Stability of Pillars and Tabular Excavations under Shear Loading Conditions – Implications for Mine Planning and Design

Fidelis T. Suorineni[1], Joseph J. Mgumbwa.[2] and Reginald D. Mfanga[2] & Kaiser, P.K.[3]

[1] *MIRARCO/Geomechanics Research Center, Laurentian University, Sudbury, Canada*
[2] *Graduate Students, School of Engineering, Laurentian University, Sudbury, Canada*
[3] *CEMI - Center for Excellence in Mining Innovation, Laurentian University, Sudbury, Canada*

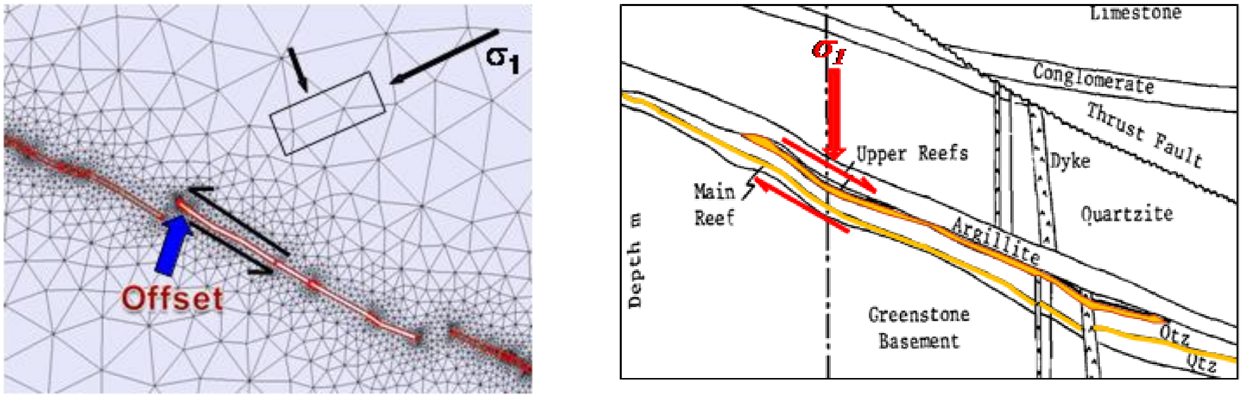
Abstract

Rockbursts are a major hazard in deep hard rock underground mining and tunneling. To date a significant number of rockbursts still defy conventional explanations. A review of rockburst case histories in the literature has shown that pillars and tabular excavations under shear loading are prone to rockbursting in situations where they are least expected under conventional knowledge of rockburst causes.

Despite the evidence of the effects of shear loading on underground infrastructure, and the frequency of their occurrence, little is known about how this loading mechanism causes such large magnitude events and extensive damage. In this paper analytical and numerical modeling are used to understand the behaviour of pillars and tabular excavations under shear loading. The numerical modelling results show that pillars under shear loading are less confined than their equivalents in loaded in pure compression in the same geologic environment, and are therefore more brittle and weak. For tabular excavations under shear loading, the behaviour depends on whether such excavations are continuous, co-planar or offset with rock bridges. Analytical results based on slit theory show releasable potential energy in tabular excavations increases nonlinearly with excavation half-span. The study results are important for the safe and economic extraction of orebodies under shear loading.

1. Introduction

Rockbursts are well known hazards in deep hard rock mines and tunnels, posing serious threats to production and personnel safety. To date, the reasons for the occurrence of some rockburst events cannot be explained with conventional rockburst genesis mechanisms. Studies in the Geomechanics Research Centre over the last ten years on three obliquely loaded orebodies (major far-field stress oblique to strike) show several characteristic problems that differentiate them from those having the major far field stresses normal to strike or dip (Figure 1). In Figure 1a the orebody is loaded oblique to strike with respect to the major far field stress (σ_1) while in Figure 1b, the orebody is loaded obliquely to its dip.



(a) Orebody in shear due to oblique loading to strike. This orebody is not continuous and contains offsets of different geometries.

(b) Orebody in shear due to oblique loading to dip. Orebodies overlap.

Figure 1. Illustration of shear loaded orebodies.

In practice room-and-pillar-type pillars are designed oriented perpendicular to footwall and hangingwall. Hence any pillars in Figure 1 will be subjected to both compression and shear stresses. Sill pillars may also be subjected to shear loading.

The major problem with orebodies in shear is the unusual frequency of seismic activity and at locations where they are least expected during mining. Kvapil et al. (1989) reported that in 1987 a rockburst occurred in the same area that a series of bursts had occurred between 1977 and 1980, which was unusual because of the common believe that rockbursting does not repeat in the same area since the previous rockburst released most energy. In addition to the severity and frequency of seismicity in these orebodies, they are also associated with major dilution problems. Typical examples of such orebodies are the F-Zone of Campbell Mine (Goldcorp) (Suorineni et al., 2007), Lac Shortt Mine (INMET, closed) (Falmagne, 2001), Quirke Mine (Rio Algom, closed) (Maybee, 2000) and Copper Cliff North Mine (Vale) (Suorineni and Kaiser, 2008).

Orebodies loaded with major far field stresses oblique to strike are subjected to both compressive and shear stresses. Despite these major problems associated with mining orebodies under shear loading, little information exist in the literature on any detailed studies to understand and mitigate the problem.

2. Objectives

Where orebodies are loaded in shear there is little information in the literature regarding their behavior and how the associated risks in the mining of these orebodies can be mitigated. This paper aims at creating awareness in both the mining and tunneling construction industries of the dangers posed by these orebodies and providing some guidelines on how risks associated with mining of these orebodies can be mitigated. The following are the specific objectives for the study:

i. Review case histories of (a) established mining case histories where seismicity and dilution problems were encountered because such orebodies were under shear loading and (b) known mining case situations where severe seismicity and dilution problems were encountered but could not be adequately explained by conventional knowledge.
ii. To develop fundamental knowledge on the behaviour of orebodies in shear: Current design approaches are based on the assumption and experience of axially loaded orebodies (pure compression). This assumption is clearly not applicable in situations of shear loading, and fundamental research as well as field investigations considering geological and geometric complexities, are required to better understand the response of excavations and pillars under inclined stresses. Empirical pillar stability charts do not account for shear and thus may be misleading.
iii. To establish procedures for proper simulation of rib and sill pillars under shear loading and provide explanation for elevated risks associated with the mining of orebodies under shear loading.

The overall goal of the study is to provide means for safe and economic extraction of orebodies under shear loading.

3. Approach

To achieve the research objectives a 3-step approach was adopted as follows:

i. Literature review on (a) established mining case histories where seismicity and dilution problems were encountered because such orebodies were under shear loading: Quirke Mine (Maybee, 2000), Lac Shortt Mine (Falmagne, 2001) and Campbell Red Lake Mine F2-Zone (Suorineni and Kaiser, 2006); and (b) case histories where severe seismicity and dilution problems were encountered but could not be adequately explained by conventional knowledge: Vale Copper Cliff North Mine 120 orebody (Morrison, 1993).
ii. Two- and three-dimensional stress analyses numerical modeling using Phase2 and Map3D codes, and
iii. Development of an analytical solution that incorporates shear loading in energy calculations.

4. Review of case histories

The literature sites a few case histories in mining where safety and economics were compromised as a result of not knowing orebodies were being loaded in shear. This section describes the geometries of the orebodies relative to the major far field principal stress, the mining practice and the arising issues.

4.1 Quirke Mine

The geology and geometry of the Quirke Mine orebody are shown in Figure 2. The orebody thickness varied between 2 m and 5 m, dipping south at about 15°- 20° and persisting to a depth of 1050 m. The orebody is sandwiched between quartzite in the footwall, and successively by beds of quartzite, argillite, and a massive 250-m thick bed of quartzite, conglomerate and limestone formations in the hangingwall. The strengths of the orebody, hanging wall and footwall rocks ranged from 210 MPa to 230 MPa. The major far field principal stress is in the east-west direction (strike) with a K_o-ratio of about 2 to 2.5 and 1.5 in the north-south direction (dip) (Hedley et al., 1984). Figure 3 shows the relationship between major far field principal stress and pillar orientations. Pillars are either on dip or strike (red).

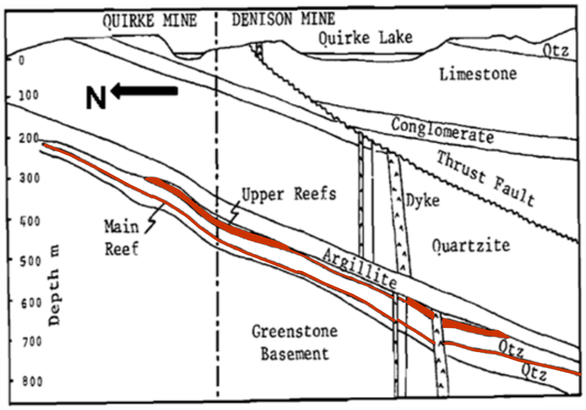


Figure 2. Geology of Quirke Mine (modified after Hedley, 1984).

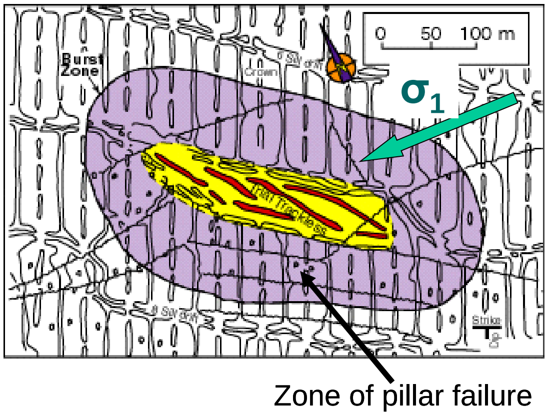


Figure 3. Mine layout showing major far field stress orientation relative to orebody and orientation of pillars (after Martin and Maybee, 2001).

Because of the geometry of the orebody, stope and pillar mining was selected as the main extraction method with an extraction ratio of 75-80%. The change of orebody geometry in the central part (locally flat) hindered the effective recovery of ore at the top of stopes using slushers and hence necessitated a change from manual to trackless mining using a trial panel (yellow area in Figure 3). The pillar orientation was thus changed from on-dip to essentially on-strike pillars to accommodate the equipment. After changing the pillar orientation mining was done without any significant ground control problem up to the completion of this part of the orebody. Pillars in the trackless area deteriorated and failed non-violently several years after mining. This was followed by violent failures in the surrounding area, especially in the squat pillars. Earlier analysis by Hedley (1984) concluded that the change in pillar orientation in the trackless area subjected them to shear loading along the long axis and thereby making them weaker.

4. 2 Lac Shortt Mine

Lac Shortt Mine was an 800 tonne per day gold mine located in northern Quebec, and operated by Minnova Inc. The east-west striking orebody was a thin (3 to 10 m) sub vertical seam extending from the surface to a depth of approximately 830 m with a strike length varying from 100 to 250 m. A simplified geology as seen on the 700L is shown in Figure 4. Detailed geology of Lac Shortt Mine can be found in Morasse (1988).

The mining method at Lac Shortt Mine was open stoping with alternate primary and secondary stopes. The primary stopes were filled with cemented rockfill and the secondary stopes were filled with cemented sand fill. Later mining at depths between 500 metres and 830 metres was accomplished using a modified AVOCA mining method with delayed backfill. The modified AVOCA method involved delaying the filling step, leaving a moving triangular shape of wall exposure.

High-stress and rockbursting conditions were experienced at depths as shallow as 250 metres. The combination of an anomalously high horizontal stress field of 2.5 to 3 times that of the overburden load (Yuen and Cook, 1983) and a brittle rock mass (elastic modulus of 60 GPa; uniaxial compressive strength of 100-150 MPa in the footwall, 250-300 MPa in the orebody) created a burst-prone environment.

Reliable source-location determination showed that the movement of the rockmass "failure front" was due to the areas of stress increase that could be followed, and was responsible for stope dilution, footwall and orebody development deterioration, and caving (Falmagne, 2001).

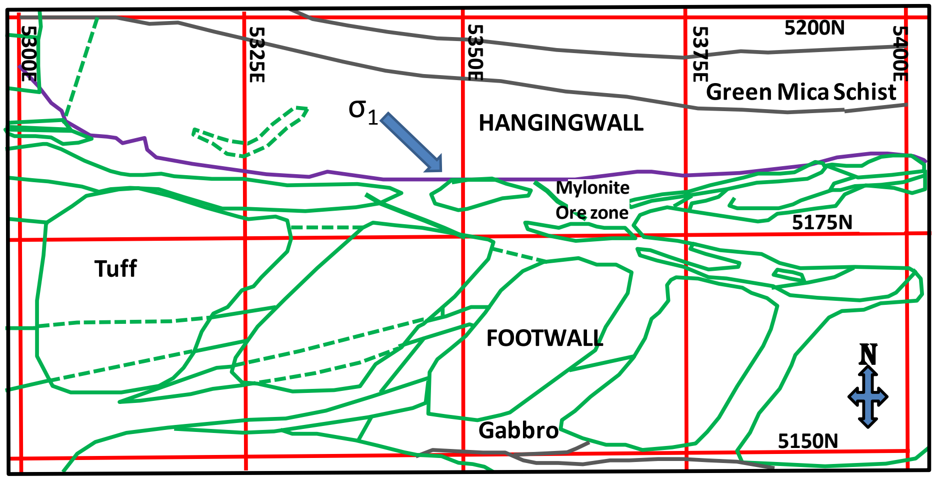


Figure 4. Simplified geology of Lac Shortt Mine as seen on 700L (modified from Falmagne, 2001). The major far field principal stress orientation relative to the orebody is superimposed.

Falmagne (2001) show the rockbursts were either in hanging wall or footwall depending on mining direction relative to the direction of the major far field principal stress. The Lac Short Mine orebody by virtue of its orientation relative to the major far field stress was under shear.

4.3 Campbell Red Lake Mine

Campbell Mine (now Goldcorp property) is located at Balmertown in Northern Ontario. The geology and geometry of the Campbell Red Lake Mine are described in Hedley (1992). Eight gold bearing ore zones are found in steeply dipping faulted Precambrian volcanic rocks (Hedley, 1992). The veins consist of replacement veins of 0.6 to 9 m widths and quartz carbonate fracture filled veins of 0.2 to 1 m widths with Andesite as the host for all veins (Figure 5).

Mining method at Campbell Mine has evolved over time. Initially, all production was from shrinkage stopes. This method was changed to overhand cut and fill and current mining is by longhole mining. The mining and rockburst history at Campbell mine is described in detail by Hedley (1992) and Suorineni and et al. (2007). The F-zone is the most seismically active zone at Campbell Mine (Figure 6). Deterioration of the shrinkage boxhole pillars in the F-Zone in 1981 was followed with a major rockburst (3.3 M_N) in December 1983 on the 11 Level. Hedley (1992) noted that the vast majority of the major bursts occurred where the sill pillars are 6 m wide on dip, with very few events in 15 m wide sills. Following the seismicity in 1983 mining was shut down in the F-zone. Suorineni et al. (2007) established that contrary to other previous reports the rockburst problems in the F-zone are due to its being in shear as shown in Figure 5.

4.4 Other cases

Both Copper Cliff North and South Mines are located in the Sudbury Basin on the Copper Cliff Offset from the Nickel Irruptive. Morrison (1993) reported that “the two mines are coupled together and appeared to have very similar mining configurations but displayed dramatically different levels of seismicity”. Mining in the 120 and 810 orebodies in the North and South Mines posed very different challenges. While no significant problems were experienced in the mining of the 810 orebody, mining of the 120 orebody was confronted with severe bursting, high dilution and blasthole instability (Morisson, 1993). Morrison (1993) attributed the difference in behavior of the two orebodies to a difference in the stress regimes, arguing that while the 810 Orebody stress regime is consistent with the Sudbury Basin regional stress model, the field stresses of North Mine’s 120 Orebody do not conform to this model. The author attributed the problems in mining the 120 orebody to this stress anomaly.

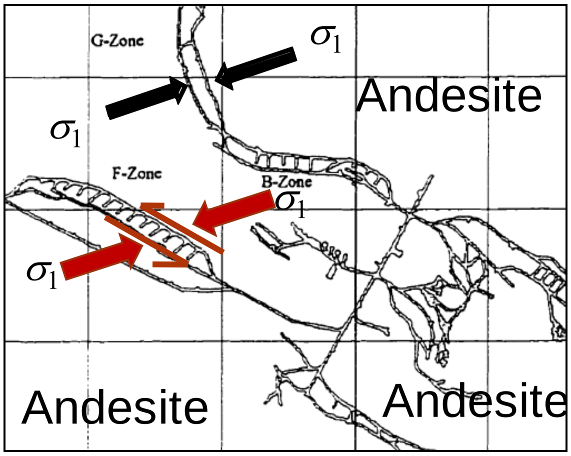


Figure 5. Simplified geology of Campbell Mine (modified from Corcum, 1997).

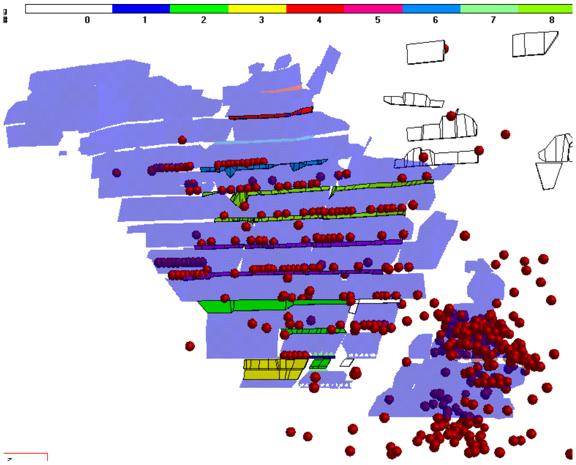


Figure 6. Rockburst history (Suorineni et al., 2007).

Suorineni and Kaiser (2008) re-assessed the ground control problem at North Mine using the Sudbury Basin stress regime. The conclusion from their analysis was that the difference in behaviour between the north and south limbs of the 120 Orebody was due to the relative orientations of the two limbs to the regional major far field principal stress and geometrical differences, and not because of an anomalous stress regime at North Mine as initially postulated by Morrison (1993).

5. Causes and characteristics of orebodies in shear

Typical orebodies in shear are vein deposits ranging in width from less than a meter to 5 m. The two most important factors for loading of orebodies in shear are complex geometries including occurrence of multiple lenses (Figure 5) and variability in insitu stress orientations that can mask actual stress orientations leading to false conclusions of normal loading. After evaluation of stress measurement data from the Canadian Shield, Arjang (1991) concluded that a common feature at mines with near vertical orebodies is that the maximum horizontal stress acts perpendicular to the strike while the minimum horizontal stress is aligned on-strike. This was found to be inaccurate for the Campbell Mine F-Zone, where it was specifically stated that the major far field principal is perpendicular to orebody strike. Grabinsky et al. (1997) state that even in the most homogeneous geomechanical domains, the stress magnitude can vary by ±15% to ±30% about the component's mean value and direction can vary by ±15° to ±30° about the mean orientation. As shown later, far field major principal stress inclination to orebody of 15° or more is significant to cause weakening in the orebody pillars. True orientation of the far field major principal stress can be deduced from borehole breakouts.

6. Numerical modeling

Numerical modeling was conducted with the objectives of:

i. investigating the effects of shear loading on stability of room-and-pillar type pillars under shear loading.
ii. providing an explanation on failure mechanisms of these pillars and suggest pillar design methods.
iii. providing an explanation on failure mechanisms of these pillars and suggest pillar design methods.

Room and pillar mining type rib pillars and sill pillars were modelled. An extraction ratio of 75% was assumed in all cases. Phase2 was used in the study, and the pillar core stresses were monitored in pillar centre. As in other previous pillar studies (e.g. Maybee, 2000) the models were first calibrated against the empirical pillar design chart by Lunder and Pakalnis (1997), as shown in Figure 7.

The analysis considered various orebody inclinations ranging from 0° to 40°, noting that orebody dip angles above 45° often require a different mining method. K-ratios of 1, 1.5 and 2 were considered in the analysis with k=1.5 as base case. The results for k=2 are shown in Figure 7. The effect of k-ratio on inclined pillar stability is shown in Figure 8. Figure 9 shows the results of stress ratio on inclined pillar stability.

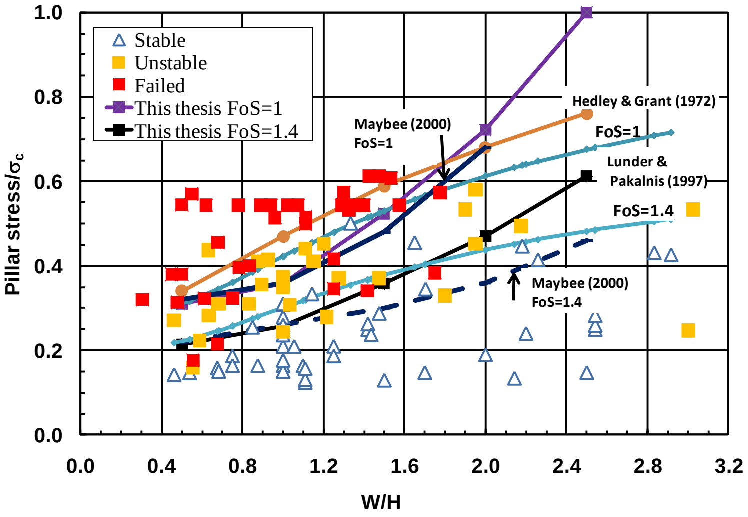


Figure 7. Model calibration, using empirical pillar design chart by Lunder and Pakalnis (1997).

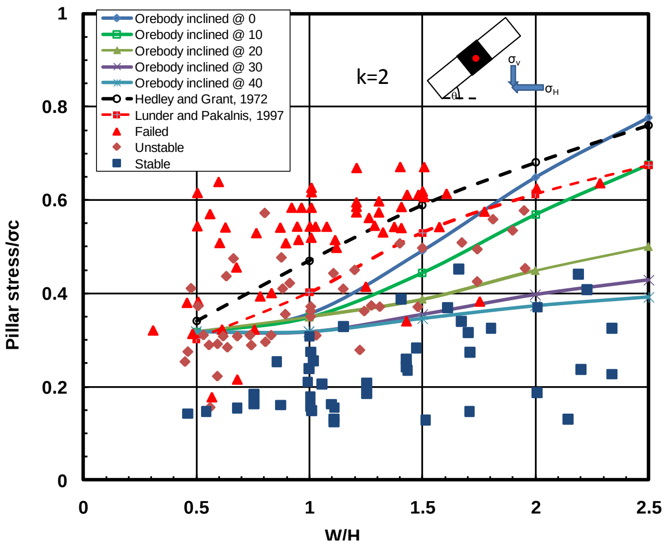


Figure 8. Effect of orebody inclination on pillar stability.

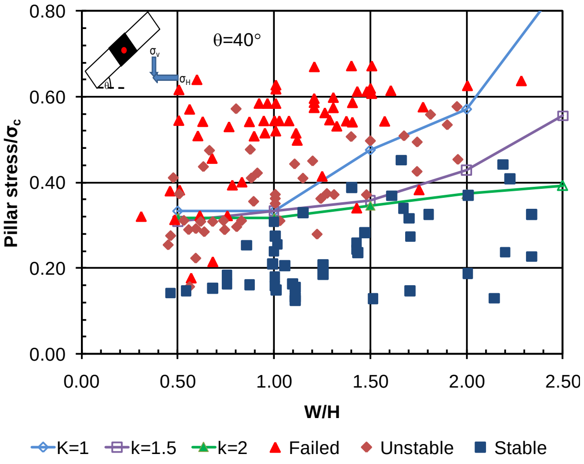


Figure 9. Effect of k-ratio on inclined pillar stability.

The study also examined why excavations in orebodies under shear loading often result in relatively high magnitude events such as that at Campbell Mine F-Zone in 1983. Figure 10 shows nonlinear excavation span energy relationship. The figure shows an increase in span from 50 m to 100 m results in a 6-fold increase in energy for an assumed k-ratio of 2. Figure 11 shows the contribution of shear energy is only significant when orebody dips are in the range of 15° to 75°.

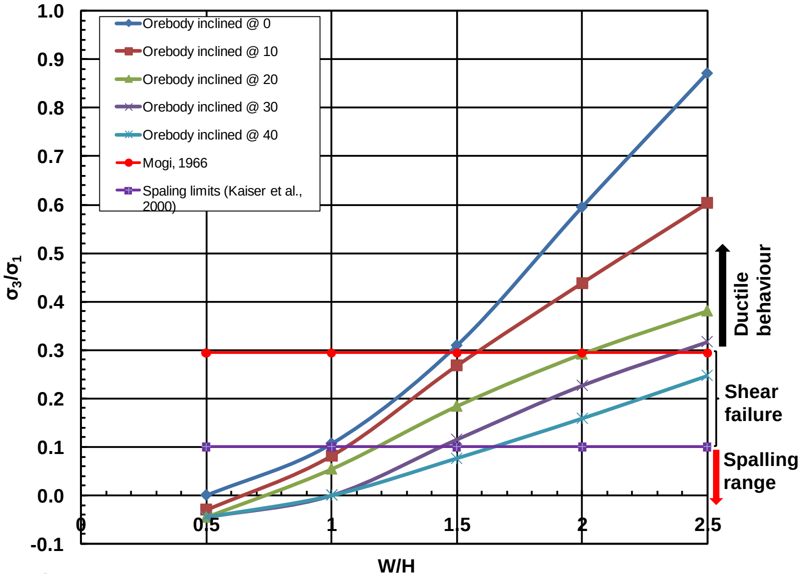


Figure 9. Effect of stress ratio on inclined pillar stability.

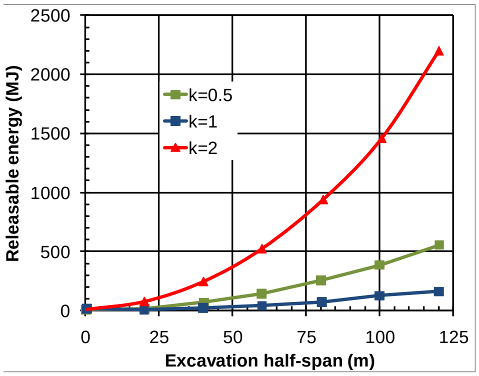


Figure 10. Effect of excavation span on releasable energy.

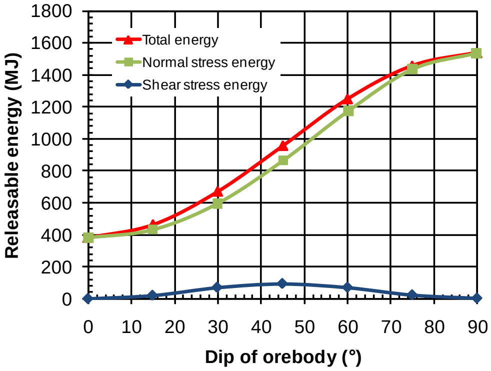


Figure 11. Contribution of shear energy in releasable strain energy.

7. Discussion of results

This study did not include effect of structures in the rock mass. However, based on the assumptions made in the analysis the results show that mine structures in orebodies subjected to oblique loading by the far field major principal stress are more brittle and weaker. In such orebodies violent failures can occur where they are least expected. The results also show that for orebodies under shear loading the empirical pillar design chart is not applicable without calibration, and numerical modeling must be used. It is also very risky when tabular orebodies occur with rockbridges in between. Failure of the rock bridges result in sudden increase in excavation span that can result in violent failure.

8. Conclusions

In mine planning and design special attention must be paid to orientation of the major far field principal stress relative to orebody so that special precautions can be taken in the process if an orebody is identified as being shear loaded. Empirical approaches cannot be applied to such orebodies without further calibration.

Acknowledgments

The authors are grateful to Vale and NSERC for funding the research.

References

ARJANG, B. 1991. Pre-mining stresses at some hard rock mines in the Canadian Shield. Bull Can Min Metall, vol. 84 (945), pp. 80-86.

CORKUM, T. B. 1997. Three dimensional triangulated boundary element meshing of underground excavations and visualization of analysis data. Ph.D. Thesis, Department of Civil Engineering, University of Toronto, 98 p.

FALMAGNE, V. 2001. Quantification of rock mass degradation using micro-seismic monitoring and application for mine design. Ph.D. Thesis, Queen's University, 401 p.

GRABINSKY, M. W., CURRAN, J. H. & BOWDEN, W. F. 1997. Interaction between stress, mine geometry and rock mass behaviour at a Canadian Shield mine. Bull Can. Min. Metall, vol. 90 (1013), pp. 45-51.

HEDLEY, D. G. F. & GRANT, F. 1972. Stope and pillar design for the Elliot Lake Uranium Mines. Bull Can Min Metall, vol. 65, pp. 37-44.

KAISER, P. K., DIEDERICHS, M. S., MARTIN, C. D., SHARP, J. & STEINER, W. 2000. Underground works in hard rock tunnelling and mining. GeoEng2000, Australia: Technomic Publishing Co. vol.1, pp. 841-926.

KVAPIL, R. L., BEAZA, J. R. & FLORES, G. 1989. Block caving at EI Teniente mine, Chile. Inst. Min. Metallurgy, vol. 98 (6), pp. A43-56.

LUNDE, J. & PAKALNIS, R. 1997. Determining the strength of hard rock mine pillars. Bull Can Min Metall, vol. 90 (1013), pp. 51-55.

MARTIN, C. D. & MAYBEE, W. G. 2000. The strength of hard-rock pillars. International Journal of Rock Mechanics and Mining Sciences, vol. 37 (8), pp. 1239-1246.

MAYBEE, W. G. 2000. Pillar design in hard brittle rocks. Master of Applied Science in Mineral Resources Engineering, Laurentian University, Ontario Canada, 120 p.

MORRISON, D. M. 1993. Seismicity in the Sudbury area mines. 3rd International Symposium on Rockbursts and Seismicity in Mines, Young, P. R. (ed.). Kingston, Ontario, Canada: Balkema, Rotterdam, pp. 379-382.

SUORINENI, F. T. & KAISER, P. K. 2008. Orebodies in shear: The role of geological controls and the implications for mine planning and design. Proceedings of the 5th International Conference and Exhibition on Mass Mining, Schunnesson, H. & Nordlund, E. (eds.), Luleå, Sweden, pp. 313-322.

SUORINENI, F. T., KAISER, P. K. AND DELGADO, J. 2007. Hazard assessment when mining orebodies under shear loading. Proceedings of the 1st Canada-US Rock Mech. Symp., Vancouver, Canada,: A.A. Balkema, Rotterdam, pp 1377-1384.