Mine Closure 2023 - Behrooz Abbasi, Jeff Parshley, Andy Fourie & Mark Tibbett (eds)

doi:10.36487/ACG_repo/2315_093

Development of a site-specific, relative hazard prioritization tool at a legacy mine district in British Columbia

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Abstract

Legacy underground historical mining sites near and around urban areas may include the presence of unsecured openings to surface (surface features), that pose a risk to public safety. These historically mature mining camps (e.g., over 100 years old) operated during previous social circumstances that led to towns being developed around the mines, and the population was more aware of the associated risks of being adjacent to an active mine. Long after the mines ceased operating, corporate mergers and land transfers occurred, new populations less connected to the mining legacy arrived and the current mine site owners face a challenge managing both real, and perceived risks.

For a specific legacy mine site in British Columbia, Canada, active management of over 400 mapped surface mining features required the development of a tool to assist the owner with prioritization of ongoing investigation, monitoring and mitigation efforts.

The objective of the site-specific, relative hazard prioritization tool was to apply a systematic and consistent approach to assist with relative prioritization of surface hazards to support mitigation effort decisions and the frequency of monitoring of unmitigated features. The tool was designed to use qualitative feature traits based on the geotechnical hazard consultant and owner's combined experience on the project site to characterize the relative geotechnical hazard of each surface feature.

This paper presents the process used to develop the tool, how it has been applied on the project site, and its potential application to other sites within the owner's portfolio of legacy underground mining sites.

Keywords: *legacy property, historical mining, geotechnical mine hazard, hazard prioritization*

1 Introduction and background

Legacy underground historical mining sites near and around urban areas may include the presence of unsecured openings to surface (surface features), that pose a risk to public safety. These historically mature mining camps (e.g., over 100 years old) operated during previous social circumstances that led to towns being developed around the mines, and the population was more aware of the associated risks of being adjacent to a mine. Long after the mines ceased operating, corporate mergers and land transfers occur, new populations less connected to the mining legacy arrive and the current mine site owners face a challenge managing both real, and perceived risks.

For a specific legacy mining site in British Columbia, Canada, active management of over 400 mapped mining and exploration features at surface required the development of a site-specific, relative hazard prioritization tool to assist the owner with prioritization of ongoing investigation, monitoring and mitigation efforts. The main property and additional claims were extensively mined for gold and copper between the late 1800s and early 1940s. The mine workings from the developed mines were all connected underground, forming approximately 100 km of underground workings and, in some areas, to a depth of over 500 m (Ministry of Energy, Mines and Petroleum Resources 2023). The present-day legacy mine property (referred to as the Site) represents an agglomeration of a principal mining complex and numerous adjacent claims which lie both adjacent to and within city limits, presenting the owner with a unique set of physical hazards, geographical challenges, and property management challenges.

1.1 Physical hazards present on site

In the past nearly 20 years, significant effort has gone into compiling records for the Site, including mine plans, assay reports, compilation maps, government and museum records and anecdotal evidence from members of the community. Using these sources, surface disturbance features related to historical mining activities identified to date include surface open-pit mining; underground stoping, vertical and inclined shafts, portals and adits associated with horizontal development; prospects; areas where underground stoping purposely intersected the surface (glory holes); and areas where underground mining has gradually caved and caused surface subsidence. Unrecorded lessee miners recovered ore by small scale mining of the surface crown pillars and other parts of the workings (Ministry of Energy, Mines and Petroleum Resources 2023), presenting uncertainty with historical records and interpretation from present day investigations. Features that may have been temporarily mitigated in the past are also sometimes subject to failure due to settlement of backfill, deterioration of timber or other support.

These surface disturbances present physical hazards in areas where the public live, drive and recreate, and in areas where emergency services personnel may require access and where workers conduct routine maintenance and other work on behalf of the owner. Physical hazards include, but are not limited to, undermining/surface subsidence, fall hazards, and accessible openings to underground mine workings. The geometry and connectivity to deeper mining of some features are poorly defined and public access to the features is highly variable (some are located on in-town properties while others are hundreds of metres through forest from the nearest trail).

'Surface features' refer to the expression of hazards related to historical subsurface mining, or potential hazards, at surface, and are classified according to the following:

- Unclassified Disturbance. Typically, a depression that is not shown on available maps or records. Disturbance features are suspected to be related to historical mining (including mine infrastructure).
- Prospect. An excavation or trench at surface for which historical records do not indicate connection to deeper workings.
- Portal. A horizontal (or near horizontal) entrance to a mine tunnel. Many portals in the surface feature database have been previously mitigated either with temporary or long-term design implementation.
- Prospect Shaft. A shaft for which historical records suggest a limited depth and no subsurface development or connection to deeper workings.
- Shaft. A vertical or inclined working from surface for which historical records suggest a connection to deeper workings (includes raises).
- Stope. The previous mapped surface expression (in some cases collapsed or mined to surface) of an excavated ore body. Many of these features were previously filled in with waste rock.
- Tunnel. The mapped location of a near-surface tunnel.

1.2 Summary of historical monitoring, investigation and mitigation

After mining operations ceased, the focus transitioned into care and maintenance at the Site. In addition to monitoring, a series of targeted investigation and mitigation programs were conducted by the owner from as early as the 1950s and are still ongoing. The owner maintains existing relationships with stakeholder groups in the community in order to maintain public access to portions of the Site, where possible. As such, temporary or permanent fencing with warning signage has been used in some instances by the owner to reduce and discourage public access to potentially hazardous surface features.

WSP Canada Inc. (WSP, formerly Golder Associates Ltd.) has assisted the owner at this Site since 2006. To augment some of the monitoring by the owner, WSP carried out an annual monitoring program which has typically included visual inspection of the condition of surface features to note change over time, either for all (more than 400) features, or a subset of features. Targeted investigation programs have included excavation and/ or downhole drilling to intersect near surface voids related to historical mining and the use of surface and downhole geophysical surveys for mapping mine workings.

While not a comprehensive list, a few examples of the historical and some more recent mitigation methods which WSP has assisted with, are presented below:

- Backfilling of shafts, stopes and prospects with waste rock or granular material and, in some cases, debris. In some more recent cases, geogrid was installed over the feature following backfilling of the opening as well as the use of a polyurethane foam plug.
- Blasting of the hanging walls of stopes to choke off the opening, followed by backfilling.
- Backfilling or blasting of portal openings, often with drainpipes installed at the base.
- Construction of cast-in-place reinforced concrete caps over stopes and shafts.
- Construction of brick walls at portal and stope openings.
- Installation of chain link fencing, mesh or steel grating over portal and prospect openings.
- Backfilling of subsurface voids with materials such as self-consolidating concrete, lean concrete and polyurethane foam.

Select examples of surface features at the Site, and the work conducted at them, are presented in Section 2. A large portion of the available Site information is stored in a project geospatial database (ESRI ArcGIS Enterprise), referred to herein as the GIS database, including for each surface feature the coordinates, historical and relatively recent photographs, monitoring program field observations, and historical and anecdotal information related to previous mining and mitigation. Many of the mine plans and other relevant maps have been georeferenced and added as layers to the database, as well as mapped access roads and trails used to monitor and access the features.

1.3 Rationale for developing a site-specific, relative hazard prioritization tool

A wide range of historical investigation and mitigation efforts have been undertaken for surface features on the Site over the years, some temporary and some intended to be longer term. Until now, there was no systematic approach to prioritize mitigation or monitoring frequency of the surface features at the Site. Typically, prioritizing hazards for investigation and mitigation was subjective and considered the interpretation of the available information, the changes over time at the Site and the owner's mitigation objectives over the past decades. With a growing database of currently over 400 features at the Site, prioritizing efforts became challenging, and a systematic approach was necessary for the owner to manage and remediate the physical hazards related to historical mining. The development of the hazard prioritization tool over the course of 2022 and 2023 also served to assist the owner with short- and longer-term resource planning for the Site and will be used to show progress in overall hazard reduction over time.

2 Development of the Hazard Prioritization Tool

2.1 Objectives

The objective of developing a site-specific, relative hazard prioritization tool (herein referred to as the tool) was to apply a systematic and consistent approach to assist with relative prioritization of surface hazards to support mitigation effort decisions and the frequency of monitoring of unmitigated features.

An initial draft version of the tool was prepared as part of a recent monitoring program and was refined with the owner at a series of meetings and a workshop, based on the following:

- The tool will consider qualitative feature traits based on the combined experience on the Site using similar descriptions and terminology used in previous work and in historical sources (e.g., prospects, shafts, etc.).
- The two factors used to assess the relative hazard level for each feature will be (1) the ease of accessibility by the public and, (2) the general, relative consequence to human health due to exposure to geotechnical hazards, the potential for property damage, and the amount of uncertainty in characterisation of the feature.
- While semi-quantitative, alphanumeric indicators would be used to represent relative ease of accessibility or hazard consequence, the tool would not be quantitative, by design and is specifically not intended to represent a risk assessment. For example, numerical values used in the calculation of a feature's accessibility factor reflect the owner and consultant's subjective, site-specific calibration based on site experience and judgement rather than a statistical likelihood of access.
- The tool will not replace engineering judgement and analysis and needs to be carefully applied in the field by staff and calibrated with experience on the Site.
- The tool should be refined iteratively.
- The tool is defined for surface features only and may not capture some specific areas of the Site. Subsurface mining hazards that are not expressed at or near surface are excluded from this tool.

2.2 Description of tool components

The hazard prioritization tool, presented below in Figure 1, consists of a colour-coded, graphical chart with an "accessibility factor" on its vertical axis and a "relative hazard rating" on its horizontal axis. The accessibility factor and relative hazard rating are discussed further in the following sections. By assigning each of these two parameters to a given surface feature, the "relative priority" value of low, medium or high can be evaluated. Further discussion on the use of the relative priority is provided in Sections 2.3 and 3.

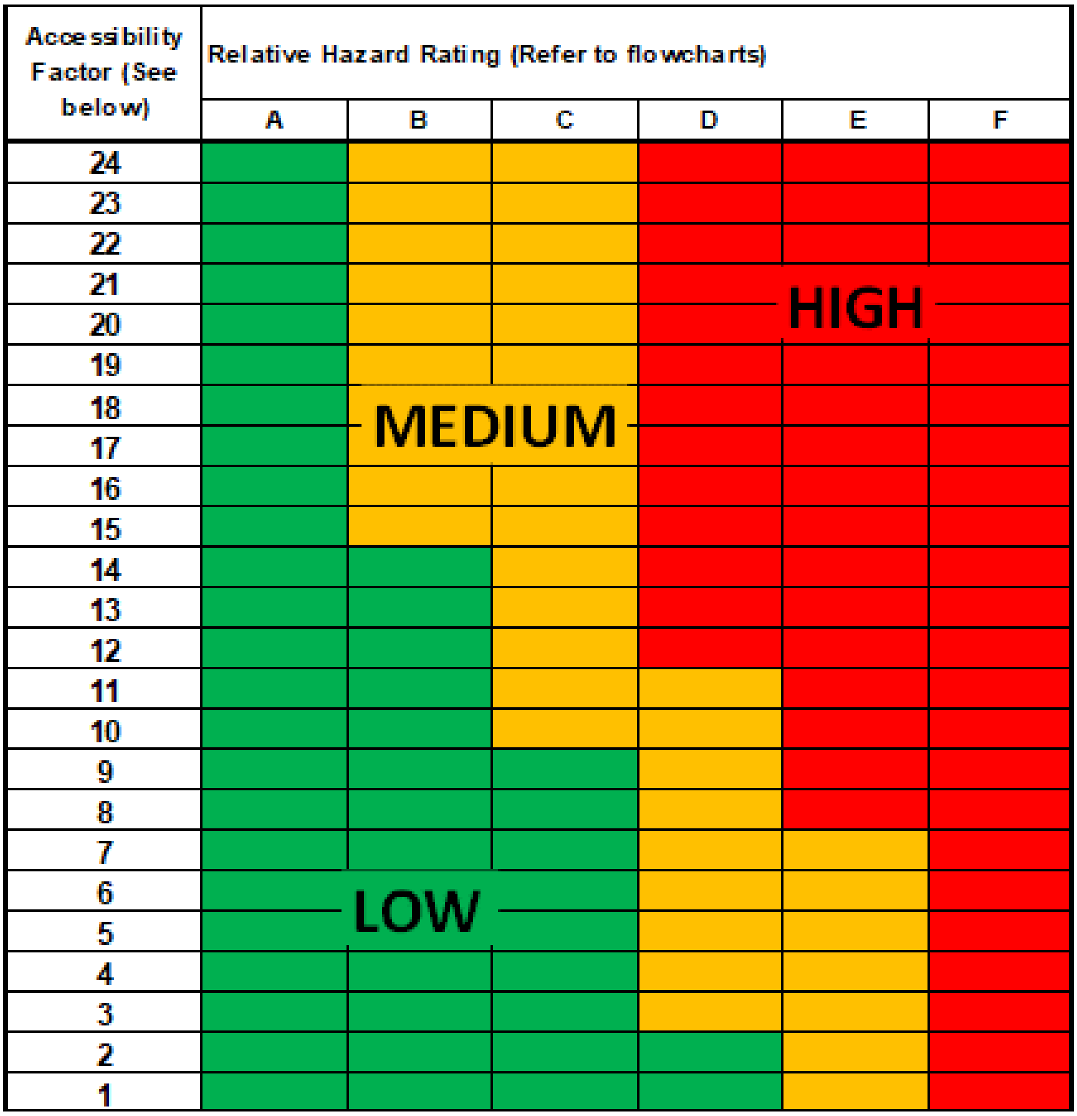

Figure 1 Hazard prioritization tool chart

2.2.1 Accessibility factor

For a given surface feature, the accessibility factor considers three questions as inputs:

1. What is the closest known type of access?
2. How far is the surface feature from the known access (or "proximity to access")?
3. Is the feature fenced and therefore requires a "correction factor"?

The closest known access type, item 1 in the above list, is assigned a relative score of one through four. A score of four is assigned to features located near paved roads, typically on or adjacent to in-town residential properties. A score of three is assigned to features for which an unpaved road is the closest known access type. A score of two is assigned to features nearest to "marked trails", which are trails that either existed in the database provided by the local trails society or which are otherwise marked with signage. A score of one is assigned to features located near "unmarked trails", representing all other trails, including those mapped during previous monitoring programs.

The proximity to access reflects the shortest distance from the closest known road or trail, in metres, and was calculated for all features using the GIS database. This distance was confirmed in the field using the most "accessible" route to the feature.

The correction factor for fenced features reflects a likely reduction in public accessibility to a feature based on the type of fence the owner has erected around the feature. The correction factor does not represent a quantitative risk reduction and was developed iteratively with the owner. No correction factor is applied for sites that are not fenced or are partially fenced. Types of fences considered for this correction factor include:

- Permanent perimeter fence (around the main property at the site): chain link fence panel, posts set with concrete
- Permanent fence around feature: chain link or wood fence panel, posts set with concrete
- Temporary fence around feature: chain link or steel fence panels placed (not set in the ground with concrete).
- Temporary fence around feature: snow fence around feature (highlighting hazard)

Multiple correction factors can be applied, for example, if a feature is surrounded by snow fencing within the permanent perimeter fence. Note that for features such as portals which have been temporarily mitigated using fencing or mesh bolted to the surrounding rock, the fencing is considered a mitigation measure rather than an accessibility reduction measure.

Once each input score has been determined, the accessibility factor can be calculated by multiplying all three inputs as shown in Figure 2.

Closest Known Access Type	Score
In-town property or paved road access	4
Unpaved road access	3
Marked trail access	2
Unmarked trail access	1

×

Proximity to Access	Score
0 m to <5 m	6
≥5 m to <10 m	5
≥10 m to <25 m	4
≥25 m to <50 m	3
≥50 m to <250m	2
≥250 m	1

×

Correction Factor for Fenced Features	Factor
Permanent perimeter fence	0.5
Permanent fence around feature	0.7
Temporary fence around feature	0.8
Snow fencing	0.9

Figure 2 Accessibility factor calculation

2.2.2 Relative hazard rating

A feature's relative hazard to the public (in its current condition) is based on a series of qualitative traits of which includes judgement on relative consequences to human health due to exposure to geotechnical hazards, potential for property damage, and the amount of uncertainty in characterisation of the feature. The relative hazard rating for a surface feature is assigned using a series of flowcharts that are dependent on the feature type. These flowcharts are provided below in Figure 3 for disturbances and prospects, Figure 4 for portals, and Figure 5 for stopes, shafts, prospect shafts and tunnels. For the various feature types, the flowcharts broadly consider (a) previous investigation and mitigation efforts and the condition of the mitigation, and (b) the presence, general condition, and size of any surface expressions.

An alphabetic relative hazard rating from A through F is determined from the relevant flow chart for a given surface feature. The letter assignments in the flow chart were developed through an iterative process that considered the variety of features on the Site.

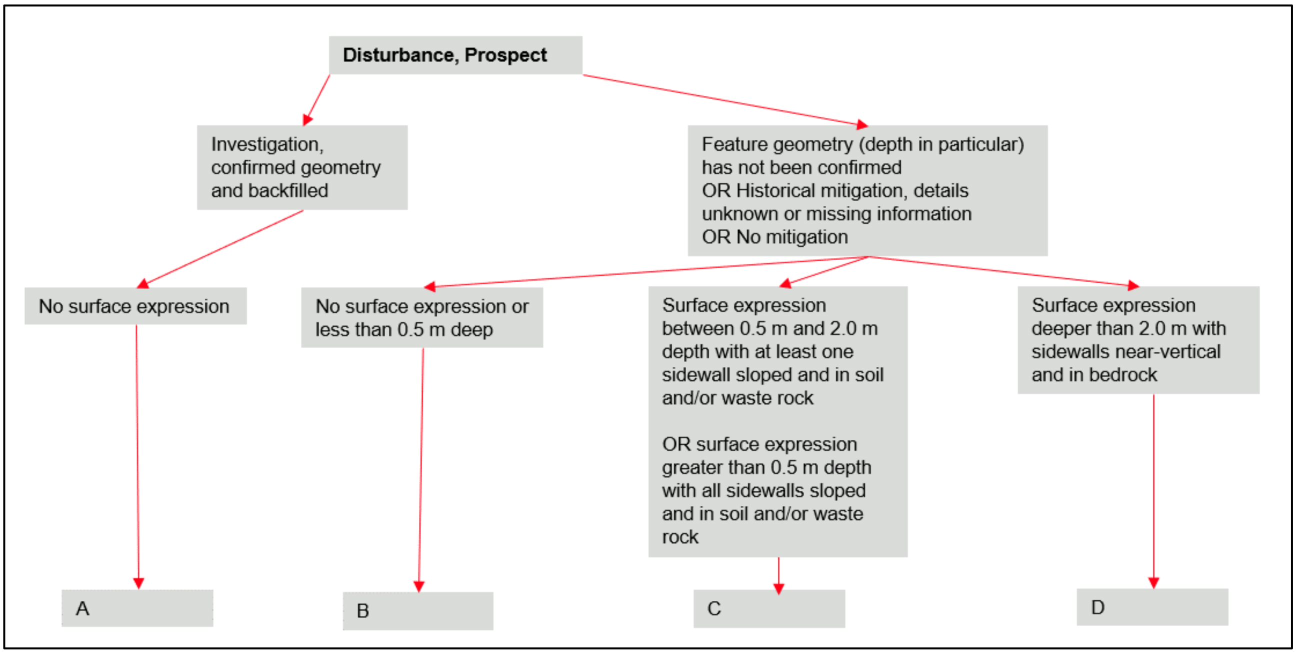

Figure 3 Relative hazard rating flowchart—disturbances and prospects

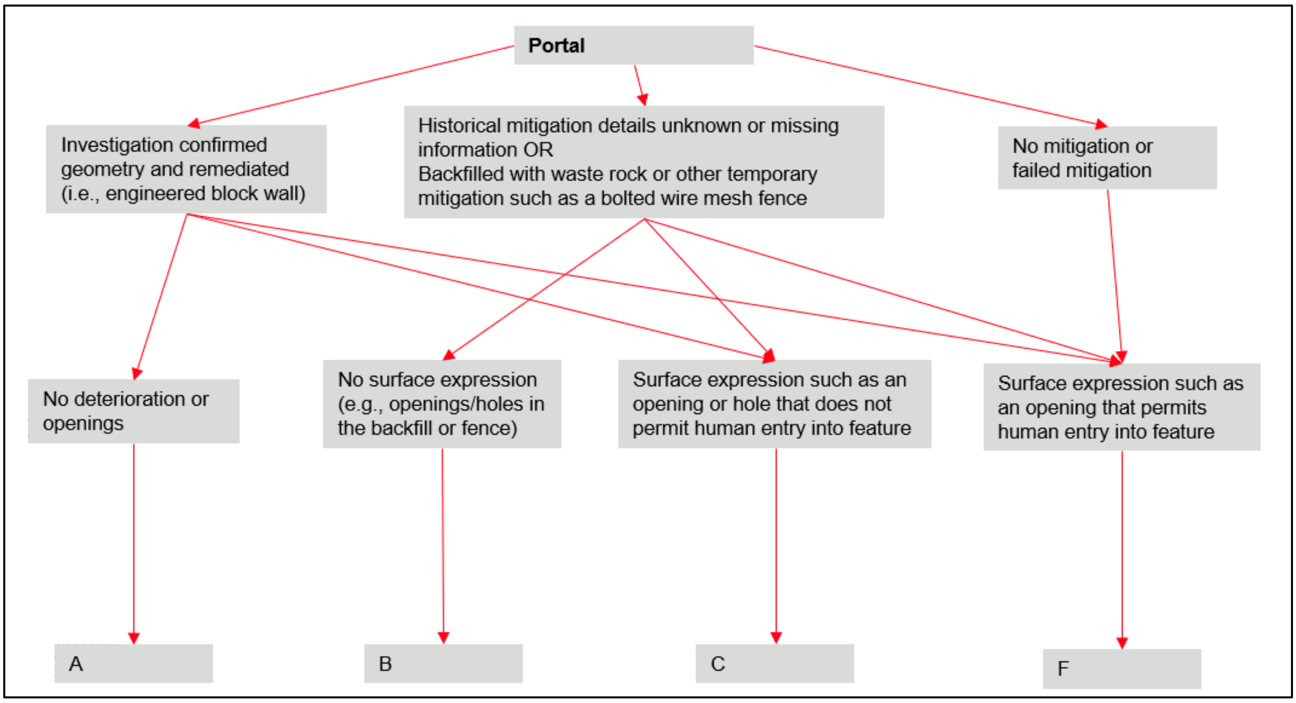

Figure 4 Relative hazard rating flowchart—portals

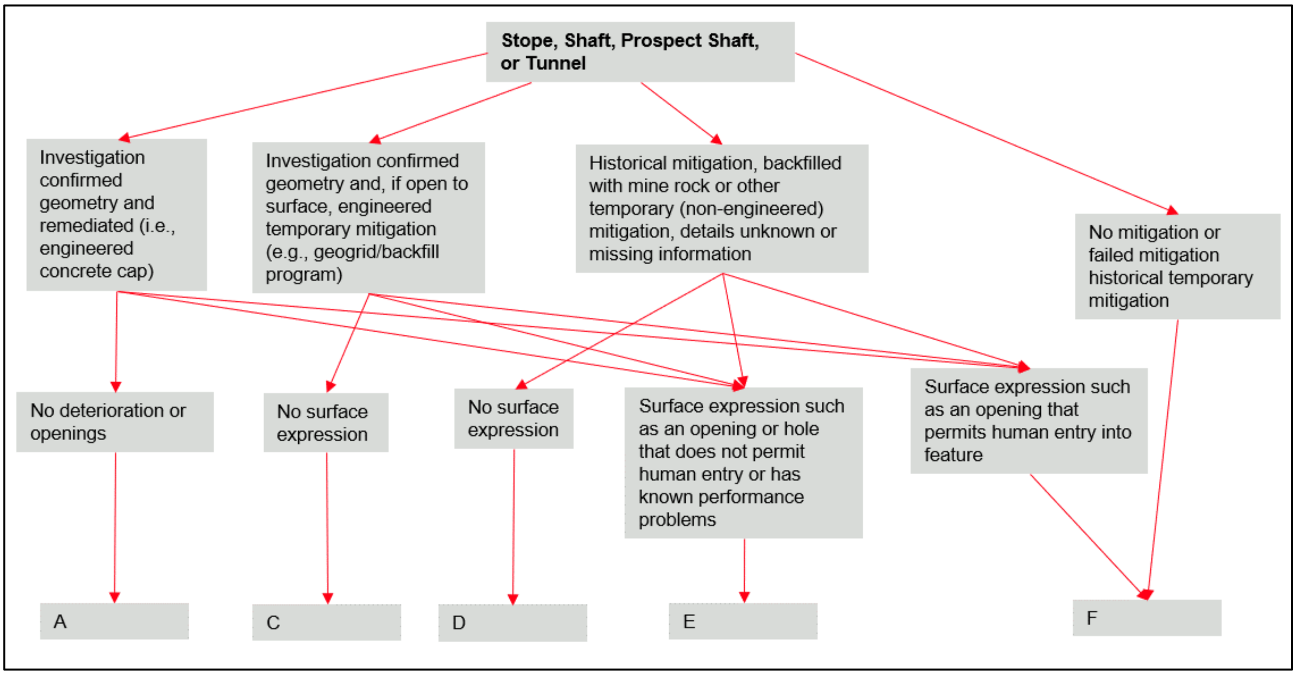

Figure 5 Relative hazard rating flowchart—stopes, shafts, prospect shafts and tunnels

2.2.3 Relative priority

The relative priority constitutes three qualitative categories, low priority, medium priority, and high priority, that represent a broad categorization of the features on the site for mitigation and monitoring purposes based on previous recommendations and discussions with the owner. Colouring of the chart, including the boundaries between colours, was an iterative process that was intended to reflect both the owner's and consultant's previous experience on the Site and previous mitigation and monitoring priorities.

2.3 Example surface features evaluated using the tool

A curated selection of surface features from the Site are shown in this section to highlight several examples of the relative priority calculation and to highlight some of the key details used to calibrate the tool, which occurred through the various development meetings as well as during on-site inspections. Four examples are discussed, referred to as Features A through D and, for three of the examples, two scenarios are described to show how the features moved on the Hazard Prioritization Tool Chart from the pre-mitigation rating to the post-mitigation rating. Note that mitigation activities for these example features commenced before or during development of the tool. They are therefore presented as examples of calibrating the tool rather than as mitigation activities prioritized through use of the tool.

2.3.1 Example Feature A

Example Feature A is a shaft which historical records indicate was sunk prior to 1915 and for which mitigation records indicate it has been backfilled by the owner twice in the past. Between the 2018 and 2019 annual monitoring programs, the backfill had collapsed to a depth of around 7 m (Figure 6a). The relative priority can be evaluated for two scenarios for the shaft feature: (1) 2022 condition, pre-mitigation, and (2) 2022 condition, during mitigation.

(a) (b)

Figure 6 Example Feature A: shaft surface feature with failed waste rock backfill: (a) Scenario 1: 2022 condition, pre-mitigation; (b) Scenario 2: 2022 condition, during mitigation (Sandve et al. 2023)

The accessibility factor can first be calculated for both Scenarios 1 and 2 by multiplying the following three inputs (refer to Figure 2):

- Closest known access type: 2 (marked trail access).
- Proximity to access: 3 (≥25 m to < 50 m, the distance from the shaft to the trail, measured in the GIS database).
- Correction factor for fenced sites: 1 (no correction factor applied; the site is not fully fenced).

The flowchart in Figure 5 is then used to evaluate the relative hazard rating. For the first scenario, illustrated in Figure 6a, the shaft feature falls within the farthest category to the right (no mitigation or failed historical temporary mitigation), which places the shaft within column F. Column F is designed to be the most critical possible category, as open features such as shafts and stopes represent the highest relative hazard to the public for the surface features recorded the Site's GIS database.

Using the accessibility factor and relative hazard rating, Example Feature A can therefore be plotted on the hazard prioritization tool chart shown in Figure 7. For Scenario 1 (failed backfill/open shaft), the shaft plots as 6F, high relative priority.

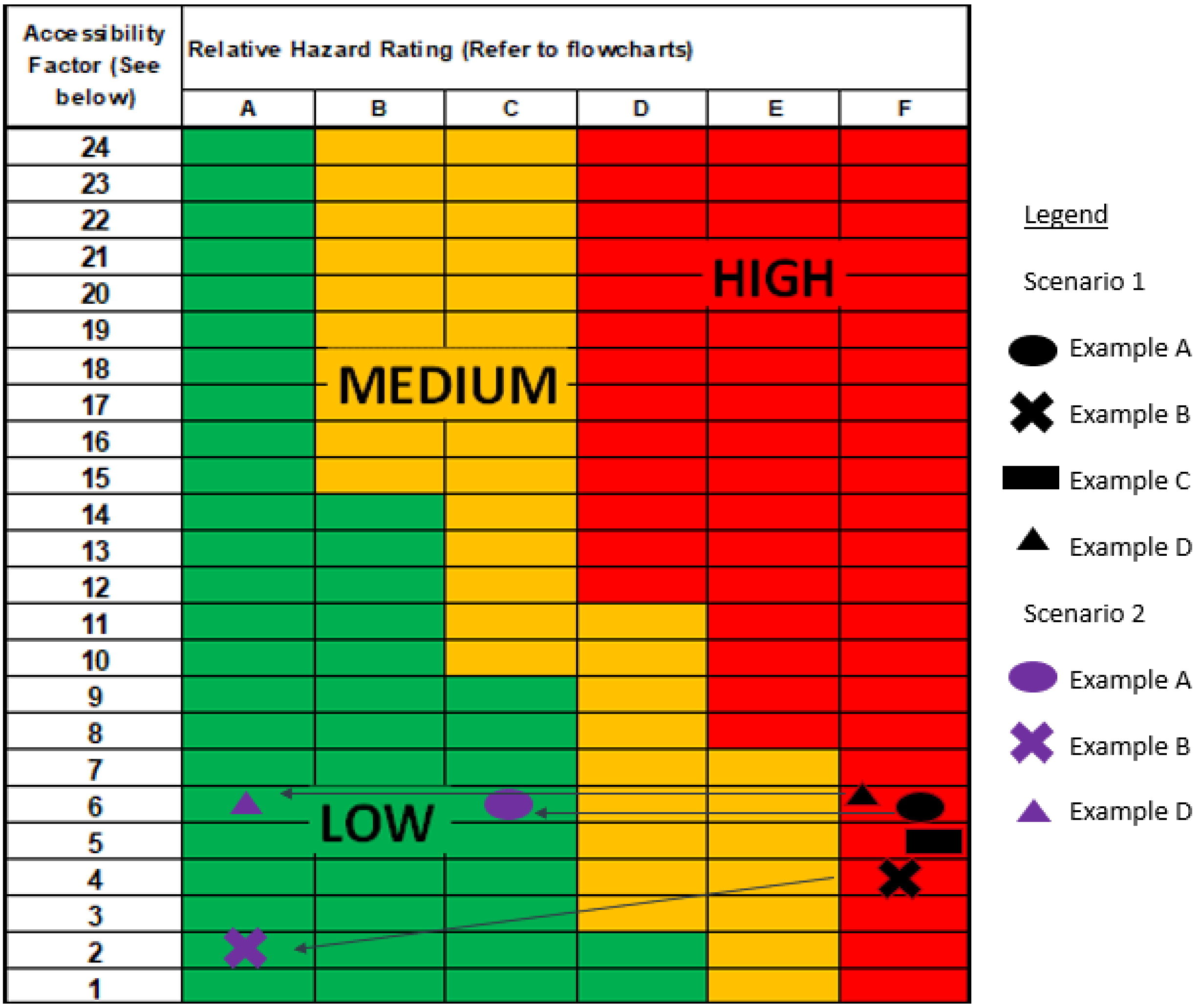

Figure 7 Hazard prioritization tool chart

For Scenario 2, the shaft feature falls within the second category from the left on the Figure 5 flowchart (investigation confirmed geometry and, if open to surface, engineered temporary mitigation). Figure 6b shows the mitigation with a polyurethane foam plug prior to the cover placement. Further information on the engineered temporary mitigation of Example Feature A is provided by Sandve et al. (2023). Moving down the flowchart, no surface expression is observed, placing the mitigated shaft feature within column C.

Using the accessibility factor and relative hazard rating, Example Feature A can therefore be plotted on the hazard prioritization tool chart (Figure 7) following the engineered temporary mitigation. For Scenario 2, the shaft plots as 6C, low relative priority.

2.3.2 Example Feature B

Example Feature B, shown in Figure 8, was an open shaft feature which had been previously temporarily backfilled with boulders and waste rock. In 2008, there was concern with migration of the backfill to deeper mine workings and a permanent mitigation solution was required. The shaft opening was observed during the investigation to be 3.9 m by 1.8 m by at least 13 m deep with a large boulder partially blocking the surface opening (Figure 8a). An engineered, reinforced concrete cap was constructed over the shaft (Figure 8b). Following the concrete cap construction this feature was also included in the permanent perimeter fence installation around the main property. The relative priority can be evaluated for two scenarios for the shaft feature: (1) pre-mitigation condition, and (2) post-mitigation condition.

The accessibility factor and relative hazard rating are assigned for Scenario 1 based on the below inputs:

- Closest known access type: 1 (unmarked trail access).
- Proximity to access: 4 (≥10 m to <25 m, the distance from the shaft to the trail, measured in the GIS database).
- Correction factor for fenced sites: 1 (no correction factor applied).
- Relative Hazard Rating Flowchart: F (historical temporary mitigation starting to fail).

Using the information above, Scenario 1 for Example Feature B can be evaluated as 4F, high relative priority, on the hazard prioritization tool chart shown in Figure 7.

For Scenario 2, a correction factor for fenced sites of 0.5 is applied to the accessibility factor as this feature was included in the permanent perimeter fence around several of the claims on the property. The feature was investigated, the geometry was confirmed and hence, the Relative Hazard Rating following the installation of the engineered concrete cap is A.

Using the information above, Example Feature B for Scenario 2 can therefore be evaluated as 2A, low relative priority, on the hazard prioritization tool chart shown in Figure 7.

(a) (b)

Figure 8 Example Feature B: shaft surface feature which had previously been temporarily backfilled with waste rock. (a) Scenario 1: investigation condition, pre-mitigation. (b) Scenario 2: shaft post-mitigation

2.3.3 Example Feature C

Example Feature C, shown in Figure 9, represents a stope that, based on historical records, appears to have been mined partially to surface (i.e., a gloryhole). It was possibly backfilled with waste rock and debris in the early 1990's. The backfill collapsed in recent years, resulting in an ovular surface expression up to 8 m long by 5 m wide with an unknown depth. In its present condition, the feature has the following inputs to the accessibility factor and the relative hazard rating:

- Closest known access type: 3 (unpaved road access, owner's private road within permanent perimeter fenced area).
- Proximity to access: 5 (≥5 m to <10m).

- Correction factor for fenced sites: 0.35 (multiplied by two factors, 0.5 and 0.7; the permanent perimeter fence around several of the claims on the property surrounds this feature, and an additional fence around the feature itself).
- Relative Hazard Rating Flowchart: F (failed historical temporary mitigation).

Using the information above, Example Feature C can therefore be evaluated as 5F, high relative priority, on the hazard prioritization tool chart shown in Figure 7.

Figure 9 Example Feature C: previously backfilled, collapsed stope feature

2.3.4 Example Feature D

Example Feature D, shown in Figure 10, represents a portal that, based on historical records, had been previously backfilled with waste rock in 2000. The waste rock showed signs of settlement, creating an opening at the crown 1 m by 0.5 m. Two scenarios are discussed for this example; Scenario 1, for the pre-mitigation condition with partially failed backfill, and Scenario 2, for the post-mitigation condition. Figure 10a shows the portal during investigation following removal of the waste rock backfill with dimensions of 2.4 m high by 2.5 m wide and extending into the slope for an unknown distance. Figure 10b was taken following scaling of loose rock around the portal entrance and installation of an engineered, block wall at the portal entrance.

The accessibility factor can first be calculated for both Scenarios 1 and 2 by multiplying the following three inputs (refer to Figure 2):

- Closest known access type: 1 (unmarked trail access).
- Proximity to access: 6 (0 m to < 5 m, the distance from portal to the unmarked trail, measured in the GIS database).
- Correction factor for fenced sites: 1 (no correction factor applied).

The flowchart in Figure 4 is then used to evaluate the relative hazard rating. For Scenario 1, the portal feature falls within the farthest category to the right (failed backfill/opening into portal), which places the portal within column F.

Using the accessibility factor and relative hazard rating, Example Feature D can therefore be plotted on the hazard prioritization tool chart shown in Figure 7. For Scenario 1, the shaft plots as 6F, high relative priority.

For the Scenario 2, the portal feature falls within category A on the Figure 4 flowchart (investigation, confirmed geometry and remediated). Moving down the flowchart, no deterioration is observed, placing the remediated portal feature within column A.

Using the accessibility factor and relative hazard rating, Example Feature D can therefore be plotted on the hazard prioritization tool chart (Figure 7) following the engineered block wall installation. For Scenario 2, the portal plots as 6A, low relative priority.

(a) (b)

Figure 10 Example Feature B: portal feature which had previously been temporarily backfilled with waste rock. (a) during mitigation provided for better view of feature – note that Scenario 1 corresponds to pre-mitigation. (b) Scenario 2: post-mitigation

3 Conclusion

For a legacy mining site, active management of over 400 mapped mining and exploration features at surface required the development of a Site-Specific, Relative Hazard Prioritization tool to assist the owner with prioritization of ongoing investigation, monitoring and mitigation efforts. This tool was developed through 2022 and 2023 with the objective of applying a systematic approach to assist with the relative prioritization of surface mine hazards to support proactive mitigation efforts of high hazard features. Additionally, the tool will be used to inform the monitoring of unmitigated features through establishing a relative frequency based on the hazard ranking, where high and medium relative hazards will be visited annually, and low ranking hazards every 2 to 3 years.

The tool was developed and calibrated over a period time through meetings, workshops, and site visits. Ranking of individual surface features within the tool resulted in the development of a prioritized list to be captured within a remediation schedule and resource plan for the Site. The tool will first be implemented on site for the 2023 annual monitoring program, where features with medium and high relative hazard priority rankings will be visited. This reduces the number of features visited for 2023 to around 160, compared to the 400 visited in 2022. Features ranked with a low relative hazard priority will be visited in the 2024 or 2025 monitoring campaigns which will further inform the long-term monitoring and mitigation strategy. Further refinement of the tool will be implemented as monitoring and mitigative work progresses on the Site.

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