Review of Ground Support Design and Performance for Donkin Mine Tunnels 2 and 3

ENGINEERING REVIEW REPORT

Prepared for
Nova Scotia Department of Labour, Skills and Immigration

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1. Introduction

On July 15, 2023, Kameron Coal Management Ltd (KCML) reported a roof fall in Tunnel 2 of the Donkin subsea coal mine in Cape Breton, Nova Scotia. The unwitnessed roof fall occurred approximately 1500 m from the entrance to the mine in Tunnel 2 and measured approximately 15.2 m in length, 4.6 m in width, and 0.9 m in height (into the roof). This incident occurred 4 days after the coal mine reopened following another smaller roof fall on July 9, 2023. No injury was reported in either incident. Because of the size of the fall on July 15th, a Stop Work Order was issued by the Nova Scotia Department of Labour, Skills and Immigration (LSI). The Stop Work Order remains in place while LSI confirms all compliances have been met, including an assessment of the repairs completed by the mine, such as the design and installation of the support system intended to mitigate further ground falls in Tunnel 2 and ongoing practices to minimize the risk of future ground falls in the mine.

LSI has requested an independent, third-party tunnelling expert to review KCML's engineering assessment of the roof fall location and cause, and the repair and support work done in Tunnel 2, which includes a secondary evaluation report by Keystone Mining Services on the Tunnel 2 support and the ground control practices for the Donkin Mine. The independent review for Tunnel 2 and Tunnel 3 access tunnels was conducted by Dr Andrew Corkum of Dalhousie University and is documented in this report. An additional expert reviewer, Dr Abbas Taheri of Queen's University, was engaged by LSI to conduct a review regarding the coal mining areas and operations, which was separate from Dr Corkum's scope of work.

2. Scope

The scope of work requested by LSI includes a review of documents and plans associated with the assessment and remediation of the Tunnel 2 ground fall from an engineering principles standpoint, and to provide review comments regarding the methods and conclusions provided in the report by KCML. The following are the key documents provided by LSI for review and assessment.

1. Compliance Orders issued under the Nova Scotia Occupational Health and Safety Act to KCML on July 15, 2023.
2. No. 2 Tunnel Assessment Report prepared by the KCML engineer for the Donkin Mine dated July 20, 2023 and attachments:
   a. Assessment Reports for Tunnels 2 and 3 of the Donkin Mine, prepared by KCML (2019-2022)
   b. 2023GeotechnicalInspectionSummaryReport
   c. 2022GeotechnicalInspectionSummaryReport
3. No. 2 Tunnel Supplemental Support Verification Report prepared by the KCML engineer for the Donkin Mine dated July 26, 2023.
4. Evaluation of Tunnel 2 and Mine Ground Support Practices for Donkin Mine completed by Keystone Mining Services, LLC/Jennmar at the request of KCML, dated August 4, 2023.

5. Previous compliance orders issued by the Department related to the Donkin Mine, and any relevant reports, plans, approvals, and other information necessary for the consultant to fulfil the Statement of Work.

A total of 45 electronic documents were provided for review that include approximately 2000 electronic pages. These included reports, letters, engineering drawings, spreadsheet data, etc. A list of the documents provided by LSI and KCML for review is given in the Appendix. In addition to the provided documents, some additional scientific literature, and documents available in the public domain where also reviewed. The purpose of the review was to provide comments on:

1. Whether KCML's assessment of the geology in Tunnel 2 and 3, and the production area of the Donkin Mine has fully considered the age of the mine, the effects of weathering, and any current environmental impacts.
2. Whether the repair and rehabilitation work performed in Tunnel 2 is consistent with current safety standards and industry best practices for a subsea coal mine operating in Cape Breton, Nova Scotia.
3. Whether the assessment of Tunnel 3 and ground control plan for the mine production area meet current safety standards and industry best practices.
4. Whether, given the subsea coal mine's age, history, geology, location, climate, and any other relevant factors, there are any additional risks that need to be further assessed.

Dr Corkum's review was limited to the Tunnel 2 and 3 review components. An additional expert reviewer, Dr Abbas Taheri of Queen's University, was engaged by LSI to conduct the review regarding the coal mining operations areas.

An underground mine site visit to the access tunnels in question was included to provide an opportunity for further observations and insights. The proposed review is limited primarily to a document review and observations from the site visit. The scope of this review did not include conducting or reproducing any stability or design calculations but was limited to evaluating those reported in the documents provided. If the review suggested that further detailed engineering work of this nature is warranted, this conclusion will be communicated in the review report.

The report contains expert opinions and commentary on the completeness of the assessment and rehabilitation work of KCML following the July 15, 2023, roof fall in Tunnel 2 of the Donkin Mine, and provides an expert opinion and comments on ground control plans for Tunnel 3. Recommendations are provided on any further assessment or rehabilitation work that may be required by KCML for Tunnel 2 and 3, given the inherent risks and identified hazards. Recommendations are provided regarding any ongoing assessment and rehabilitation work that may be required by KCML for Tunnel 2 and 3, given the inherent risks and identified hazards that should be undertaken after work has been safely resumed to ensure reasonable safety is maintained going forward.

3. Overview and Historical Context

The Donkin Mine project began with studies dating to over 4 decades ago. The undersea coal mining project includes two parallel, twin access tunnels, referred to as Tunnel 2 and 3, that are the focus of this report. The following summary is based on information reported from several sources, most notably: Gilby (1989); Pelli et al. (1991); Seedsman (2009). The tunnels were built between January 3 and December 21, 1984, using a Lovatt 7.6-m-diameter, full-face, shielded, M-300, Tunnel Boring Machine (TBM). Tunnel 2 was mined first with the TBM and Tunnel 3 was mine secondly with the TBM, after some initial drill-and-blast excavation was first carried out. The twin tunnels are approximately 3.6 km long from surface, grading down to the coal mining level with a maximum depth of approximately 180 m below seabed. A depth of approximately 35 to 50 m of seawater overlies the seabed and the tunnel at its deepest. The 7.6-m diameter parallel tunnels are approximately 50 m apart, center-to-center.

Broadly, the geological setting includes Carboniferous age sedimentary rock dipping approximately 10°. The dip direction is approximately north towards the sea. Based on the site investigation and geological mapping, the access tunnels intercepted seven major lithological units. These units are listed in Table 1.

Table 1 Summary of lithological units

Type	**Lithological Units**
I	Sandstone
II	Interbedded sandstone and siltstone
II	Siltstone
IV	Interbedded siltstone and mudstone
V	Mudstone
VI	Carbonaceous mudstone
VIA	Coal

The ground support design consisted of steel sets with specifications of W150 x 23 at 1 to 1.5 m spacing. The ground support was designed based on several studies based on an anticipated intact rock brittle failure instability mode. The brittle rock failure mode is characterized as spalling and fracturing of relatively unjointed intact rock. In this context "failure" refers to fracturing of the rock and not tunnel failure. Some rock bolting was required in a few locations where weaker rock mass was encountered. State-of-the-art, for the time, analysis was conducted during design and construction involving universities and consultants. This included finite element numerical modelling which, at the time, was a relatively new computer analysis approach for tunnel design. During construction, there was extensive instrumentation, predominantly featuring multi-point extensometer (MPBX) used to monitor tunnel performance. These were carefully monitored and were used in back analysis by Pelli et al. (1991) and were also analyzed much later by Corkum et al. (2012).

The tunnel was flooded initially in 1992 and dewatered in 2006-7. The tunnel was again flooded in 2013 and dewatered in 2015. Since the initial flooding, the mine changed ownership to Xstrata Coal Donkin Management (XCDM) in the mid-2000s and was later purchased by KCML who currently operate the mine. There were some significant ground falls associated with the initial mine dewatering. Seedsman (2009) conducted some analysis of the support rehabilitation of the dewatered tunnel's ground support and recommended patterned rock bolts between steel sets based on brittle rock analysis. Seedsman described some observed brittle spalling (concentric rock fractures), but most ground falls and instabilities were related to mudstone weakening. The original designs did not anticipate or suitably account for tunnel flooding, and its resulting effects on mudstone and steel set support elements. Weathering and softening of the mudstones have changed the rock mass behaviour substantially.

There have been several other ground falls since the rehabilitation of the access tunnels, most notably, two ground falls in July 2023 that resulted in a Stop Work Order. KCML have revised the ground support and ground control plan extensively. The tunnel and revised ground control was evaluated by Keystone Mining Services, LLC (Keystone). Keystone's report (Mirabile and Swartz 2023) identified the mechanisms of softening/slaking and failure of mudstone and interbedded siltstone-mudstone, and the relation to weathering and humidity. They suggested that rock bolting would inhibit weathering by clamping beds and reducing access to moisture within the rock mass.

4. Site Visit

A site visit to Donkin Mine was conducted on October 26 and 27, 2023. The visit included technical reviewers Andrew Corkum (Dalhousie University) and Abbas Taheri (Queen's University), along with representatives of LSI: Scott Nauss, Fred Jeffers and Don Hartt. Anthony Webb, Ian Shaw (Mine Manager), Cameron McLennan (Mine Engineer), were the primary representatives of KCML.

4.1 Initial Meeting

An initial kickoff meeting was held on October 26, 2023. The meeting included a safety training session and an overview of the mine operations, along with some general orientation discussions to facilitate the underground visit for the following day. On October 27, 2023 an underground mine site visit was carried out. The underground inspection was conducted in two separate groups. Dr Taheri visited the coal mine working areas to support his review scope. Dr Corkum conducted an inspection of Tunnel 2 along with Mr McLennan, Mr Webb, and Mr Nauss. Dr Corkum and Mr McLennan also made a brief visit and drive through most of Tunnel 3. During the inspection of Tunnel 2, numerous locations were visited, specifically areas where ground falls occurred, additional ground support was installed, unique geology could be observed, and other reasons. This provided a broad, overall understanding of tunnel stability, ground support installation and performance. A brief survey of Tunnel 3 was also conducted but access and visibility were more challenging than in Tunnel 2. Following the underground inspection, a debriefing and information gathering meeting was held with Abbas Taheri, Andrew Corkum, Don Hartt, Anthony Webb, Ian Shaw, and Cameron McLennan. Specific discussions were held regarding the nature of the geology, ground support design and performance, instrumentation and monitoring, and the Hazard Assessment classification program, and additional pertinent issues.

4.2 Geology and Rock Engineering Conditions

The geological conditions were generally in agreement with those described in numerous reports, such as Gilby (1989); Pelli et al. (1991); Seedsman (2009), and many reports issued by KCML and their agents. The geological description seemed consistent across all reviewed reports. The rock mass was fully visible throughout most of Tunnel 2 and Tunnel 3 except for the shotcrete and lagging lined sections. As described by others, the geology was observed to consist of a gently dipping, sedimentary rock sequence with zones of sandstone, siltstone, some closely interbedded siltstone mudstone, mudstone and occasional coal. Geological structures consisted of persistent bedding dipping approximately 10° to the north (direction of tunnel downward grade). There were infrequent signs of cross bedding or other significant structures. At the time of the visit, there was limited directly observed free water seepage into the tunnel, but there were some signs (dampness) of the presence moisture/water. There were extensive signs of corrosion on some rock bolts and particularly the lower portions of the steel sets, in addition to observable rock weathering. The mudstone was highly weathered in several locations. Some of this was a consequence of the historical tunnel flooding and dewatering, and some was likely due to ongoing moisture conditions in the tunnels both through seepage within the rock mass and through tunnel air humidity variation.

4.3 Instability Mechanisms and Ground Falls

In general, Tunnel 3 was in a better overall stability state than was Tunnel 2. Tunnel 3 was mined after Tunnel 2; however, given their 50-m distance apart, it is unlikely that there was significant stress interaction between the two tunnels during construction to result in excavation-inducted damage. The reason for the observed difference is likely due to better historical maintenance and stabilization in Tunnel 3. It is also due to the nature of the air ventilation flow and the resulting variance in humidity between the two tunnels. KCML and others have suggested this as a likely source of the difference in observable performance. This speaks to the sensitivity and impact of humidity on ground behaviour and the tunnel stability, which is commonly observed in argillaceous, clay-bearing rocks, such as mudstones. Weathering also occurs to a lesser extent in other sedimentary rocks, such as siltstone and sandstone. Seasonal performance of the tunnels over annual cycles consistently indicates that most ground falls have been related to mudstone rocks and have occurred during relatively high humidity seasons.

There were several other ground falls observed during the site visit that have been documented in previous reports. Two large ground falls occurred in Tunnel 2 in conjunction with initial dewatering were observed along with several other smaller ground falls that had since occurred. The most recent ground falls occurred on July 9 and July 15, 2023 which resulted in a Stop Work Order issued by LSI. Some ground falls and instabilities have also occurred in Tunnel 3 associated with initial dewatering, otherwise the conditions appeared to be overall better than in Tunnel 2. At the time of the mine site visit, all the ground fall locations had been stabilized and re-supported.

Stress-driven instabilities, such as spalling and brittle rock fracturing, was not extensively observed, although it is expected to have occurred in the roof, due to high horizontal stresses, and has been documented to exist (Seedsman 2009). This historic fracturing could also be a contributor to weathering of rock in the roof. The dominant source of instability is related to the presence of the mudstone, or siltstone/mudstone interbedded units. There were some occasional issues that appeared to occur in other units, such as the sandstone or siltstone due to weathered. In places, the mudstone was somewhat competent, but in other places the weathering had been extensive, and the rock exhibited low strength (could be easily broken by hand). The mudstone seemed to have a tendency towards slaking with wetting and drying cycles. It was unclear if the mudstone had significant swelling or squeezing potential, but typically with mudstones there is some combination of these characteristics. In addition to roof instabilities, there was frequent observed instability in the tunnel springline area. Weak beds have eroded or fallen in leaving voids of approximately 0.5 m and greater in the walls. This is an indication of potential progressive behaviour that if left to continue could potentially eventually impact tunnel roof stability. Overall, it appeared that tunnel stability is affected by multiple modes of instability and oftentimes these were occurring together in a somewhat complex manner. For example, slaking and softening of the mudstone beds sometimes interacts with other bedding plane structures to results in instabilities and ground falls.

4.4 Ground Support

In Tunnel 2 the steel sets were observed to be severely degraded, particularly in the lower wall segments. This seemed to be due to corrosion and also from contact with passing mine vehicles. Partial remediation of the steel sets was done by KCML by installing bolted steel channel beams across the steel sets near the tunnel springline in an effort to “pin” the sets above the damaged lower segments. Circular steel sets are designed to carry the load as a thrust, or “hoop” stress and if the circular section is compromised, it cannot function as intended. The steel set degradation is often extensive enough that, having lost their ability to transmit a thrust load adequately, their load capcity cannot be safely relied upon. Moreover, any residual load capacity cannot be readily determined from an engineering perspective.

KCML indicated that they will not rely on the steel sets as a meaningful component in the ground support system going forward. They have documented that they have installed patterned rock bolts with steel mesh in most of Tunnel 2. The rock bolting details seemed generally well documented. In areas where stability was more of a concern, the rock bolt pattern was enhanced and has been supplemented by installation of cable bolts and steel channels. The rock bolting pattern varies based on the Hazard Assessment classification system as well as based on judgement of the Mine Engineer.

The observed ground fall zones were almost entirely in areas where mudstone or interbedded siltstone/mudstone were present. The zones with major ground falls have been remediated. The large failure zones (locations) have been remediated with shotcrete, rock bolts and cable bolts and steel channels. The more recent ground fall areas have been remediated with rock bolts, steel mesh, cable bolts, and steel channels. According to KCML, the design of these remediated systems was largely based on experience from similar mining conditions and engineering judgement. Documentation of the revised ground support survey and design has been provided by KCML (McLennan 2023). In Tunnel 2, rock bolt spacing consists of 2.44 m (8’) fully resin grouted, tensioned rock bolts in the roof in a four-rock bolt radial ring pattern located midway between each steel set. This results in typical spacing of approximately 1.5 m along the tunnel and 1.8 m radially.

Tunnel 3 is mostly supported with its original ground support. Apart from a major fall that has been documented and remediated with additional steel ribs, lagging and Heintzmann Jacks, the tunnel is generally in overall much better condition. As mentioned, during the site visit, Tunnel 3 could not be carefully inspected.

4.5 Monitoring and Instrumentation

KCML has instituted a formalized monitoring program as part of their Hazard Assessment classification system. The inspections and Hazard Assessment are updated, documented, and reported on a systematic schedule. The system includes aspects of tunnel conditions such as geology, and also observations of tunnel and ground support performance (e.g., water/moisture observations), deformation of support elements (e.g., steel sets crown deviation), and tell tale monitoring. Tell tales were used for instrumentation in Tunnel 2. Tell tales are used by KCML at various locations throughout the mine, including several locations in Tunnel 2. They were installed in zones identified as potentially hazardous or in remediated areas, but few are installed in other locations. The tell tales are multi-point devices capable of providing ground movement (displacement) measurements from two points within the rock mass strata along the installation drill hole located in the roof. Based on discussion with KCML, monitoring of the tale tales is typically based on observing the large colour coded 25 mm increments, but typically not at greater precision. A response to tell tale readings is primarily through the Hazard Assessment classification system, but also on a case-by-case, engineering judgement basis. The Hazard Assessment classification system or other inspection observations did not seem to predict the imminence of the July 2023 ground falls.

4.6 Follow-up Meeting

The site visit follow-up meeting included broad ranging discussions related to the underground site visit and the documentation provided for review. A discussion was held on the engineering basis of the ground support design. KCML suggested that the ground support design in Tunnel 2 was primarily based on the experience of KCML staff and engineering judgement. KCML agreed to provide an up-to-date survey of Tunnel 2 ground support installation with all pertinent details, which was provided by email on October 30, 2023. Additionally, during the meeting, KCML indicated that their Hazard Assessment classification system requires some revision to reflect the newly installed patterned rock bolt and steel mesh ground support.

5. Review Assessment

The Donkin Mine is regulated by the Nova Scotia Underground Mining Regulations (NS 2022) which contains stipulations regarding ground support. The Tunnel 2 and Tunnel 3 access tunnels are considered *critical mine infrastructure* because all mine access and ventilation/air flow must pass through these two tunnels. It is industry standard that the stability of the access tunnels must meet a higher level of safety than other operational mine openings and can sometime approach the safely level of some civil engineering tunnels. This is particularly true given that Donkin Mine is located undersea with few similar, comparable operations world-wide. Knowledge of the existing margin of safety and associated risk level for the ground support system is necessary to assess the appropriateness of tunnel stability.

The KCML ground control plans reviewed where generally well documented. The tunnel performance, included observed instabilities and ground falls, was adequately described. The instability mechanisms, especially associated with mudstone behaviour and its relation to seasonal humidity fluctuations, was described. The ground support installation appears to be documented accurately and in a timely manner and seems to include good descriptive observations and information. A full survey of the recent ground support installation has been prepared and provided. The engineering basis for the ground support design, such as rock bolt type, length and pattern spacing, and steel mesh vs shotcrete, was not clearly presented in the documentation.

During initial design and construction of the access tunnels in the 1980s, the assumed dominant failure mode was brittle fracture of intact rock with some bedding related movement. The observations, instrumentation (e.g., extensometer readings) and monitoring conducted during driving of the TBM tunnels was in general agreement with the anticipated conditions. This was the basis for the design and use of steel sets, which are a “passive” ground support element. Passive elements typically carry the ground load applied, in contrast to “active” reinforcement elements, such as rock bolts, that enhance the strength of the rock mass itself. Due to the history of flooding and dewatering of the tunnels, and the presence of mudstone units, the current instability is quite different than originally anticipated. As a result, the original design assumptions are not suitable for the current tunnel behaviour and a different ground support evaluation approach is required for the current conditions that are predominantly associated with time-dependent degradation (i.e., weathering) of the mudstone containing units. The reason it is important to understand the mode of failure around the access tunnels is that there are no universal design methods or ground support approaches that are applicable for all tunnelling conditions. For this reason, engineering of underground openings must carefully consider the unique, site-specific conditions because this greatly affects the selection of appropriate stability calculation methods, the suitability of different ground support elements (e.g., rock bolt type selection), and monitoring approaches. It appears that KCML and their consultants have identified these issues and generally appear to be working under this understanding (Mirabile and Swartz 2023).

KCML have stated that going forward they will largely disregard the steel sets as a ground support component. They have remediated the ground fall areas and other unstable areas in a manner that seemed to be performing adequately to date; however, time-dependent, progressive mudstone weathering with time can be expected, and ongoing monitoring of tunnel performance is essential. In discussion with KCML, the ground support was largely based on experience at Donkin and at other mines in environments KCML considered similar, combined with engineering judgement, and input from their consultants and ground support suppliers. The designs were developed on a case-by-case basis by the Mine Engineer in consultation with other KCML personnel. The ground support was often implemented in conjunction with the Hazard

Assessment classification system. In addition, Keystone's recent consulting report (Mirabile and Swartz 2023) provided a brief, broad overview of current stabilization measures of Tunnel 2 and 3 and provided general agreement with the ground support measures. Experience is an important and valid component of ground support design in mines, but the level of safety of such designs cannot be determined without careful monitoring and/or a historical record of adequate performance. This may be especially true given the unique mining environment at Donkin Mine.

Shotcrete was used in Tunnel 2 in the past to effectively stabilize the large ground falls that occurred during dewatering. Although rock bolts reinforcement can effectively reduce access to water and humidity within the rock mass, typically shotcrete (spray on concrete) liner support, used in conjunction with patterned rock bolts, is considered the most effective means of managing tunnel environment affects and time-dependent degradation of mudstone units in tunnels. Shotcrete acts as a barrier between humid air and the rock mass. It also offers much greater stability and resistance to potential ground falls. This level of support (i.e., shotcrete) may not be necessary in the Donkin Mine access tunnels at this time, but should be given consideration, at least in areas where significant mudstone is present.

The Hazard Assessment classification system generally seems reasonable and accounts for many of the critical tunnel stability criteria. However, the Hazard Assessment system was not successful in providing prior indication of the impending ground falls of July 2023. The enhanced ground support in Tunnel 2 will reduce hazards, but the underlying Hazard Assessment system should be reviewed and revised to include more refined and quantifiable instrumentation and monitoring. Moreover, the Hazard Assessment classification system was partially based on steel set performance (observed deflection) which are no longer considered a reliable part of the ground support system and may not provide meaningful and reliable information.

The current monitoring program is based on observations of tunnel conditions, ground support element performance, and tell tale instrumentation. The tell tale instruments are monitored visually. Given the distance, visibility, and nature of the instrument, tell tales have low measurement precision and are probably not being accurately tracked at greater than 25 mm accuracy. The tell tales are installed at most major instability areas but are otherwise sparsely used.

6. Conclusions and Recommendations

A review of Tunnel 2 and Tunnel 3 mine access tunnel stability and ground support was conducted. The review was based on provided literature (approximately 45 documents), an underground mine site visit, and meetings with LSI and KCML. The review was limited to the above information and did not include conducting or reproducing independent engineering analysis, but of reviewing the engineering and ground support installation carried out by KCML, their pertinent consultants and venders. The review scope included providing a review evaluation and recommendations to LSI to support their overall safety assessment. There are many ways to analyze and stabilize underground excavation, and the review scope was not intended to be overly prescriptive regarding the means by which KCML achieves the required safety objectives, such as achieving suitably safe tunnel stability.

There has typically been limited signs of instability in the access tunnels during the low relative humidity winter months. The revised ground support (i.e., rock bolts) installed in Tunnel 2 has improved stability and safety, although the degree of improvement has not been determined with either engineering analysis or by a record of long-term performance. Given the past record of performance during low humidity seasons and the improved stability, Tunnel 2 can be anticipated to perform reasonably safely during the upcoming winter months, at least in the short term before further weathering occurs. Tunnel 3 has historically performed better than Tunnel 2 and also can be anticipated to perform reasonably safely during the upcoming winter months. However, it is not clear if this will hold true when high humidity returns in spring and, especially, summer. Given these observations, a phased approach is recommended which will consists broadly of two phases: 1. resumption of access tunnel use during the winter months, and 2. simultaneously conducting a fuller engineering evaluation and remediation of the ground support prior to allowing continued operations in spring/summer 2024. The work components of the two phases can be initiated simultaneously. Further detailed recommendations regarding the suggested two-phase approach are provided below.

Phase 1 Recommended Actions

Prior to resuming access to Tunnel 2 and 3, KCML should provide a revised Hazard Assessment classification system consistent with the current ground support. Careful consideration should also be given to other improvements that could be made to the Hazard Assessment classification system with respect to the ground falls of July 2023 and if there are ways to improve prediction of potential similar cases.

Additional monitoring should be incorporated into systematic tunnel inspections. More extensive use of tell tales and other efforts should be made to monitor the tunnel displacements. Installation of more tell tales should be undertaken in areas where potential instability is a concern. Selection of monitoring locations could be tied to the Hazard Assessment classification system. The measurement increments on the tell tales should be observed and recorded at the highest practicable precision available by the instrument. The measured data should be plotted and reviewed regularly. Any increase in movement and other significant changes should be identified and acted upon appropriately. This revised monitoring should be incorporated into the Hazard Assessment classification system.

Although Tunnel 3 has generally performed better than Tunnel 2, careful monitoring and inspection is also recommended in Tunnel 3. This is particularly true given the presence of the conveyor which complicates both monitoring and any potential future remediation that may be required.

Phase 2 Recommended Actions

At this time, an engineering evaluation of the long-term performance of the access tunnels, Tunnel 2 and 3, has not been demonstrated by engineering analysis or by an extensive historical record of adequate performance. Although ground support has been substantially improved, this is also true of the recently enhanced and revised ground support comprised of patterned rock bolts, cable bolts, steel mesh and steel channels. KCML should provide an engineering basis for the ground support system that demonstrates it has a suitable safety margin and an acceptable associated risk for these critical mine infrastructure tunnels. Suggestions regarding engineering approaches to an engineering evaluation are provided below. The engineering evaluation may demonstrate that the existing current ground support in Tunnel 2 and 3 is reasonable and suitable, or perhaps it will be determined that some further stabilization measures (e.g., shotcrete) are needed for the spring/summer and also for long-term performance.

Engineering calculations for these tunnelling conditions are challenging and some reliance on experience is necessary. The conventional basis for tunnel support calculations often use some or all of the following: the standard rules-of-thumb method of Lang and Bischoff (1982), Q-system (NGI 2015), closed form solutions, and limit equilibrium analysis are typical examples. The Donkin Mine access tunnels are within a laminated sedimentary sequency with bedding structures striking perpendicular to the tunnel access. As a result, some of the conventional methods are not ideally applicable. Often limit equilibrium calculations of anticipated delaminated roof beams and dead loads on rock bolts are used in these cases. The circular shape of the TBM tunnel in these bedded sequences is a complicating factor. The weathering, softening and slaking of the mudstone over time is an additional complicating factor. Although these methods may not be directly suitable for the tunnelling situation, by conducting engineering analysis using multiple methods, a fuller, holistic understanding of loads and predicted performance can be gained. This can be used to support an engineering evaluation of the ground support. Numerical modelling computer simulation was used to aid with construction in the 1980s and was an advanced approach at that time. Today, numerical modelling, such as *RS2* software (Rocscience 2022), to support ground support evaluation is done routinely in practice, particularly in difficult/complex conditions or when instabilities exist. The tunnel geometry, geological structures (e.g., bedding planes) and ground support loads (e.g., rock bolts) can be reasonably simulated and evaluated.

Given the complexity of the engineering problem, there are also other established methods that are well-suited to achieving suitably safe tunnel performance. *Performance*-based or *observational*-based methods, such as described by Schubert (2008), or a modification of these methods, is a reasonable approach for the Tunnel 2 and Tunnel 3 ground support evaluation. In simplified terms, performance-based methods first establish an initial ground support design from preliminary calculations and/or experience. This is followed by extensive and careful monitoring, with pre-determined corrective action taken as needed based on predetermined monitoring thresholds. These methods also utilize KCML's experience gained from observed tunnel behaviour specifically at Donkin Mine. These methods rely heavily on performance monitoring and an important component is to select, in advance, appropriate courses of action (e.g., ground support modifications) for all foreseeable deviations of performance from *anticipated* performance based on specific monitoring thresholds (e.g., tunnel wall displacement thresholds or other instability indicators).

Tunnel boundary displacement is one of the best indicators of performance and it can often be readily measured directly. Increasing and accelerating movement typically indicates instability and normally precedes failures. Decreasing and decelerating movement typically indicates a tendency towards a stable tunnel. Displacement monitoring also provides insight into seasonal fluctuating behaviour and time-dependent degradation weathering of mudstone. There are many ways to measure displacement, such as multi-point extensometers, convergence arrays, surveying-based methods, instrumented rock bolts, and tell tales. Over the past decade or more, LiDAR surveys (laser scanner) are often used to capture a full tunnel scan. The data from additional surveys is then compared to an initial datum survey and displacement of much of the tunnel is measured. These different instruments and approaches have various levels of coverage and precision. Other less quantifiable observations and inspections (e.g., signs of water and rock bolt face plate deformation) should also be utilized. The appropriate selection, extent of use and measurement frequency must be given consideration by an experienced engineer. The Hazard Assessment classification system should be revised and updated to include all ground support changes and the evolution of the monitoring program.

The use of electronic equipment in the Donkin Mine does present a known safety hazard and KCML typically must seek approval for their use. This needs to be balanced against the hazards of not utilizing instrumentation monitoring. If an appropriate monitoring system is not implemented, then the ground support should be engineered to be *demonstrably conservative* to account for variability, uncertainty, and long-term performance (e.g., weathering).

An experienced engineer specializing in mining and tunnelling should be tasked with determination of a suitable combination of engineering approaches to arrive at a design method. This should include an appropriate level of instrumentation, monitoring and response plan consistent with the engineering approach. It is recommended that a top-tier engineering consulting firm with engineers experienced in weak-rock tunnelling, would be a good choice to conduct the required engineering evaluation.

As mentioned previously, Phase 2 can be initiated simultaneously to Phase 1. If the engineering evaluation identifies deficiencies in anticipated ground support performance and determines that additional ground support (e.g., shotcrete use in specified areas) and/or monitoring instrumentation is needed to achieve safety requirements, these improvements should be made. The Phase 2 component should be required to be completed and implemented prior to continuing with Tunnel 2 and 3 access into spring/summer 2024.

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Appendix

Summary of Documents Provided for Review

Ref#	Filename	Reference	# of Pages
1	Proposal Province of NS-Donkin Independent Review v2 CVattached	Corkum, A. G. (2023, September). Assessment of Tunnel 2 Support and Ground Control Plan for Donkin Mine. Department of Civil and Mineral Resource Engineering, Dalhousie University. Report to Nova Scotia Department of LSI.	14
2	RoofFailureMechanism_ DFcompletereport_20070518	Forrester, D. (2007, May). Assessment: Ground Failure Mechanism, Fall area, at the 1750 m mark, Tunnel No. 3 (reference – Order No. 711610007-004). DJF Consulting Limited. Technical Report to Xstrata Coal Donkin Exploration Project.	9
3	COP_GroundAssessment_DF_ 20070514	Forrester, D. (2007, May). Ground Assessment: area inbye of fall location to the first cross-cut, Tunnel No. 3 (reference – Order No. 700102595-001 and -007). DJF Consulting Limited. Technical Report to Xstrata Coal Donkin Exploration Project.	4
4	Study of tunnel deformation 1989	Gilby, J. L. (1989, December). Study of deformation characteristics of the Donkin-Morien tunnel development. Department of Mining and Metallurgical Engineering, McGill University.	263
5	2022-08-24_Ground Control Procedure 2022 R1	Kameron Coal Management Limited. (2022, August). Donkin Underground Coal Mine - Ground Control Procedure (Revision 1). Technical Report to Nova Scotia Department of LSI.	136
6	2022-08-30_Ground Control Procedure 2022 R2	Kameron Coal Management Limited. (2022, August). Donkin Underground Coal Mine - Ground Control Procedure (Revision 2). Technical Report to Nova Scotia Department of LSI.	134
7	2022-06-21_Donkin Mine_ Ground Control Procedure 2022_Submission	Kameron Coal Management Limited. (2022, June). Donkin Underground Coal Mine - Ground Control Procedure (Revision 0). Technical Report to Nova Scotia Department of LSI.	1

Ref#	Filename	Reference	# of Pages
8	2022-06-21_Ground Contol Procedure 2022	Kameron Coal Management Limited. (2022, June). Donkin Underground Coal Mine - Ground Control Procedure (Revision 0). Technical Report to Nova Scotia Department of LSI.	133
9	2022-10-12_Ground Control Assurance Program	Kameron Coal Management Limited. (2022, October). Donkin Underground Coal Mine - Ground Control Assurance Plan. Internal Standard of Procedure to Kameron Coal Management Limited.	2
10	2022-09-20_Ground Control Procedure 2022 R2 A1	Kameron Coal Management Limited. (2022, September). Ground Control Procedure 2022, Revision 2, Amendment 1: Pillar Splitting for Initial Development of West Mains Panel". Technical Report to Nova Scotia Department of LSI.	5
11	2023-0715 Investigation-Roof Fall 2T 1460	Kameron Coal Management Limited. (2023, July). Investigation: Unplanned Roof Fall (No. 2 Tunnel at 1460 meter-mark). Technical Report to Nova Scotia Department of LSI.	9
12	2-Tunnel Verification Report 2023-07	Kameron Coal Management Limited. (2023, July). No. 2 Tunnel Verification Report (Compliance Order No. 17136177-002). Technical Report to Nova Scotia Department of LSI.	124
13	R_2016-06-30_McElroy Bryan DonkinResourceRptsecured	McElroy Bryan Geological Services. (2007, April). NI 43-101 Technical Report: Donkin Coal Project (Report# 259/2/1). Technical Report to Xstrata Coal Donkin Management Limited and Erdene Gold Inc.	105
14	KMS Report Certification Letter 2023-0804	McLennan, C. (2023). Engineering Certification Letter: “Evaluation of Tunnel 2 and Mine Ground Support Practices.” Kameron Coal Management Limited.	1
15	2Tunnel Bolting Survey Summary 2023-1030	McLennan, C. (2023, July). 2 Tunnel Bolting Survey Summary. Internal Report to Kameron Coal Management Limited.	9

Ref#	Filename	Reference	# of Pages
16	2Tunnel Deadload Calculations 2023-1107	McLennan, C. (2023, November). 2 Tunnel Deadload Calculation. Internal Report to Kameron Coal Management Limited.	2
17	Golder_Donkin_Sale_1408858_Final	Meister, W. G., Partington, L. R., & Ganey, D. G. (2014, December). Technical Due Diligence of the Cline Group – Sale of the Donkin Project (Project No. 1408858). Golder Associates Ltd. Technical Report to Geoscience and Mines Branch Department of Natural Resources.	49
18	2023_Evaluation of Tunnel 2 and Mine Ground Support Practices	Mirabile, B., & Swartz, G. (2023, August). Evaluation of Tunnel 2 and Mine Ground Support Practices for Donkin Mine. Keystone Mining Services, LLC. Technical Report to Kameron Coal Management Limited.	7
19	R_2016-06-30_Analysis of Ground Strain in.Response to Development Only Mining in the Habour Seam Rev 4-21-2016 secured	Newman, D. (2016, April). Analysis of Ground Strain in Response to Development Only Mining in the Harbour Seam. Appalachian Mining Engineering, Inc. Technical Report to Kameron Coal Management Limited.	99
20	KCML Inspection July 15 2023 orders	Nova Scotia Department of LSI. (2023, July). Compliance Orders: Roof Fall Event in Tunnel 2 (Order# 17136177-001). Report to Kameron Coal Management Limited.	
21	Donkin_Technical_2012	Partington, L. R. (2012, November). Technical Report: Donkin Coal Project. Marston and Marston, Inc. Technical Report to Xstrata Coal Donkin Management Limited and Erdene Resource Development Corporation.	76
22	Revised Version Slope Tunnel Roof Fall Rehabilitation Plan_Part1	Renk, U. H. (2015, September). Donkin Project - Slope Tunnel Roof Fall Rehabilitation Code of Practice (Revision No.1). Technical Report to Occupational Health and Safety Division, Nova Scotia Labour and Advanced Education.	22

Ref#	Filename	Reference	# of Pages
23	Revised Version Slope Tunnel Roof Fall Rehabilitation Plan_Part2	Renk, U. H. (2015, September). Donkin Project - Slope Tunnel Roof Fall Rehabilitation Code of Practice (Revision No.1). Technical Report to Occupational Health and Safety Division, Nova Scotia Labour and Advanced Education.	22
24	Revised Version Slope Tunnel Roof Fall Rehabilitation Part 3	Renk, U. H. (2015, September). Donkin Project - Slope Tunnel Roof Fall Rehabilitation Code of Practice (Revision No.1). Technical Report to Occupational Health and Safety Division, Nova Scotia Labour and Advanced Education.	28
25	Figure 20 2015-0925- Amended from 8-20-2015 PE	Renk, U. H. (2015, September). Slope Tunnel Roof Fall Rehabilitation Code of Practice (Revision No.1). Amended Drawing to Occupational Health and Safety Division, Nova Scotia Labour and Advanced Education.	1
26	R_2016-06-30_Calculations Secured	Renk, U. H. (2016). Certified Report: “Donkin Mine - Ground Control Procedures (Revision: 2).”	13
27	R_2016-12-21 Provisional Ground Control Procedure Rev 1 - File #1 (Submission)	Renk, U. H. (2016, December). Donkin Mine - Provision Ground Control Plan (Revision 1). Technical Report to Kameron Coal Management Limited.	24
28	R_2016-12-21_FIgures 5-33 Revision 1	Renk, U. H. (2016, December). Donkin Mine - Provision Ground Control Plan (Revision 1). Technical Report to Kameron Coal Management Limited.	30
29	R_2016-06-30_Certified tunnel long term assessment Secured	Renk, U. H. (2016, June). Long-term Assessment Tunnel Nos. 2 and 3 Donkin Project. Technical Report to Kameron Coal Management Limited.	21
30	R_2016-11-22 Ground Control Procedure Rev 2 - Attachment #1 (Submission)	Renk, U. H. (2016, November). Donkin Mine - Ground Control Procedures (Revision: 2). Technical Report to Kameron Coal Management Limited.	1

Ref#	Filename	Reference	# of Pages
31	R_2016-11-22 Ground Control Procedure Rev 2 - File #1 (Report)	Renk, U. H. (2016, November). Donkin Mine - Ground Control Procedures (Revision: 2). Technical Report to Kameron Coal Management Limited.	46
32	R_2016-11-22 Ground Control Procedure Rev 2 - File #2 (Drawings)	Renk, U. H. (2016, November). Donkin Mine - Ground Control Procedures (Revision: 2). Technical Report to Kameron Coal Management Limited.	14
33	R_2016-11-22 Ground Control Procedure Rev 2 - File #3 (Appendix A)	Renk, U. H. (2016, November). Donkin Mine - Ground Control Procedures (Revision: 2). Technical Report to Kameron Coal Management Limited.	8
34	R_2016-11-22 Ground Control Procedure Rev 2 - File #4 (Appendix B)	Renk, U. H. (2016, November). Donkin Mine - Ground Control Procedures (Revision: 2). Technical Report to Kameron Coal Management Limited.	145
35	R_2016-11-22 Ground Control Procedure Rev 2 - File #5 (Appendix B)	Renk, U. H. (2016, November). Donkin Mine - Ground Control Procedures (Revision: 2). Technical Report to Kameron Coal Management Limited.	99
36	R_2016-11-22_FIGURE 1 BOUNDARY MAP 2016-1110 Certified	Renk, U. H. (2016, November). Donkin Mine - Ground Control Procedures (Revision: 2). Technical Report to Kameron Coal Management Limited.	1
37	R_2016-11-22_Figure 2A Site Property Map 2016-1110 certified	Renk, U. H. (2016, November). Donkin Mine - Ground Control Procedures (Revision: 2). Technical Report to Kameron Coal Management Limited.	1
38	R_2016-11-22_Figure 2B Site Layout 2016-1110 Certified	Renk, U. H. (2016, November). Donkin Mine - Ground Control Procedures (Revision: 2). Technical Report to Kameron Coal Management Limited.	1

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39	R_2016-11-22 Provisional Ground Control Procedure - Attachment #1 (Submission)	Renk, U. H. (2016, November). Donkin Mine - Provisional Ground Control Plan. Technical Report to Kameron Coal Management Limited.	1
40	R_2016-11-22 Provisional Ground Control Procedure - File #1 (Submission)	Renk, U. H. (2016, November). Donkin Mine - Provisional Ground Control Plan. Technical Report to Kameron Coal Management Limited.	24
41	R_2017_06-15_Evaluation 1. Phase of the Provisional Ground Control_060917	Renk, U. H. (2017, June). Evaluation 1 - Phase of the Provisional Ground Control Procedure. Technical Report to Kameron Coal Management Limited.	79
42	R_2017-01-04_FIGURE 4A - Mine Plan 2016-1221 Revision B	Renk, U. H. (2015, September). Slope Tunnel Roof Fall Rehabilitation Code of Practice (Revision No.1). Amended Drawing to Occupational Health and Safety Division, Nova Scotia Labour and Advanced Education.	1
43	Update of ground conditions of tunnel	Seedsman, R. W. (2009). An update of conditions in the Donkin-Morien tunnels. Proceedings from the 3rd Canada-US Rock Mechanics Symposium, Toronto, Ontario, Canada.	7
44	Environmental Assessment Study	Xstrata Coal Donkin Management Limited. (2013, April). Comprehensive Study Report - Donkin Export Coking Coal Project (Issue April). Technical Report to Canadian Environmental Assessment Agency.	104
45	Donkin scoping plan - June, 2008	Xstrata Coal. (2008, May). Donkin Project: Project Description for Underground Exploration Phase. Internal Report to Xstrata.	14