Design Considerations for Sill Pillars at Deep Underground Hard Rock Mines

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Abstract: Mining of sill pillars in burst prone mines is a problem that the mining industry is currently faced with. Although it is evident that leaving sill pillars is a practice which causes significant difficulties when mining in burst-prone ground, it is often the case that a mine cannot avoid developing sill pillars. Optimization of mine design parameters means cost savings for the mine operation and minimization of the rockburst hazard. Implementation of sill pillar design requires cooperation between mining, engineering and geology departments in order for a feasible plan to be achieved and executed accordingly. It is important to foresee problems related to sill pillars and their impact on the mine operations before these pillars are formed. The mine operator will then have to impose cost-effective, practical solutions to them, adjust the production requirements accordingly, and construct contingency plans. Such decisions can critically affect the safety of the workings, the production cost, the ore dilution, and the anticipated recovery of the orebody. The up-to-date knowledge of sill pillar design, the implications that this can have for a mine operation, and the methodology required to conduct sill pillar design, are summarized in this paper. A number of case studies from Ontario’s underground mines with rockburst problems are described, with emphasis on the current sill pillar practices and the possible alternatives that can be introduced.

Key words: Sill pillars, underground mine design, mining methods, mining at depth, rockbursting

Introduction

With cut-and-fill or open stoping mining methods progressing to greater depths, underground operators are often faced with decisions pertaining to the mining of highly stressed sill pillars that are formed after the extraction of the “easy parts” of the orebody at the first stages of mining. Such decisions can critically affect the safety of the workings, the production cost, the ore dilution, and the anticipated recovery of the orebody. Although it is evident that leaving sill pillars is a practice which causes significant difficulties when mining in burst-prone ground, it is often the case that a mine cannot avoid developing sill pillars, in order to keep up with its production requirements by mining different stope areas at the same time. The geometry of an orebody and the progressive discovery of its extensions are other factors that often result in the creation of waste pillars or ore pillars that have to be mined at a later stage. The stability of a sill pillar will be dependent on the in-situ stresses, the local geology, and the geometry of the pillar stope area.
The design of sill pillars at depth, therefore, becomes a critical issue, the consequences of which can have a significant impact on a mine, especially when the mine is in the last years of its operation. The mine operator needs to identify the means to enable him to conduct mining of a sill pillar in a way that minimizes personnel exposure to rockbursting and rockburst potential to the sill, while maximizing the sill recovery with the minimum possible dilution and operating cost.

**Operational concerns for mining of sill pillars at depth**

To minimize exposure of personnel to rockbursting, and, indeed, the potential for rockbursting to occur in the vicinity of a sill pillar, the mine operator has to make decisions about mine design parameters pertaining to:

- the size of the sill pillar;
- the access drifts to the sill (size, shape, orientation);
- the mining sequence and method;
- the blasting and destressing methods;
- the type of backfill;
- the support of the drifts and the stope panels;
- the use of equipment which can reduce worker exposures in workplaces; and,
- the monitoring of the in-situ conditions during mining of the sill.

Optimization of these parameters means cost savings for the mine operation and minimization of the rockburst hazard. Implementation of sill pillar design requires cooperation between the mining, engineering and geology departments in order for a feasible plan to be achieved and executed accordingly. Design of sill pillars at depth should meet the following objectives:

- ensure the stability of the mine as orebody extraction proceeds;
- preserve unmined ore in a minable condition;
- protect major service openings until they are no longer required;
- provide secure access to safe working places;
- minimize the potential of rockbursting at locations where workers are exposed;
- ensure that the solutions which meet the above objectives are cost effective.

The timing of the sill pillar design will critically affect the available options. In order to assess the whole problem, a successful design will require a knowledge of key input parameters such as the behaviour of the rock mass at the sill pillar area under certain stress conditions. Knowledge of these parameters increases as the mine matures and more becomes known about the response of the rock mass to mining.

![Figure 1: Effectiveness of design analyses](image-url)
In addition, problems related to the development of sill pillars increase as the mine moves towards the last years of its operation (Figure 1). With the possible alternatives for changing the mine design parameters diminishing as the mine matures due to operational constraints, it is important to foresee problems related to sill pillars and their impact on the mine operations before these pillars are formed. The mine operator can then impose cost-effective solutions to sill pillars, adjust the production requirements accordingly, and construct contingency plans. In this way, he minimizes the risk for sill pillar related problems to disrupt the mining operation.

**Rock mechanics for sill pillars design at depth**

It is demonstrated by Kazakidis, 1997 that there is a significant difference between general design of pillars in shallow depth and sill pillar design at burst prone mines. Although the traditional design approach can be used to demonstrate by parametric analyses the influence of pillar shape, size, and rock mass quality on pillar strength, it is inadequate for a complete design analysis of sill pillars at depth.

Today there is no established approach for sill pillar design in burst prone mines. Certain mining companies have adopted through experience simple rules of thumb for sill pillar design in their mines, with respect to critical sill pillar height and the mining method that can be used to mine them. Nevertheless, they are applicable only to the specific mine site where they have been developed, and can only be used for the current mine depth. When different rock mass conditions or orebody geometries are encountered, these rules of thumb are often found to deviate significantly from the encountered mining conditions, and can overestimate or underestimate the anticipated problems.

It is questionable whether a single engineering design method can ever be developed and applied to any mine prior to the method becoming calibrated for the specific mine conditions. What can be developed and become applicable to sill pillar mine design in burst prone mines are the procedures and the approaches, that need to be followed in order for the mine to develop its own reliable guidelines that fit the mine design requirement of the specific operations.

The stability of a sill pillar will be dependent on the in-situ stresses, the local geology and the geometry of the pillar stope area. The sill pillar design is usually conducted using a combination of observational, analytical, and empirical design methods. Such analyses involve:

- evaluation of the local conditions (stress-geology);
- analysis for previous cases of mining of sill pillars in the mine;
- conventional and seismic monitoring;
- numerical modelling; and,
- application of experience on sill pillar design gained from other mines.

**Evaluation of local conditions**

It is often the case that sufficient knowledge is available in terms of stress, geology, and geometry with respect to the sill pillar by the time that it is formed. Mining in the area above and below the sill, along with the development of access drifts and raises in the area, should have given an adequate picture of the rock mass quality, the existence of
discrete structural features and different types of rock. Structural mapping, rock mass classification, and fault characterization need to be conducted in order to provide geomechanical assessment of the rock material in the sill area. Information obtained from geological mapping conducted during mining of the areas above and below the sill pillar should reveal adequate information to allow projections of the structural features in the sill area.

Analysis for previous cases of mining of sill pillars in the mine
Documentation of mining of sill pillars in the same mine can provide significant information for planning the extraction of sill pillars formed in the future. Such documentation includes descriptions of the sill dimensions, local geology, encountered problems, failure mechanisms, seismic activity at the stope, dilution, behaviour of the support systems installed, and the backfill used, mining sequence, needs for access rehabilitation, and blasting methods. Although the conditions may vary from sill to sill, it is important in any analysis for a future sill extraction, to know what kind of rock mass behaviour might be anticipated on the basis of previous experience. In this way, a reliable database that can provide key input for future decisions pertaining to sill pillar design in the mine can be maintained.

Conventional and seismic monitoring
Monitoring of a sill pillar provides a way of observing the rock mass behaviour during mining of the sill. It is important that any instrumentation should be placed prior to initiating mining of the sill. Conventional instrumentation usually includes extensometers or stress meters. Uniaxial extensometers can allow the determination of the convergence between the hangingwall and the footwall of the stope, or the evaluation of the stability of an access drift (ground movement monitoring). Stress meters can indicate the build up of stress during mining of the sill in the areas where they are installed. Although the above means of instrumentation can provide useful data in the assessment of a sill pillar, conventional instrumentation can prove to be limited for monitoring a burst prone sill pillar. Monitoring of the seismic activity through a mine-wide or portable microseismic system provides a means to observe the behaviour of the sill pillar on a constant basis. Accurate event locations can pinpoint the areas where seismic activity occurs. The magnitude of events and the event density can provide a picture of the rate of energy release during mining of the sill. This can have a direct impact on both the safety of the working, and the identification of possible troublesome areas within or around the sill.

Numerical modelling
Numerical modelling is a computational tool with which one can improve the understanding of a problem, analyze the significance of the parameters that control it, and explore the possible alternatives. A mine operator or an engineer responsible for mine design has to assess the stability requirements of a sill pillar, forecast foreseeable problems, and impose cost-effective solutions to them. Numerical modelling can play the role of a "bridge" that connects the available experience and knowledge of an existing mine design problem to a possible solution to it. In this way, its use and applicability is limited by the extent of knowledge of the above factors, and the likelihood of modifying them. The distribution of stress or energy around a complex sill pillar mine geometry, the significance of the existence of geological features, and their possible impact on the rockburst potential during a sill, can be evaluated through numerical modelling analyses.
that are readily available. Although the numerical analysis is based on rather complex calculations, the phenomenological mechanisms that are considered are conceptually simple. It is important that it be understood that the models are simplifications rather than imitations of reality.

Application of experience on sill pillar design gained from other mining operations
Experience gained from other mining operations in terms of mining sill pillars at depth can provide significant insights into current and future practices of a mining operation with similar problems. Although each operation has its own specifications and particularities in terms of the controlling factors for sill pillar related problems, there are certain concepts, ideas, and methodologies that can be transferrable throughout the mining industry.

Integration of rock mechanics with mine design

In order for well-established rock mechanics approaches to become applicable to a sill pillar design problem, they have to be able to provide answers to simple mine planning questions that can have a direct impact on both the safety and the efficiency of a mine operation. It would be a pointless exercise to discover, after putting in significant effort to analyze a sill pillar related mine design problem, that the only effective controlling factor could not have been known before the problem appeared or that there was not much that could be changed to alleviate the problem! Thus, in order for rock mechanics to become effective, it is necessary that it be coupled with mine design.

The options that an operator examines for the extraction of a sill pillar should be discussed at an early stage with the rock mechanics department in order to establish the basis for evaluation of the possible alternatives to the problem. Depending on the particular mining situation, these options can vary significantly. However, there are certain options that are often examined during mining of sill pillars, and they are listed below:

Access to the sill pillar
Depending on the sill geometry, in-situ stress orientation, rock mass quality, and the existence of discrete structural discontinuities or contacts, there are favourable and less favourable locations and orientations for access drifts to the sill pillar. Depending on where these drifts are located, different ground conditions (e.g., loose or highly stressed ground) should be anticipated throughout mining of the sill. The location, distance from the orebody, the development of a sublevel, and orientation of an access drift can be decided based on standard geomechanical analyses that are available in the literature. Even if the least favourable option has to be selected for operational purposes, the support requirements, possible future rehabilitation needs, the optimum shape of the access drift (flat versus arched backs) and the need for instrumentation of the drift can be evaluated at an early stage. Maintaining short term temporary accesses to the stopes versus a single access that is expected to last throughout mining of the sill should be examined. Obtaining access to a sill by driving drifts through fill is an additional option that is feasible today, and should be examined. Development of sublevels within burst prone sills should be avoided.
Mining method

Today, transverse or longitudinal open stopeing (blasthole, longhole, or VRM) are the typical methods for the extraction of sill pillars. Although these bulk mining methods can be considered efficient, they are often accompanied by high seismic activity or excessive dilution. It is often the case that the dimensions of open stopes commonly followed elsewhere in the mine are excessive for the size of panels within a sill pillar. For the determination of the size of a stable open stope within a sill from the waste dilution point of view, and the possible need of hangingwall support, standard empirical methods for open stope design (e.g., Mathews-Potvin) can become a basis for engineering design provided that high stress conditions and differentiation in rock mass quality are taken into account.

Mining sequence

A pillarless sequence is a common sense approach for mining sill pillars today. Nonetheless, avoiding high stress concentration is almost impossible in most cases of sill pillars. The areas with high stress concentration in a sill when this is formed will be dependent on the overall geometry and geology of the sill. The location and orientation of structural features (e.g., dykes, faults) with seismic potential within the sill are issues that require particular attention. Since these areas should be avoided due to rockburst hazard, it is important that they be identified at an early stage in order to follow an appropriate mining sequence or to prepare accordingly. Such areas can be identified and understood through analysis of microseismic data, underground observations, previous experience in the mine, drilling or instrumentation within the sill and numerical modelling. It is considered favourable that the mine sequence starts from areas where lower stress levels exist and gradually move toward higher stress areas without leaving any pillars within the sill. In this way, the interface between fractured and overstressed rock mass will be gradually moving toward the highly stressed areas following the excavation sequence. However, in cases where high stress conditions are anticipated throughout the sill, or the fractured-overstressed rock mass interface does not move adequately with the progress of mining, destressing practices will be required. Excavation of destress slots and destress blasting techniques are two alternatives in such situations. Old development drifts and raises near the sill often become the source of high seismic activity during mining of the sill. It is imperative that such old “open holes” be filled prior to initiation of mining within the sill pillar in order to minimize the potential seismic activity. In addition, the effect of the excavation sequence within the sill on permanent openings (e.g., ore passes, raises, ramps) in the vicinity of the sill that can significantly disrupt the mining operation should also be examined. In cases of multiple sill pillars that are close to each other, it is important to examine sequencing extraction of the sills in such a way that rockbursting problems are minimized.

Identification of burst prone areas and ground support

To minimize the exposure of personnel at locations where the potential of rockburst occurrences exists and to provide sufficient ground support to protect workers from the rockburst effects, it is necessary to identify rockburst prone areas. Minimization of the rockburst potential in such locations is an additional concern of the mine operator. Identification of areas that are prone to rockbursting can be based on previous experience, analysis of microseismic data, knowledge of the sill geology, and numerical modelling.
If areas that have been identified as burst prone cannot be avoided, then minimization of the rockburst hazard can be achieved through a local reduction of spans, destress blasting, and installation of the appropriate support that can withstand the dynamic loading of the seismic waves generated by a rockburst. Stope brows and intersection of cross cuts with access drifts have particular support requirements. Evaluation of the support requirements at an early stage and installation of appropriate support systems for rockburst conditions, can significantly improve the efficiency of mining in the sill and minimize rehabilitation costs. Minimization of the exposure of personnel to rockburst conditions can be achieved through monitoring of seismic activity in the sill, especially after blasting times. Introduction of remotely operated equipment can further minimize worker exposure to possible rockbursting conditions that can be encountered in the sill.

The size of the sill pillar
The dimensions of the sill pillar on a plan view are delineated by the shape of the orebody. It is the height of the sill that can be designed. It is usually the case that conversion of a cut-and-fill mining method to open stoping and formation of the sill are required when the ground conditions at the last cut have deteriorated to the point that further mining with cut-and-fill methods is not considered feasible. However, maintaining the undercut access to the sill can be important for future mining with open stoping, and, therefore, it is important to convert the mining method to open stoping at the right time. Determination of the optimum height of the sill will be a function of the open stoping method that will be followed (i.e., acceptable drilling deviation, orebody dip), along with a rock mechanics analysis where the critical size of the sill can be estimated through numerical modelling, and previous experience of mining sills in the same mine and depth. Guidelines for estimating the optimum sill size at different depths can be developed and applied for further sill extractions.

Backfilling practices
The ideal fill is the one that is sufficiently compressible to avoid its own destruction, while providing maximum resistance to stope closure. Using fills that can have high stiffness when placed above and below a sill, can improve the stress conditions that can develop within the sill pillar when this is formed, by controlling the stope closure. Developing the conditions that enable the stiff fill to perform in a favourable manner will also be a function of the orebody stiffness and width, as well as the stress conditions. Backfilling of the open stops within the sill will maintain the local stability of the stope walls and will further minimize seismic activity and deterioration of ground conditions. Since it is desirable that no pillars are formed within the sill, maintaining the stability of the fill walls is required to minimize ore dilution and to avoid uncontrolled failure of a loose fill. The fill quality control in the panels (e.g., cement content, dip angle of the fill wall and blasting method) should be adequate to fulfill that purpose. Generally, it is considered favourable from the point of view of stability to fill each panel prior to blasting the next one within the sill. Fill stiffness is less of an issue for backfilling panels within the sill.

Blasting practices
Longhole, blastholc, and VRM, are the three open stoping methods commonly used for mining sill pillars. Operational constraints are: available equipment and personnel experience, acceptable drilling deviation, layout for raise development, orebody dip and
thickness and required stope access. These constraints dictate design requirements for a blasting method. Pre-drilling of the sill versus a drilling and blasting sequence are the two options. The latter becomes more favourable when hole squeezing is encountered. Although mass blasting in the sill can be considered as an option to minimize the exposure of the workers to rockburst hazard, this cannot be conducted until a large part of the sill has already been mined. In certain cases, it can be found that high seismic activity occurs in these initial stages of sill extraction, rather than the later ones. However, this is something that can be analyzed through the use of a calibrated numerical model and verified through underground observations and seismic analysis.

Case studies

Case study #1: Determination of critical sill height and sequence among sills
In a narrow vein mine, steeply dipping gold bearing veins are found within volcanic rocks. Cut and fill mining results in the creation of sill pillars that can then be retrieved with longhole stoping methods. With mining having exceeded the depth of 3000 feet, rockbursting in the stope areas creates significant operating problems in terms of worker safety, access rehabilitation, and dilution. A rock mechanics analysis for the determination of the critical sill height, the mining sequence within the sill, and the extraction sequence among a number of sills in the same area, was undertaken. A combination of underground observations during the extraction of two sills, knowledge of regional stress field, rock mass classification, analysis of seismic data and numerical modelling were employed for the purpose of this study (Kazakidis, 1995a). An energy analysis (Figure 2) indicated that the overhanging stope geometry significantly affects the active cut of a cut and fill stope, when the sill height becomes 33 feet. Assuming an average cut height of 9 feet, a sill height of approximately 40 feet was recommended. A sequence where the lower sills are mined first is considered more favourable.

![Figure 2: Energy analysis for different sill heights for the problem described in case study #1](image-url)
Case study #2: Pillar versus pillarless sequence

Years of practice have indicated that sequencing the extraction sequence within stressed sill pillars can be a difficult task that can affect the whole mine operation. A rule of thumb is not to leave solid pillars during mining of a sill pillar since the already high stress conditions become even higher and the rockbursting potential increases. A pillarless sequence versus an extraction sequence where pillar are formed within a sill were examined, as shown in the simplified geometry of Figure 3. The rate of energy release was selected as a criterion for evaluating the two sequences where it is assumed that the pillars have not failed prior to them being extracted. Minimization of the rate of energy release is most likely to result in less overloading problems. The volume of each panel was maintained to be the same and the amount of released energy per excavation step was determined for each sequence using a numerical model. It can be seen in Figure 4 that, for the case of mining with pillars, the amount of released energy increases dramatically after the third excavation step, while it retains a rather constant rate of increase for the case of the pillarless sequence. Although the results of the above problem can be obvious to an operator, it may be more complex to determine the effects of a mining sequence for a much complex stope geometry or geology. In such cases, a similar analysis can have a significant input into operating decisions pertaining to sill pillar design.

Figure 3: Mining with pillars versus pillarless mining within a sill (case study #2)

Figure 4: Energy analyses for two sequences described in case study #2
Conclusions

Sill pillar design in burst prone mines cannot be performed through traditional design approaches for pillars. Since sill pillars can critically affect a mine during the last years of its operation, it is imperative that sill pillar design be performed at an early stage before the problems appear. With no generally accepted design approach currently being available for sill pillar design at depth, a methodology which enables the operator to develop reliable sill pillar guidelines for a mine is proposed in this paper. Focusing on the alternatives that the operator can have in sill pillar design within his mine enables the development of realistic and cost-effective solutions to mine design problems. In this way, integration of rock mechanics with mine design is achieved for the specific conditions of the mine operation.

References


