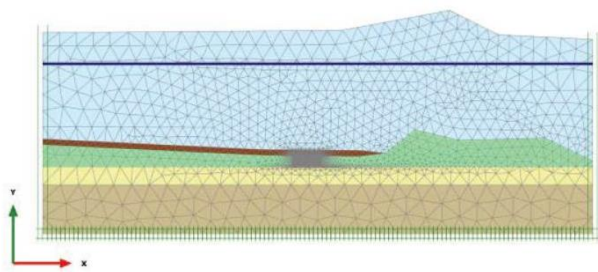

Figure 3: Modelled pre-mining topography (mid 1960s). Tunnel in grey.

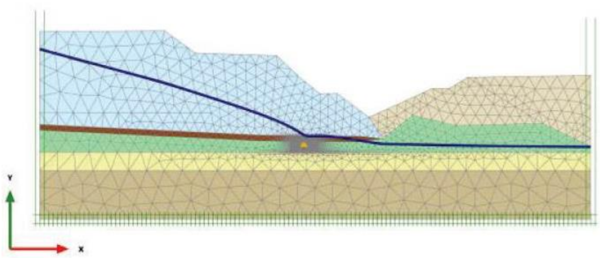

Figure 4: Modelled current topography. Tunnel in grey.

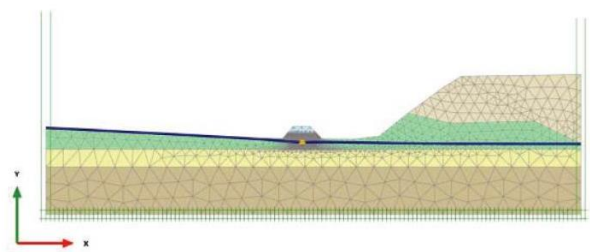

Figure 5: Modelled post-mining topography. Tunnel in grey.

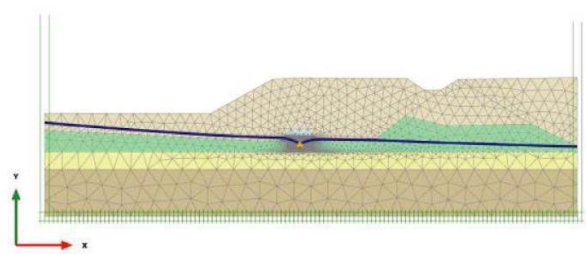

Figure 6: Modelled completion of mining with backfill topography. Tunnel in grey.

An empirical design approach was used to assess critical tunnel sections based on existing geometries and on future mining configurations. The underground drilling program helped to refine the empirical design parameters (such as σ_{ci}, σ_{ti}, and υ_i) to generalize the rock mass properties (RMR/Q) and establish the initial support parameters required for upgrading the tunnel (Barton et al, 1974, Bieniawski, 1989).

The subsequent design iteration used a numerical modeling process through the PLAXIS software platform. The PLAXIS model, using Hoek Brown (HB) and Mohr Coulomb (MC) plastic failure models, focused on multiple sections of concerns across the length of the tunnel and through each of the different rock types. The exception to the HB/MC parameters was in the modeling for the footwall strata, where the software allowed for the direct input of rock parameters (including GSI and D) into the model.

GSI varied from 75 in good sandstone down to 15 in coal and fault zones. D was modelled as 0 throughout as the rock mass was undisturbed.

Based on the underground drilling and geophysical results, the behavior of the footwall strata was found to exhibit some anisotropy where the rock strength perpendicular to the bedding was typically higher than that parallel to the bedding. It was determined that the ubiquitous joint model would be better suited for this strata.

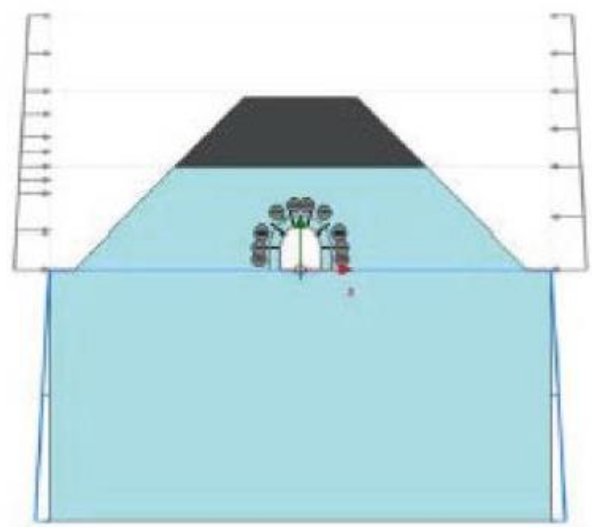

Figure 7: Representative model input diagram illustrating rock yield or plastic zones is shown for general illustration in Figure 8:

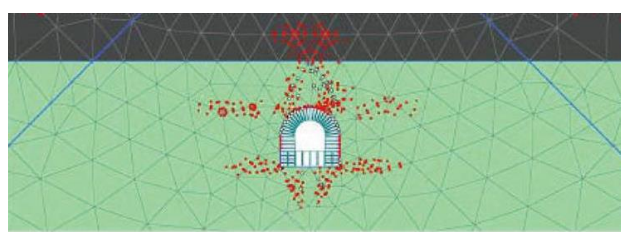

Figure 8: Representative model output diagram, simulating the most common failure modes currently observed inside the tunnel.

In situ stresses were approximated based on field observations and regional information. The underground drilling and geophysics data did not provide useful information to improve on this parameter.

Rock reinforcement was modeled and subsequently refined by constructability factors, primarily on managing the existing infrastructure within the tunnel. A complete tunnel support design was proposed with variation in support structures by section, including rock bolts/mesh, shotcrete, concrete, and injected backfill grout. The geophysical program allowed for an optimized design that would have otherwise been overbuilt.

For example, the geophysical program allowed for more accurate modelling of tunnel support requirements by zone. The weakest zones required lattice girder reinforcement as a supplement to the more standard ground support treatments prescribed elsewhere. The accurate modelling of the weaker tunnel zones optimized the extent and spacing of the supplemental support which would otherwise have been overestimated to ensure adequate performance.

5 CONCLUSIONS

The geophysics program was crucial in supporting the assessment of jointing and bedding characteristics of the rock mass and lithology overlying the tunnel. The geophysical data was used to refine the results of the core log, which was used to improve initial modeling parameters. This program added significant value to the tunnel support design by supporting an optimized reinforcement model.

6 REFERENCES

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