INNOVATIVE SOLUTIONS FOR PHYSICAL MINE HAZARD REHABILITATION

Jonathon J. L. Taylor[1]
Paul G. Palmer[1]
Sue Longo[2]
[1]Golder Associates Ltd., Sudbury, ON, P3C 4Y1
[2]Golder Associates Ltd., Calgary, AB, T2A 7W5

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Closing of mines can be complex, expensive and occur over a long duration often due to location (remote or adjacent a community), era of mining (type of mining and when mining occurred) and availability of reliable information. Successful rehabilitation of mine operations require multidiscipline teams and the integration of these various expertise can result in innovative solutions for physical mine hazard rehabilitation.

Mine sites can consist of several types of physical hazards, such as mine openings to surface (shafts, raises, adits, etc.), near surface mine workings (i.e., crown pillars), waste rock piles, and tailings storage facilities. These physical hazards are often problematic as they can present risks to the general public (i.e., injury, fatality, damage to property) if left un-rehabilitated, and generally speaking they get worse with time. These hazards might have been a low risk situation during operations or directly after closure, but can become a high risk if they are left to degrade over years and/or decades. For example, mine openings to surface can be deep open holes which, if left open and accessible to the public, can result in fatality if a person were to fall into the open feature. In Ontario, preventing inadvertent access and protecting openings are the primary focus of rehabilitation solutions for physical mine hazards that have a connection to surface.

The rehabilitation of physical hazards requires the integration of various disciplines of science and engineering. For example, mine openings to surface and crown pillars are often investigated and assessed by a rock mechanics or mining engineer and the rehabilitation is designed in conjunction with a structural engineer, whereas waste rock pile and tailings facilities are often investigated and the rehabilitation is designed with input from geochemists, hydrologists, and geotechnical and environmental engineers and then typically constructed by third party contractors. In some cases, the stability of the crown pillars on site are not well understood until later in the project while rehabilitation of mine openings to surface (raises and shafts) have progressed. This can lead to a situation where a raise that is connected to a near surface stope is capped before the stability assessment of the crown pillar is completed, and the crown pillar stability assessment may show that the crown pillar is not long term stable and requires rehabilitation. In this example the rehabilitation of the crown pillar could have also included the raise with no additional cost negating the need of building a concrete reinforced cap over the raise.

Recent rehabilitation project experience has shown that developing an overall property rehabilitation strategy that considers all of the physical mine hazards on a site or in an area can have cost saving benefits and technical efficiencies. Optimizing the rehabilitation strategy for all hazards with all disciplines means avoiding duplication of cost and effort as described in the example above. In addition, by assessing and applying innovative rehabilitation methods, such as the use of pre-cast concrete in remote areas or with challenging hazards or the use of newer products, such as foam, the rehabilitation strategy becomes a targeted specific plan for that site and not a one-size-fits-all solution, which can lead to higher costs.

This paper will discuss the process of developing a rehabilitation strategy and options focused on near surface crown pillars and mine openings to surface.

Phases of Closure of Mine Openings

Closure of physical mine hazards generally progresses in five phases. This allows for use of existing data to complete preliminary assessments and plan the investigations, which are then used to develop the rehabilitation plan. The five phases are:

- Phase 1 – collection and review of historical data
- Phase 2 – preliminary desktop studies
- Phase 3 – physical investigation, assessments, and rehabilitation planning
- Phase 4 – implementation of the rehabilitation solution
- Phase 5 – monitoring

Phase 1 – Collection and Review of Historical Data

For older abandoned mines, historical data may be lost, or the amount of information may be insufficient to complete the preliminary desktop studies. Often, the only information available is a report that includes a plan drawing and a simple composite longitudinal section showing many stope areas. These can be difficult to assess in areas where there are several vein systems to the ore body, which would result in several stopes showing in the same area on the longitudinal section, and can be even more complex when the strike and dip of these veins vary from location to location. For this reason, it is important to use as many surface features available on the plan drawings to geo-reference the plan and longitudinal drawings. Establishing surveying control with these features is also important at the onset of the project so that there is more confidence in the crown pillar locations when developing a drilling plan in the later stages of the project.

Identification and collection of geological and geotechnical data is also key as this data has implications in the preliminary desktop study stage. Geological information can come from old exploration drillhole logs, geological plan/section maps, or other regional maps from provincial sources (i.e., Ontario Geological Survey in Ontario). Historical geotechnical information is the most challenging piece of information to collect. Often, geotechnical data was not well documented, or documented in such a way that it is not useful for completing the preliminary desktop study. In many cases, a conservative assumption of geotechnical properties (i.e., rock mass quality) are made during this stage based on some visual observations or assuming a poorer rock mass property than might actually be there. In addition, in some areas recent experience has shown that discussions with the local population may provide some useful direction during investigation. Inevitably someone had a mother/father/grandfather/uncle who worked at the mine and can provide additional information. Sometimes they have old maps and level plans, and sometimes they worked at the mine and can describe the underground situation especially if access is no longer available.

Information about existing rehabilitations (i.e., previously constructed concrete caps, backfilling of openings, etc.) is also useful information to identify at an early stage as these can potentially be used as mitigating measures, or can be integrated as part of the rehabilitation design during the rehabilitation planning stage.

Phase 2 – Preliminary Desktop Studies

Once the process of collecting and reviewing historical data is completed, a desktop assessment of physical mine hazards is completed. This process involves completing preliminary stability assessments of the crown pillars, as well as prioritization and preparation for the physical investigation stage of the project.

The industry standard practice for assessing the stability of crown pillars is to use the Scaled Span method, which was developed by Golder in 1990 under contract with CANMET (Golder, 1990). Golder has subsequently updated and maintained a crown pillar database since that time, which now consists of over 500 crown pillars at 110 mines, and includes 85 failure cases. Updates have also been completed to include estimates of the probability of failure (POF) of the crown pillar, which was used to develop an acceptable crown pillar risk exposure guideline (Carter, 1992; Carter & Miller, 1995; Carter et al., 2008). The method takes into consideration the geometry and properties of the crown pillar (span, strike, thickness, dip, and density) to calculate a 'scaled span' number, which is then graphed against the rock mass quality, Q (Barton, 1974), as shown on Figure 1.

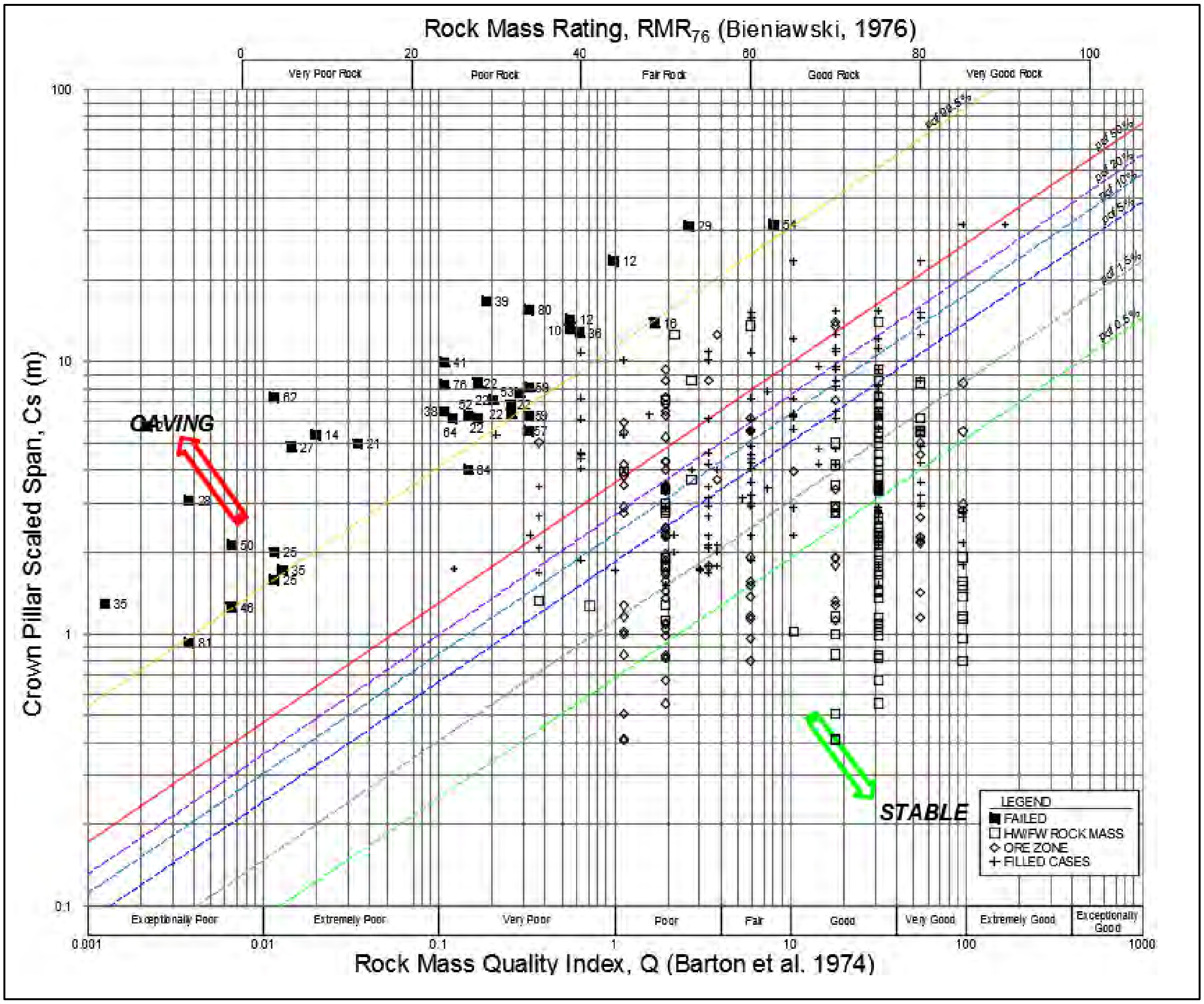

Figure 1: Scaled Span Graph (Golder 1990, Carter et al., 2008)

The Scaled Span method can also be used to calculate the POF percentage, which was developed based on logistic regression of the empirical database (Carter et al., 2008). The POF for several crown pillars can be summarized into ranged bins to estimate the duration of stability of the crown pillar, ranging from effectively zero to very long term stability, as shown in Table 1.

Table 1: Simplified Crown Pillar Risk Exposure Guidelines for Mine Closure Purposes (after Carter et al., 2008)

Class	FOS (%)	Minimum FOS	Serviceable Life	Public Access	Potential Monitoring Requirements
A	50 - 100	<1	Effectively zero	Forbidden	Ineffective
B	20 - 50	1.0	Very, very short-term: temporary mining purposes only	Forcibly prevented	Continuous/regular sophisticated monitoring
C	10 - 20	1.2	Very short-term:	Actively	Continuous/regular

Class	FOS (%)	Minimum FOS	Serviceable Life	Public Access	Potential Monitoring Requirements
			quasi-temporary stope crowns	prevented	monitoring with instruments
D	5 - 10	1.5	Short-term: semi-temporary crowns, e.g. under non-sensitive mine infrastructure	Prevented	Continuous/regular simple monitoring
E	1.5 - 5	1.8	Medium-term: semi-permanent crowns, possibly under structures	Discouraged	Conscious superficial (i.e., visual) monitoring
F	0.5 - 1.5	2	Long-term: quasi-permanent crowns	Allowed	None to Incidental superficial (i.e., visual) monitoring
G	< 0.5	>> 2.0	Very long-term: permanent crowns	Free	No monitoring required

For closure purposes in Ontario, it has generally been accepted that crown pillars with a POF of less than 1.5% (i.e., Class F and G in Table 1) are considered to be long term stable and do not require rehabilitation, while crown pillars with a POF of 1.5% or greater require further investigation that may result in rehabilitation. The POF from the desktop assessment is used to prioritize the investigation and rehabilitation during the subsequent phases of work.

Phase 3 – Physical Investigation, Assessments, and Rehabilitation Planning

After the desktop assessment is completed and is defined as not long term stable, a physical investigation is required to update the stability assessment, and to start planning the rehabilitation strategy. This stage is where the highest degree of engineering input is required, as it involves completing physical investigations, updating stability assessments, completing rehabilitation trade-off studies to determine the most cost effective rehabilitation, and planning the rehabilitation work.

In most cases, crown pillars with a high risk of long term instability (i.e., POF > 20%) are unlikely to be deemed long term stable after a physical investigation unless the estimated parameters used in the desktop assessment were overly conservative. Investigation work for these crown pillars should focus on confirming the geometry, extent, and connectivity of the void space to other workings in preparation for closure rehabilitation planning. Investigation of these crown pillars should proceed cautiously as there may be a high degree of unknowns (i.e., geometry and extent of the void space, backfill conditions, etc.), and there may be a risk of localized instabilities during the investigation.

For crown pillars with a medium risk of long term instability (i.e., POF 1.5 to 20%) have the potential to be reassessed as long term stable after a physical investigation. Often times the rock mass quality is conservatively underestimated, and data collected from drill core can show that the rock mass quality is higher than originally estimated during the desktop assessment. The investigation for these crown pillars should focus on confirming the geometry (span and thickness) of the upper portion of the stope, as well as collecting geotechnical information in the crown pillar rock mass.

Investigation techniques for crown pillars consists of safety/access drilling for high risk crown pillars, geotechnical diamond core drilling, surveying of void space (using in-hole laser scanners or sonar survey tools), and surveying of surface topography. In some instances, digging may also be useful to find reference points (i.e., surface mine openings) to increase the confidence of the georeferenced mine plans. In some cases surface geophysical methods (ground penetrating radar, seismic and electric-resistivity imaging) can be utilized where void sizes are large relative to crown pillar thickness and there is sufficient surface space to complete surveys.

Safety/access drilling consists of drilling a series of holes from a safe location towards the planned geotechnical drilling area. This type of drilling can effectively be completed by using an air-percussive drilling rig (also known as a hydraulic or air-track drill). The holes are drilled at an angle to a specified depth to confirm the thickness of competent rock ahead of the drill. Once safe access is established to the first geotechnical drill area, additional air-percussive drilling can be completed to first locate the void space, or diamond drilling can commence. Safe access drilling can be eliminated for areas once the void space has been found and surveyed, as the survey can be used to adjust the diamond drilling plan to ensure that the drill is set up in a safe location.

Surveying of the void space should be completed on every hole that intersects void space, and then used to modify the investigation plan accordingly. The survey of the void space can also be used to update the geometry of the crown pillar and stability assessment.

Many abandoned sites have previously rehabilitated mine openings to surface, traditionally achieved through concrete capping. Previous concrete capping standards often do not meet current regulatory requirement, and in most cases, these older concrete caps will need to be replaced. Drilling should also be completed through these caps or through bedrock into the void space so that a survey can be completed of the void space. This information is useful in completing the rehabilitation design and planning.

Investigations can often consist of several phases occurring over several years, and can also overlap the rehabilitation phase. For example, it has been common to quickly investigate surface mine openings and start rehabilitation on these features before the investigation of the crown pillars has been completed. In some instances, these surface mine openings are connected to voids below crown pillars. For this reason, it is important to consider a site wide, or area specific, rehabilitation strategy and plan. At several sites in Ontario, capping of the surface mine openings was completed before the connected void space/crown pillars were fully investigated, and then these crown pillars were found to be not long term stable. Recent experience has shown that it is almost always more cost effective to fill void spaces for crown pillar rehabilitation than to construct massive concrete caps over them. In this instance, the incremental cost of backfilling a raise connected to the stope void is often much smaller than to construct a concrete cap over the raise as well.

Many of these mine sites also have waste rock and tailings storage facilities on site, and the closure project can involve rehabilitation of these hazards. In most cases, this is material that is useable for making cemented or paste backfill products for filling underground voids. Using this free source of material is often discounted as the project cost is often judged on a per feature cost basis rather than a site wide basis. For example, digging and transporting tailings material appears expensive in order to rehabilitate the tailings storage facilities, and often times the underground voids that require rehabilitation are not large enough to handle all of the tailings, but when considering that this is material that would otherwise need to be purchased for filling the underground void space, it can quickly become a cost effective solution.

Once the investigation and site characterization work is completed, a trade-off study to determine the best site wide rehabilitation strategy is completed. This includes consideration of different rehabilitation strategies, such as more traditional methods as capping or backfilling described above, or more innovative solutions described later on in this paper.

The schedule of the rehabilitation can be a function of risk mitigation and cost, or may also include complexity of the construction in consideration of other activities on site. For example, a mine owner may only have enough budget in one year to mitigate part or all of the highest risk hazards in one year, leaving other hazards until subsequent years to complete the rehabilitation. In some cases, different regulatory bodies may also have jurisdiction, and additional rules for rehabilitation may apply. One example of this is a uranium mine, where the provincial department of mines regulates rehabilitation standards with respect to the physical hazards on site and a federal government agency, in this case the Canadian Nuclear Safety Commission (CNSC), also regulates the site, more specifically with respect to radon emissions. In this case, elimination of radon emissions can hold precedence for rehabilitation over the physical mine hazards from a regulatory perspective and this will drive the rehabilitation schedule.

Phase 4 – Implementation of the Rehabilitation Solution

Once the trade-off study and rehabilitation planning is completed, the construction can begin. During this stage, most of the engineering work has been already completed, however, there is still a requirement for quality assurance and quality control. This is one of the most important parts of the construction phase as it ensures that the rehabilitation is constructed to the design specifications, and should any change in conditions be noted, they are well documented and become part of the as-built records.

The goal of the investigations and preliminary work is to eliminate uncertainty, but these are dynamic situations and all phases of the rehabilitation strategy should be viewed as an iterative process.

Input can also be sought from the design team should there be a major change in conditions so that designs can be modified if necessary. It is also important to document the as-built information so that certification of the rehabilitation can be completed and any financial assurance can be released or obligation to the regulatory body can be fulfilled.

Phase 5 – Monitoring

Monitoring can involve either monitoring as the rehabilitation solution (i.e., stability monitoring through instrumentation) or monitoring of the rehabilitation to ensure that it remains stable and performs as expected.

Example of monitoring as the rehabilitation solution are installation of multi point borehole extensometers or other monitoring instruments such as tilt metres and time-domain reflectometry cables, radar surveying, LiDAR surveying, and satellite surveying. These methods can be effective for monitoring crown pillars with a low to moderate risk of crown pillar instability (i.e., < 20% POF), but are ineffective for high risk crown pillars.

Monitoring of rehabilitations mostly involves visual inspections on an annual, or multi-annual basis (i.e., every 2 to 5 years). In some cases, rehabilitations can also be monitored using instrumentation. An example of this is a tilt-meter that monitors for movement of an unconsolidated sand fill.

Innovative Rehabilitation Solutions

Recently, advances have been made in technologies and the application of new techniques for rehabilitation of mine workings. These options include the use of sprayed polyurethane foam, precast concrete, stainless steel caps, and paste backfilling with a mobile plant.

Sprayed polyurethane foam has not been accepted in Ontario for use as the only means of rehabilitation as there are concerns about the longevity and strength of the material, however, it has been used recently in three applications in Ontario for mine closure projects as a component of a larger rehabilitation plan. One of the scenarios was the closure of a vertical shaft inside of a building, which involved spraying the foam over a timber blockage in the shaft to a specified minimum thickness, and then pouring concrete in two lifts to backfill the remainder of the shaft. The foam was only used as formwork inside the shaft, and was not used for long term support of the cemented backfill material poured on top of it. The other two scenarios involved spraying the foam remotely through a borehole into an underground stope. In both cases, the intent was to use the foam to block a raise at the bottom of the stope that was connected to other large void spaces that did not require rehabilitation, and then pour paste backfill to tightly fill the void space above the foam, resulting in a long term rehabilitation of the crown pillar.

Precast concrete is a potential solution for capping of surface mine openings for areas with difficult access or site restrictions. An example of this would be for a remote fly-in community where there may not be a local concrete contractor, or the site is such that the mine hazard is not easily reachable by contractor equipment. Another use of precast concrete is for installation of caps during the winter months. In some cases, this may be the only time to complete the work due to schedule restrictions. In this scenario, cast in place concrete would require heating and hoarding, and additional curing techniques, which can significantly increase the cost of the cap. Precast sections can be manufactured to any size or load specification and constructed in ideal curing conditions, and then transported to site and installed. Stainless steel bolts are used to permanently pin the cap to bedrock or a concrete collar. Precast concrete could also be used in a scenario of temporary mine closure, or where protection of the mine opening is required during filling stages and they can be constructed in such a way that they are removable at a later date.

In other provincial jurisdictions, such as Saskatchewan, stainless steel caps have been constructed in remote communities to cover several surface mine openings. These caps have the potential to be a cost effective long term solution in remote, sparsely populated areas where the likelihood of access by the public is low, however, are likely to be cost prohibitive or impractical in areas near populated areas where the likelihood of access by the public is high. It is noted that permanent stainless steel caps have not been constructed in Ontario to date, and there are no current regulatory standards for stainless steel capping in Ontario for final closure.

Paste backfilling is a common practice in operating mines and has been used for over 20 years especially as it is an efficient use of tailings material, but this involves building large paste batch plants that are fed by the output from the mill. Recently, methods have been developed to use mobile plants for abandoned sites. The process involves digging old tailings or other local feed material (i.e., overburden), adding a binder, and in some cases adding other aggregates, using a continuous mobile mixing plant, and pumping the paste into underground stopes through boreholes drilled from surface. The advantage of mobile mixing plant is that it can achieve the same throughput as a batch plant, on the order of approximately 500 m^3/day, without having to build or mobilize large batch plant equipment. Mobile plants can also be moved from location to location, avoiding the requirement of pumping and having a fleet of redi-mix trucks to deliver the paste to the delivery points.

The innovative techniques presented above can be used in conjunction with each other or with more traditional methods of rehabilitation. For example, traditional methods for backfilling of abandoned mines would involve filling part of the stope with non-cemented fill in order to block the connection point of the stope to other workings, filling to a specified height in order to reduce the cost of cemented fill, and then topping up the remainder of void space with cemented fill, such as concrete. This same approach could be used but instead of using concrete, paste could be used to ‘top up’ fill the stope.

In older mines where narrow vein mining techniques were employed, it was common practice to develop a raise through the planned stope area between the first level of mining and surface, and then mine the stope through this raise. In some cases, there is an upper stope and lower stope connected by this raise. Traditional methods for rehabilitating this situation, where the lower stope crown pillar is long term stable but the upper stope crown pillar is not, would be to fill the lower stope and raise with sand or gravel, and then filling the upper stope with cemented fill. Polyurethane foam can be used in this scenario to block the raise in the area of the upper stope, and then filling the upper stope progressively with paste fill. This can result in a cost saving as the lower stope could be a very large volume and could require purchasing a substantial amount of material if locally sourced/free material is not available.

Summary

Using a phased and planned approach to mine hazard rehabilitation allows for the ability for mine site owners to investigate, assess, prioritize, and implement rehabilitation measures in a cost effective and efficient manner. This involves consideration of rehabilitation options for the site as a whole. It has been the authors’ experience that developing a rehabilitation strategy for the entire site that is a targeted specific plan for that site and not a one-size-fits-all solution is the most cost effective method of closing out a mine site. No one solution will fit for the whole site, rather, it is a collection of applications that requires a strategy to implement efficiently.

In most cases, using the “do nothing” approach, or delaying the rehabilitation by a long period of time, is often not acceptable from a regulatory stand point, and can often lead to higher costs over the duration of the project as work tends to happen independently of each other in this scenario. This is another reason why a strategy for rehabilitation needs to be completed for the site as a whole.

Innovation is also always changing and improving the way that rehabilitation is achieved. Consultants, mine site owners, and regulatory bodies need to work together and need to be constantly evolving in their ways of thinking to allow for these improvements and advances.

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