

REHABILITATION OF HISTORICAL UNDERGROUND MINE WORKINGS—A PHASED APPROACH

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INTRODUCTION

Rehabilitation is essential in legacy mines as mine hazards do not improve with time; they will always get worse. Most hazard mitigation techniques address immediate risk but do nothing to actually fix the problem. The current impetus is to move away from simply identifying and managing risks and towards long-term solutions that eliminate the hazards in a planned way. This article will describe a proven approach to identify and eliminate hazards in such a way as to preserve the positive legacy of mining while eliminating issues that affect the environment and communities in proximity to legacy mine sites.

KEYWORDS

abandoned mines, orphaned mines, historical mine workings, stability, backfill, rehabilitation options, crown pillar stability, mine closure

MINING HISTORY

Mining has been done in many different ways, shapes and forms for thousands of years. There are some regions that have a long history of mining ventures and others that may have only recently begun their mining journey. Humankind has always looked below the earth's surface to supply its needs, whether that be material in its original form (e.g. peat to heat houses or coal to run factories) or after it has been refined, such as gold for jewelry amongst the Inca civilization or, more recently, rare earth minerals used in the production of cell phones or bitumen refined for gasoline. With any industry, technology evolves over time, and while this is certainly true for mining, the basic principle has remained the same: dig a hole, separate the target material from the waste, use or sell the good stuff and leave the rest behind. Depending on how this is done, the legacy of mining can be very positive for communities or it can prove to be an ongoing liability.

Legacy sites can be former open pit and/or underground mines that may or may not still have associated tailings storage areas, waste rock dumps, surface infrastructure and access to the underground or pit. The mining activities on a legacy site may have been done in a systematic way with a publicly owned mining company having purchased the rights, gone through permitting processes and having operated a full-scale mining operation. Or it could be a junior mining company doing small-scale mining. These two examples will carry different legacy

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hazards and risks, and it is important to understand the difference. Historical workings can also exist within an active mining footprint or they can be an orphaned or abandoned site that is under the purview of the local, regional or federal government. Orphaned sites are typically defined as mine sites for which an owner cannot be found or no longer exists. Abandoned sites are mine sites for which an owner does exist but is financially unable or unwilling to perform remediation activities. In most jurisdictions the terms are used interchangeably.

Typically, historical mining sites that have legacy issues have been abandoned, orphaned or closed to a level that does not meet current standards. Abandoned or orphaned mines are often in a state where little to no closure or remediation activities have been performed. Bankruptcy or low commodity prices are common reasons for some of these sites being left as they are. Some mines were closed and decommissioned according to the rules of the day, but in light of today's knowledge, the sites are not up to an acceptable standard to be returned to public use.

When the legacy from mining proves to be problematic, there are generally two main areas where it manifests itself: the physical stability of the mine workings and surrounding area, and the geochemical stability of the site and beyond. Physical stability means the ability of the surrounding rock to support the mined-out areas along with any other uses in the area such as wildlife, recreation activities (e.g. hiking trails), other industrial or private use (e.g. buildings), and transportation routes (e.g. roads, railways). Geochemical stability refers to the water, soil, rock and air in and around the site and whether they are inert and harmless after the mining activity has ended or are they actively generating or transporting contaminants that adversely affect the surrounding environment. This article will focus on physical stability.

What does physical instability look like?

Physical instability typically appears as ground disturbances around the site. This can include sinkholes, subsidence, shifting of the ground, collapse of features, or surface cracking. These incidents can be adjacent to surface openings from the mining operations or merely in the vicinity of the mining operations. Ground disturbances are caused by insufficient support for the remaining rock in the vicinity of the mined-out areas of underground workings. Any of the hazards mentioned above can present themselves gradually or as a sudden event.

The rate and amount of ground disturbances over time is difficult to predict as it depends on a complex combination of site-specific factors such as, depth to the voids, rock characteristics, and the failure mechanics of the rock and soil material amongst other considerations like weather events. Collapse may take decades to occur; however, the consequences cannot be ignored. Of late, historical mines are in the public spotlight across the world due to the risks they present to the environment and the public. In far too many regions, there are multiple stories that tell of sudden collapse of roads, pathways or houses, that can be traced back to historical mines—some of which are known and some of which have no records. Many jurisdictions have local or regional departments devoted to dealing with these sites. Photos of some of these incidents are in Figure 1 and Figure 2.

Rehabilitation is essential

The physical hazards discussed above do not improve with time, they will almost always get worse over time. Hazard mitigation measures in the past typically included fencing off the affected areas to restrict access, capping of the voids, and monitoring. While these types of solutions mitigate some of the immediate risk, they do nothing to actually fix the problems. The current impetus amongst the public, the regulatory bodies and the mining industry is to

FIGURE 1. Sinkhole in Timmins, Ontario, in 1963 near a gas station from large well-known mining operations.



FIGURE 2. Sinkhole in Central America in 2018 near a village from an illegal unknown mine.



move away from simply identifying and managing the risk and towards long-term solutions that eliminate the hazards in a planned way.

Rehabilitation planning

A rehabilitation plan for abandoned, orphaned or closed sites should consider the process of investigating, mitigating and rehabilitating hazards on the site for both physical and geochemical hazards. The problems associated with these sites can be complex and difficult to manage from a technical, social, environmental and especially economic perspective. Hazard origins can be difficult to understand, making assessments of risk and identification of suitable mitigation or remediation efforts complex. In some cases, there is considerable uncertainty around the entire site due to a lack of information. All these elements make planning the most critical step.

The most common mistake that is made is to manage and mitigate all hazards individually. Recent experience has shown that developing a holistic site-wide investigation and rehabilitation approach can result in benefits to the mineral rights holder (if they exist), government and general public / landowners in the area, resulting in cost savings and/or less intrusive rehabilitation methods. This type of plan can be used by mine managers, environment and risk managers, and regulatory personnel to deal with issues related to land adversely impacted by historical mining—either through active mining near closed historical workings or abandoned/orphaned mines.

Physical stability rehabilitation planning

Planning for physical stability rehabilitation covers five main technical components:

- Assessment of stability of the underground mine openings
- Identification of suitable remediation options for hazard mitigation
- Design of the system for the preferred option
- Execution of stabilization options
- Evaluation of the solution post implementation

Stability assessment of voids, openings and workings

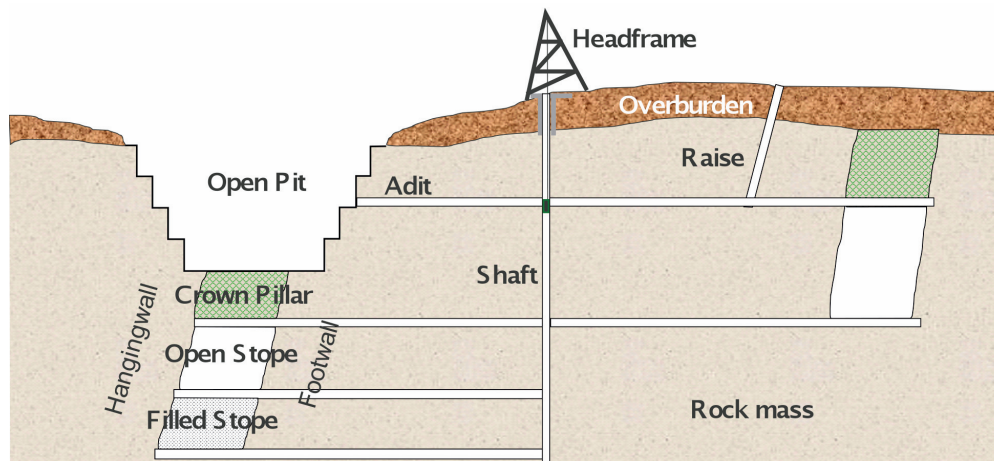
Stability assessments are generally completed using an iterative/phased approach involving the following steps:

1. Data gathering and validation
2. Desktop stability and data gap assessments
3. Planning and execution of the physical investigation
4. Stability assessments
5. Identification of the mine openings requiring rehabilitation

In Figure 3 below, a schematic shows potential hazards in an underground mine. Mine hazards can be defined in two broad categories:

- Openings to surface—shaft, raise, adit, stope mined to surface
- Openings near surface—bedrock crown pillars over mined stopes

FIGURE 3. Schematic of mine workings.



Any of these features over time could evolve into a ground stability issue that can impact the surface. Many of these mine openings will have unknown conditions such as the exact location, current stability conditions, and current state (e.g. filled or partially filled with material, depth below surface and rock mass quality). During the data gathering phase, the critical information is the geometry of the mine workings and the geotechnical and geological characterization of the mine area. Mine plans are essential for this step and, more often than not, obtaining accurate and complete plans for historical mines is not an easy proposition. The key outcome of this step is to get a broad idea of the extent of the potential physical hazards.

In the first step, data gathering and validation, the purpose is to gather as much information about the site as possible. This should be done through all available resources. Mine drawings, technical reports, and information from the mine have been found in all sorts of places including basements of second- and third-generation families in the local community or in the town records offices. A thorough and wide search is likely required and often involves spending a lot of time in mine drawing vaults, museums and regulatory archives.

Most of the documents retrieved tend to be paper copies (or even vellum or other medium such as microfiche) and/or hand drawn. Mine plans are almost always in a mine grid that needs to be converted into a useable coordinate system. While any information is valuable, hand drawings do not always represent the “real” story and do not always show the whole picture. Once all the information has been gathered, it is important to do an investigation to prove that the mine drawings and records are accurate. An initial walkover on site can prove invaluable in confirming the location and current status of any hazards. In addition, if safely possible, a walk through the underground can provide additional verification. The purpose of the data gathering is to be able to build a model of the mine. Surveying of key surface features (shafts, raises, etc.) is critical to building an accurate mine model.

Once all data has been vetted, a mine model is completed by geo-referencing the mine drawings into a 3D model. This will be the first picture of what the mine looks like and will be used as the preliminary identification of the openings to surface and potential near surface openings. The mine model can be used to give preliminary coordinates to find mine openings

to surface that are difficult to locate, or that could not be located during initial walkovers. Mining engineers are critical members of the rehabilitation team as they can decipher the mining methods used at the site. Assessing the mining method(s) used during operations can give hints as to the presence of other features that may not have been captured on the mine plans. By understanding the typical approaches used during the era of mining, any missing information can be reasonably assumed based on those historical practices. For example, older mines were often mined using methods that are not common practice today, and these methods involve a fairly standard geometry in how the ore is extracted from the mined stope, such as drawpoints at the base of the stope. Many of the hand-drawn mine plans will not illustrate these drawpoints but knowing the context of the mining method would allow identification of the potential existence of these openings.

From the mine model, a preliminary desktop stability assessment should be performed. There are several methods for assessing the stability of openings and crown pillars:

- Scaled Span Method (Crown Pillars) (Golder, 1989)
- Mathews Stability Graph (Stope Walls) (Golder, 1980)
- Numerical Modeling (Crown Pillars and Stope Walls, stratigraphic mines [coal, limestone, etc.])

Each method has its pros and cons, and the rationale for choosing one should be well documented and consider the geotechnical and geological setting of the mine. For example, it would not be applicable to complete a stability assessment intended for use in coal mines when the setting is a hardrock mine.

The results of the stability analysis will help to identify openings that may be of concern and areas requiring further investigation. Several questions should be answered in this preliminary assessment:





- What are the dimensions and orientation of the openings?
- Are the openings connected to other workings?
- How effective are the previous mitigations, and do they meet current standards or do they need to be upgraded?
- How do the openings interact with surface?
- Is more data required?

If the current remediation appears to meet current standards, more data may be required to prove it. If additional remediation is required, an investigation should focus on gathering enough data to support the new remediation option.

The goal of the preliminary stability assessment is to understand the probability of failure for each one of the openings and crown pillars. In the preliminary assessment, all near-surface openings/crown pillars would be categorized per the typical hazard classes in Table 1 below.

In one recent example, three raises and one stope to surface were identified on the surface plans that were obtained from historical records. The site walkover found two of three raises that were on the original surface plans. A new raise that was not on the plans was also found, as was a stope to surface that had been previously capped. There were no records of how the raises and the stope to surface had been closed previously.

TABLE 1. Acceptable Crown Pillar Risk Exposure Guidelines (after Carter et al., 2008 & Carter and Miller, 1995).

			Design Guidelines for Pillar Acceptability/Serviceable Life of Crown Pillar						
Class	POF (%)	Minimum FOS	Serviceable Life	Years	Public Access	Regulatory Position on Closure	Typical Mining Ranges	Surveillance Required	
A	50–100	<1	Effectively zero	<0.5	Forbidden	Totally unacceptable		 Ineffective	
B	20–50	1.0	Very, very short-term (temporary mining purposes only; unacceptable risk of failure for temporary civil tunnel portals)	1.0	Forcibly prevented	Not acceptable			Typical range for temporarily open stopes
C	10–20	1.2	Very short-term (quasitemporary stope crowns; undesirable risk of failure for temporary civil works)	2–5	Actively prevented	High level of concern		Continuous monitoring with instruments	
D	5–10	1.5	Short-term (semi-temporary crowns, e.g. under non-sensitive mine infrastructure)	5–10	Prevented	Moderate level of concern		Typical range at closure	Continuous simple monitoring
E	1.5–5	1.8	Medium-term (semi-permanent crowns, civil portals, possibly under structures)	15–20	Discouraged	Low level of concern		Continuous superficial monitoring	
F	0.5–1.5	2.0	Long-term (quasi-permanent crowns, civil portals, near-surface sewer tunnels)	50–100	Allowed	Of limited concern		Incidental superficial monitoring	
G	<0.5	>> 2.0	Very long-term (permanent crowns over civil tunnels)	>100	Free	Of no concern		No monitoring needed	

Note: FOS = Factor of Safety

The preliminary stability assessment results provide the parameters for the next step: the physical investigation. Physical investigations involve the collection of new data for each of the areas of concern identified in the preliminary assessment. This step is typically done via drilling and geophysics. Drilling is most common for closed/abandoned mines and, in addition to collecting geological and geotechnical data for characterization, drilling is targeted to intersect void space, so underground surveys can be completed. Data on the geometry of the mine and confirmation of locations of site features are also part of this stage. The biggest challenge is drilling accuracy, coupled with potential uncertainty of the mine model. While some verification is completed, that does not mean that the model is a full and accurate representation of the underground. It is important to keep this fact in mind—the mine model is a guide not an as-built. In conjunction with drilling, surveying and inspections are also completed during the physical investigations. Some typical survey examples are listed below:

- Lidar—good for surface features
- Borehole Cavity Monitoring Surveys (CMS) for dry openings, sonar for flooded openings
- Drones—flown in the underground to explore areas not available by drilling or areas unsafe to enter
- Borehole cameras—360° panorama cameras to visually observe the underground
- Conventional surveying

Geophysics used during the physical investigation can work very well in some cases, but even with geophysics there will still be some drilling required to prove the geophysical findings and collect geotechnical data.

The results of the physical investigation are also used to update the mine model and provide the first real rock properties for the detailed stability assessments. The more detailed stability assessments are completed to ultimately identify which hazards need to be fixed. Some parts of the detailed assessment occur “live” while the investigation is ongoing so that the investigation can be modified as required (e.g. it is easier to add an extra hole during an investigation than to find out later that more information is required and need to remobilize for a new investigation).

The stability assessment and investigations are an iterative step. We need to iterate because new information can be gained through the process, so it is important to keep circling back and testing that new information against what we already know. In particular, for historical mines there is a great deal of uncertainty and it can be categorized as follows:

- Known knowns (things we know that we know)
 - Mine plans
 - Underground access
 - Access to people with first-hand knowledge of the mine and its operations
 - Cavity surveys, hazards visible on surface
- Known unknowns (things we know that we don’t know)
 - Missing mine plans from years or decades
 - No access underground so unconfirmed connections or locations of raises or other underground features
- Unknown unknowns (things we don’t know that we don’t know)
 - Connections that don’t exist on any available drawing/record and can’t be seen during investigations

- Environmental changes that affect the underground/openings, e.g. extra cold winters which results in underground ice formation

The key step of the detailed assessments is to make a decision for each opening based on the current understanding on what the final status will be per the crown pillar classification table (Table 1). The ideal scenario is that every crown pillar gets to a “long-term stable” status (e.g. Class F or G per Table 1). The detailed assessment should decide whether there is enough information to make a conclusion. If the conclusion for a particular opening will never be long-term stable, further investigations should be pursued, focused on identifying the appropriate rehabilitation option. If the conclusion can change to long-term stable with more information, then the recommendation would likely be to add more investigations to prove long-term stability conclusively.

Once all the hazards have been categorized, the next step is to prioritize the order of fixing the hazards. In other words, a risk assessment is performed to understand the criticalness of each hazard in terms of the potential for failure. Items considered include:

- Instability—Probability of failure occurring
- Consequence—In most cases, always considered major as not enough information is known about the progression of failure through the mine
- Exposure—How close is it to people (e.g. near a house versus in a remote setting)?
- Accessibility—How easy is it for people to access (e.g. are there trails or roads leading to it, or difficult to find)?

Risk tolerance will vary depending on the owner and the site-specific circumstances, and it is important to engage with the owner at this stage to participate in the risk evaluation.

Options development for hazard mitigation and risk management

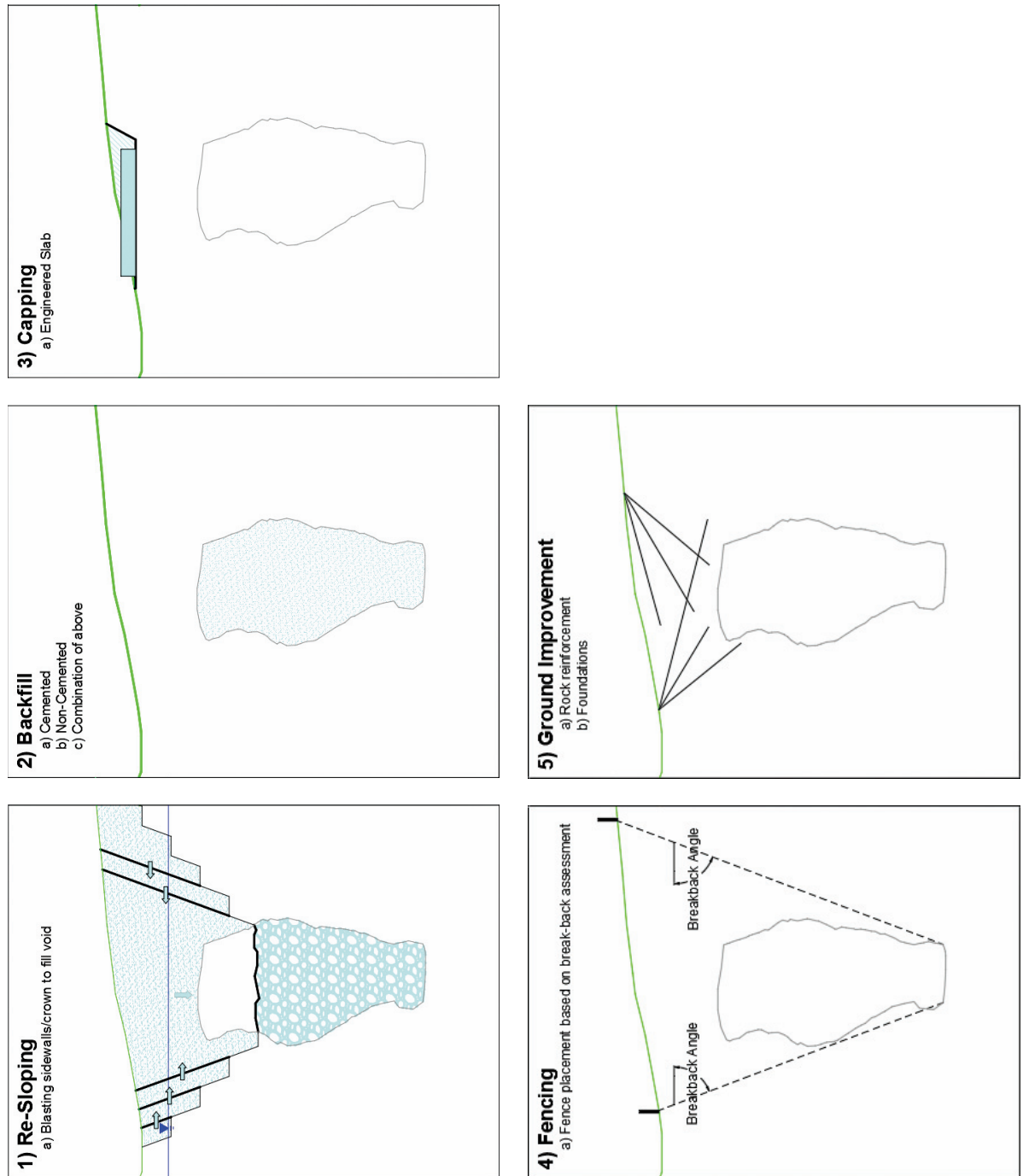
Once the openings have been classified, the next step is to develop options for those openings that require rehabilitation. The typical steps for options development are as follows:

1. Identification of potential rehabilitation options
2. Assessment of order of magnitude costing and data gap/advantages/disadvantages of each option (long list)
3. Design and evaluation of options’ short list
4. Prioritization of rehabilitation methods
5. Development of a rehabilitation strategy

Identifying options typically includes a long list of technically feasible options for the site. A few examples of rehabilitation options for unstable underground openings are shown below in Figure 4 (1 to 5).

Once the long list of potential options is established, the next step is to develop a preliminary cost and advantages/disadvantages assessment. This would provide the framework for dismissing options and getting to a short list of one to two options. The preliminary assessment documentation is typically quite important to demonstrate to the regulatory body and other stakeholders that multiple options were considered and to document the reasons for elimination

FIGURE 4. Typical options for the rehabilitation of underground voids.



of options and selection of others. Depending on the jurisdiction, the regulatory body may fall under several different government organizations. A few examples include:

- Ontario, Canada—the Ministry of Energy, Northern Development and Mines governs remediation activities
- Alberta, Canada—the town of Canmore has instituted its own regulations around undermining rehabilitation.
- Canada—different mines have different requirements e.g. a uranium mine must adhere to the requirements of the Mining Act as well as the requirements of the Canadian Nuclear Safety Commission (CNSC)
- United States—Department of the Interior—Bureau of Land Management and the Environmental Protection Agency typically govern the rehabilitation of Abandoned Mine Lands
 - each state typically has an Abandoned Mine Lands (AML) department that manages / funds the rehabilitation programs e.g.
 - North Dakota Abandoned Mine Lands Division—<https://psc.nd.gov/jurisdiction/aml/>
 - California State Lands Commission—<https://www.slc.ca.gov/abandoned-mine-remediation/>

Identifying all of the regulatory requirements (and organizations that may require input) is critical and the first place to start would be the Mining regulatory body in a particular region.

Getting regulatory approval may sometimes be challenging, so a robust preliminary assessment is required. In addition, any gaps in information would be identified in the preliminary assessment, and then the next stage of design would be completed to facilitate a more detailed evaluation of the options to arrive at the preferred option.

A sustainability-based evaluation tool should be used in the detailed evaluation to consider all factors: technical, environmental, social, economic and risk. The following would be considerations in the evaluation:

- Order of magnitude design and costing
- Advantages and disadvantages
- Technical complexity
- Schedule
- Uncertainty
- End land use
- Client drivers (e.g. social perception, public pressure, legal)
- Environmental restrictions
- Constructability (e.g. access, surface restrictions, remoteness)

The evaluation should not focus on a fatal flaw type analysis as it is unlikely that one solution will be perfect in all respects—the level of complexity associated with historical sites means that a collaborative approach to the solution will likely be required. The evaluation process should include the owner and any additional stakeholders to ensure that the final solution is supported by the entire team. Depending on the scope of the project or risk profile of the

owner, this can make a big difference for how options are assessed and what option is selected to move forward.

For example, in a recent project that was being executed in Canada on First Nations' land (the First Nations are the indigenous inhabitants of Canada and have large landownership across the country; they typically have different or additional requirements around land rehabilitation than the government regulatory bodies, which need to be incorporated), two options were being considered: capping and backfilling. Backfilling is an option that eliminates the risk posed by the voids in the underground by filling it in (see Figure 4-2). Capping minimizes the risk but the hazard itself still exists (see Figure 4-3). This group of stakeholders holds a long-term (multi-generational) point of view and to them the capping option would only mitigate the risk for 50 to 100 years, which was too short a timeframe. They chose to permanently rehabilitate the hazard for all future generations by opting for backfilling.

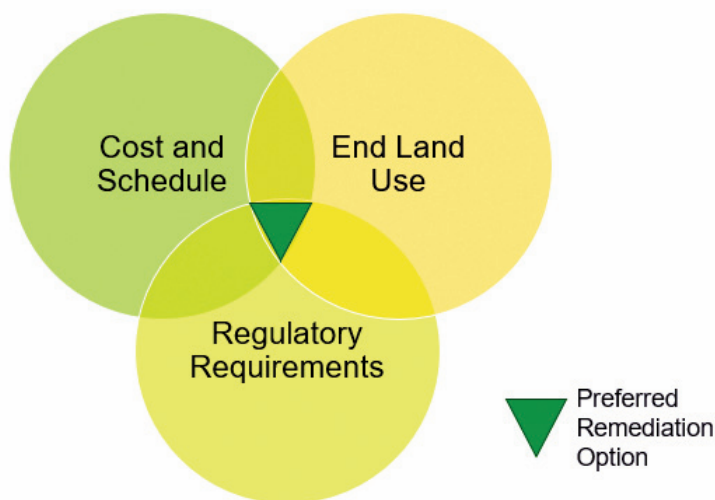
The other thing to remember is that one solution for all hazards is unlikely; there may be multiple solutions to be implemented depending on the results of the stability analyses and the options evaluations.

In order to optimize the rehabilitation effort to address hazards posed by historical mining activity, it is important to develop an overall rehabilitation strategy for a site considering the potential end land uses. The land-use question is key as this will shape the options under consideration. As an example, if the end land use for a particular site was going to be public recreational activities, then fencing around an open hazard in that area would be unacceptable.

The overall strategy should be developed in a phased approach and should consider cost/schedule, end land use and the regulatory framework for that region (Figure 5).

The first consideration in developing a remediation strategy for all the hazards on site is using a holistic iterative approach. This means considering other site issues when developing the strategy. For instance, geochemical instability issues or environmental impacts might be occurring on the same site. Backfilling is a technical option for filling voids but might be eliminated as an execution option because of the cost of bringing in off-site material to use as fill. However, if a holistic approach were used, then the team would realize that unreclaimed tailings that are

FIGURE 5. Venn diagram of considerations when selecting the preferred remediation option.



available on most sites can make excellent backfill. In some instances, backfilling can be utilized to remediate both geochemical hazards and physical stability hazards of underground openings by encapsulating the material in a cemented backfill. In other instances, merely placing the geochemically unstable material underground would eliminate further contamination of surface water bodies, thus helping to solve two of the issues on site.

The other point is that there is always a balance between quick fixes and the longer-term staged approach. Teams will sometimes advance to remediating one specific hazard without doing the first few steps of assessment and prioritization, and then later find the work was unnecessary. A common example is early works that have been completed to apply a concrete cap on openings to surface, but later it was found that these openings are connected to other voids that require backfilling, and thus the early capping was proven to be redundant.

Design of the system for the preferred option

Once the evaluations are complete and the options are selected, the next step is to move into the design phase. Depending on the remediation option chosen the design duration and complexity will be different. For example:

- Concrete caps
 - Require structural engineering design services with input from geotechnical/mining engineers, would take a relatively short period of time to design, and the sequence would be relatively straightforward
- Re-sloping/blasting
 - Requires geotechnical engineering services and potentially mining/blast engineering services, and would be longer to plan and to execute compared to capping
- Backfill
 - Requires geotechnical, mining, materials and mechanical engineering services and would take longer to design the system and plan/execute the sequence

The remainder of this section will discuss the use of backfill as a rehabilitation option for historical mines as backfilling is commonly the preferred approach for long-term remediation of underground voids.

There are multiple types and methods for applying backfill in these situations. The design and planning steps for a backfill solution comprise the following:

1. Backfill type / method assessment
2. Testing programs and recipe development
3. Planning and sequencing strategy development
4. Quality assurance / quality control (QA/QC) planning

The first step is establishing the performance criteria for the backfill—this will help narrow down the types of backfill that would be practical. The critical performance criteria could include:

- Strength
 - This is the most important criterion and is the indicator for long-term stability.
- Permeability
 - What is the permeability of the backfill and will there be degradation over time?

- Does the backfill have (or need to have) the ability to encapsulate contaminants of concern?
- Set time
 - How long will the backfill take to set/settle before another layer can be poured?
- Flowability
 - How far can the backfill flow or move in the underground? This directly influences the number of delivery mechanisms required.
- Pumpability
 - How far can the backfill be pumped? This is the key indicator to determine where the backfill system can be located and if a pump is required versus trucks and of what size.
- Bleed water
 - How much water will bleed out of the backfill? This is tied to permeability and the shrinkage potential of the backfill.

There are additional criteria that can be added to the assessment depending on the site, so it is important to get the development of the criteria right. There are many different types of backfill used in active mines, so it makes sense to consider them for a historical site as well. The main backfill types are as follows:

- Unconsolidated waste rock
- Cemented/uncemented rock fill
- Cemented/uncemented aggregate fill
- Cemented/uncemented hydraulic fill
- Concrete
- Grout
- Foam
- Paste

When considering the holistic strategy for a particular site, it helps to understand the advantages and disadvantages of each material in the context of a historical site. Largely, the availability of the materials used in the backfill is the main constraint. If the site has no waste rock or aggregate stockpiles, then the first options using waste rock or aggregate would not be technically feasible to execute without importing material from off site. Another consideration is the regulatory environment. There are many regions where the regulator does not allow the use of foam in the underground, thus eliminating that option from consideration. Much like the remediation options assessment, the decision on which backfill type to use should be done in as holistic a manner as possible considering the performance criteria as well as other site-specific circumstances.

In Table 2 below, the various backfill types are presented in comparison to the critical performance criteria along with a few other criteria. The evaluation of these backfill types is general in nature, as site-specific criteria need to be considered.

Once a backfill type has been chosen, the next step is to develop a recipe to meet the backfill performance criteria. Typical steps would include the following:

1. Identify materials available on site.
2. Get samples.

TABLE 2. Performance criteria and general rankings of each backfill type.

Performance Criteria	Uncemented Fills	Cemented Waste Rock/Aggregate	Cemented Hydraulic Fill	Concrete	Grout	Foam	Paste
Strength	✗	✓	?	✓	✓	✗	✓
Permeability	✗	✗	✗	✓	✓	✗	✓
Set time	✗	?	?	✓	✓	?	✓
Flowability	✗	✗	✓	?	✓	?	✓
Pumpability	✗	✗	✓	?	✓	?	✓
Bleed water	✗	✗	✗	?	✓	?	✓
Flexibility of recipe changes	✗	✗	✗	✗	✗	✗	✓
Surface access requirements	✗	✗	✓	✗	✓	✓	?
Ease of implementation	?	?	?	✓	✓	✓	?
Technical complexity	✓	?	?	✓	✓	?	?
Cost	✓	✓	✓	✗	✗	✗	✓
Use of on-site materials	✓	✓	✓	✗	✗	✗	✓
Sub-aerial or sub-aqueous deposition	✓	✗	✗	✓	?	✗	✓
Use of waste materials (divert from surface)	✓	✓	✓	✗	✗	✗	✓
Management of AMD and contaminants of concern	?	?	?	?	?	✗	✓

Notes:

AMD = acid mine drainage

✓ indicates good performance against that criteria.

✗ indicates poor performance against that criteria.

? indicates an unknown performance that would need to be evaluated for that particular site.

3. Develop two to three blends/recipes.
4. Conduct bench-scale trials for key criteria.
5. Identify range of performance.
6. Move to larger scale testing as required.

From the recipe and testing program, the next step is sequencing. This part of the design includes developing the step-by-step plan outlining how the openings will be filled. Key considerations would be what recipe is required to be delivered in which area, what quantities would be placed for each recipe, and from which location they will be placed. This step-by-step planning is essential to make sure any uncertainties in the underground can be addressed prior to depositing backfill, to understand what monitoring requirements should be in place prior to backfilling, and a secondary plan for addressing uncertainties if they do arise during deposition.

In the design stage, it is also necessary to develop the Quality Management Plan (QMP) for the backfill program. The quality data collected during the program will go into the rehabilitation report to the regulator to prove that what was placed in the underground meets the requirements of the rehabilitation strategy. The QMP centers on two components

- Product performance testing
 - Proof the backfill meets the performance criteria
- Monitoring/confirmation of void filling
 - Proof the underground openings are full

Execution of stabilization options

This is the actual site execution phase of the remediation work. The previous design and planning stage leads into the development of a Construction Execution Plan, which could include:

- Health, Safety, Security, and Environment (HSSE) planning
- Water management (e.g. permit to take, discharge)
- Industrial hygiene
- Material and equipment specifications
- Equipment layouts
- Traffic controls
- Sequencing plan
- Staffing
- Monitoring and QA/QC plan
- Documentation and record keeping
- Post-remediation evaluation and monitoring

The execution phase is the ultimately where the investigation assessment and design activities coalesce. As with all projects, HSSE is paramount to successful execution, and in historical mine applications HSSE issues often appear that were previously unknown, so there should be a robust program with contingency worked into the schedule to manage these eventualities. Along with the HSSE challenges, there will always be some uncertainty around the underground and how it behaves during rehabilitation. Some of these mines have been closed/abandoned for decades, and there is no way to tell for sure how the underground will respond when the rehabilitation solutions are applied. This is why planning the execution sequence is so critical

and why updating of the plan needs to be fluid and done in real time. There are many examples where even after all the investigations and assessments have been completed, a whole new area of the mine is discovered that was not on any plans once execution is underway. One good way to think about the execution plan is via a “if/then/else” philosophy. Potential risks can be identified ahead of time, and then the plan should be robust enough to have the ability to shift the execution without disrupting it to respond to changes if an unknown item is encountered.

Post-remediation evaluation and monitoring

Remediation is not necessarily the end. It depends on the solution—filling can mean a walk-away solution, fencing means long-term monitoring, capping means restriction of access to the problem but does not resolve the problem in the long term. Each option will have different regulatory and monitoring responsibilities in the long term. Monitoring may consist of:

- Visual—fences/signs/berms, rock/soil slopes, evidence of ground movement (building cracking, etc.), caps
- Instrumentation and surveying±crown pillars, rock/soil slopes

Regulators typically require that a qualified engineer sign off that the completed remediation meets the regulatory requirements/standards/law/codes. Some examples of this sign off are:

- Technical as-built report prepared by a qualified engineer
- Technical certification of a contractors’ rehabilitation program
- Review board which approves and vets any rehabilitation activities on a site

CONCLUSIONS

Rehabilitation of mine hazards is not an easy enterprise but if a few key things are remembered, the common pitfalls can be avoided. The main point is not to go straight to the fix and skip the investigation; enough data needs to be gathered to develop and understand the mine hazards before deciding how to fix them. Mine hazards don’t generally improve with time and doing nothing is not a viable long-term solution.

There is a trade-off between investigations and uncertainty: the more money spent on investigations, the better the understanding of the situation; however, there is a limit where more investigation yields diminishing returns. Risk tolerance will vary by owner, and the owner’s drivers will have an impact on any rehabilitation options selected. For this reason, they need to participate and buy into the process. Selection and prioritization should be done using a risk assessment method. Keeping good documentation of the options evaluation process is becoming ever more important. Stakeholders also want to participate in the options selection to make sure cost isn’t the only driver.

Evaluation of the rehabilitation options is based on the remediation strategy goals with the understanding that not every option will work with every site. Site specifics (e.g. access, available materials and the underground circumstances) and the performance criteria are essential to making the right decision. When planning the rehabilitation execution stage, it is important to identify and understand the “known knowns / known unknowns / unknown unknowns” to be able to respond effectively when circumstances change (and they will change). Real-time monitoring is required during execution to document the process and the progress of the rehabilitation and will ultimately make its way into the final report used for regulatory sign-off.

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