Failure Mechanisms of Pillars Under Shear Loading

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Abstract

Pillars are any structures left between two or more underground openings. The stability of pillars is normally considered to depend on shape (defined by width to height ratio), rock mass strength, extraction ratio, in situ stresses and the gross structural features (i.e. joints, contacts, faults etc). Recent experience has shown that pillar stability is also controlled by the relative orientation of the orebody with respect to the in situ principal stress. In inclined orebodies, pillars are loaded in compression and shear, thus creating unsymmetrical stress distribution. Failure mechanisms of these pillars are little known. This paper investigates the failure mechanisms of pillars under shear loading. Two dimensional elastic numerical modeling was used to examine the behavior of pillars in different orebody inclinations relative to the major farfield stress orientation. First, the paper reviews pillar design approaches including the empirical pillar design chart and uses numerical modeling to investigate the effect of the major farfield stress orientation on pillar stability. It is concluded that the empirical pillar design chart be used with caution, and that for orebodies under shear loading mine planning and design should take this into consideration since such geometrical orebody/stress relations put mine structures at higher risk of instability.

Introduction

Pillars are any structures left between two or more underground openings. The stability of the pillar is crudely defined by its factor of safety which is the ratio of the strength of the pillar to its stress. The strength of the pillar depends on the rock mass strength of the pillar material, the shape and size of pillar defined by its width and height and the gross structural features such as clay bands, unfavorable orientated faults and joints (Esterhuizen, 1997; Stacey and Page, 1986). The strength of a pillar is estimated empirically based on field and laboratory observations of pillar failure mechanisms. The pillar stress depends on its depth and the extraction ratio. The tributary area theory is the most widely used method for determining pillar stresses, and it is applied to situations where similar-sized pillars are developed in a large regular array in flat lying orebodies.

For inclined orebodies, there is a geometrical stress relation problem that leads to considerable change in pillar loading mechanisms. Pillars in inclined orebodies are loaded in compression and shear, thus creating complex patterns of stress distributions leading to different failure mechanisms from those axially loaded. Because of the different pattern of stress distributions, these pillars behave differently from axially loaded pillars even if they are designed in the same extraction ratio and in situ stress environments. Failure mechanisms of pillars under shear loading have not been investigated adequately. Because of the unknown failure mechanisms of eccentrically loaded pillars the application of empirical methods for pillar strength estimation needs to be cautiously used for pillar design in orebodies under shear loading. The stability charts created in this paper can help to guide in understanding the pillar behavior in different orebody inclinations.

Orebody under shear 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. Based on this statement, in mine planning and design in most cases (at least in the Canadian Shield) it is assumed that the maximum principal stress is normal to the strike of an orebody. This assumption is not applicable in situations where there is a geometrical change in orebodies relative to the major farfield stress.

The shape of an orebody is controlled by geological features such as dykes, faults and shear zones. These features also control the orientation and magnitudes of in situ principal stresses. The effect of geological controls is the rotation of the stress tensor from what might generally be considered normal. In that case some parts might be loaded in shear and compression while some parts are loaded perpendicular to the strike, etc. The same can be said where an orebody occurs in not one but multiple lenses. A change in loading mechanism changes the behavior and response of rock masses to mining.

In the last decade, the Geomechanics Research Centre identified several orebodies in various underground mines which tend to be more rockburst prone than would normally be expected (Kaiser and Suorineni, 2005). These orebodies defy known factors governing burst-prone conditions. Examples of such underground mines are Quirke, Lac Shortt and Campbell Red Lake. The common denominator of these mines is that the maximum principal stress is oblique to the strike of the orebodies. The failure mechanisms of these orebodies are not well understood.

Failure mechanisms of pillars under shear loading

Pande et al. (1990) stated that a rock mass in pure shear gives rise to diagonal tension and compression of the same magnitude as the applied pure shear. However, in underground mines, pillars cannot be subject to pure shear. In inclined orebodies, pillars are loaded in compression perpendicular to the dip of orebody and in shear along dip. The shear stress loads the pillar top and bottom but is absent at the pillar walls. The absence of companion shear stress in the side walls of the pillar offsets the action of normal stress away from the pillar long axis, thus creating stress concentrations in only two opposing diagonal corners of the pillar (Pariseau, 2006), resulting in the crushing of contact walls and pillar.

In an effort to find out the effects of changing the nature of loading on pillar stability, Kvapil et al., (1989) conducted an experiment on a pillar-like sample in which one sample was loaded in compression only and the other sample was slightly changed in its geometry and loaded in compression and shear (Figure 2 (a) and (b)). The finding was that the addition of shear forces due to change in sample geometry resulted in the addition of shear deformation from shear stresses. Kvapil et al., (1989) also found that a larger amount of energy was liberated in the compression and shear loaded sample than in the sample which was loaded in compression only. Kvapil et al., (1989) also used a photoelastic method to study a pillar-like sample which was loaded in compression and shear. The results from the photoelastic model indicated visible destruction of the rock mass in the upper corner of the pillar with the roof (Figure 2 (c)). Based on this finding, Kvapil et al. concluded that the nature of loading has great impact on the behavior and strength characteristics of rock masses. They used these findings to explain the domino rockburst which occurred at EI Teniente Mine in Codelco-Chile. Figure 2(d) shows actual pillar behaviours when loaded in axially and in combined shear and compression as observed in the field (Hedley et al., 1984).

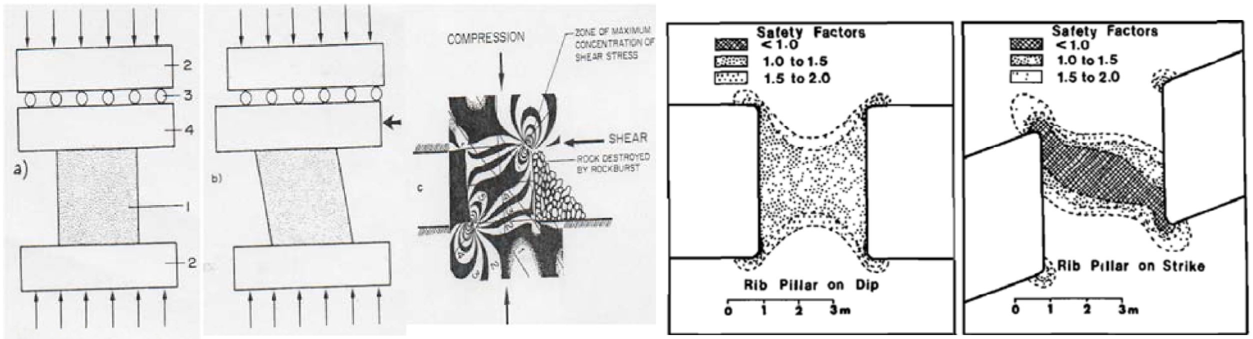

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Figure 2: Effects of changing loading mechanism on pillar behaviour; (a) uniaxial loaded pillar; (b) pillar loaded in shear and compression; (c) model of damage of pillar and roof (after Kvapil et al, 1989); (d) Stability of rib pillars aligned on dip and strike (after Hedley et al., 1984)

Current pillar design approach-accounting for shear loading

The role of pillars in underground mines cannot be underestimated, and hence significant efforts have been made to establish reliable pillar design methods. There are number of empirical formulae which are currently used to estimate pillar strength, a summary of which can be found in Lunder, (1994) and Martin and Maybee, (2000). Maybee (2000) compared the most widely used empirical pillar formulae and found that most of them gave consistent results (Figure 3). It can be seen from the figure that the pillar strength as predicted by these graphs is non-linearly concave downward as the width to height ratio increases. This can be interpreted to mean that after a pillar width to height ratio of 2.5, no significant increase in pillar strength occurs. However, as shown by Stacey and Page (1986) there is a sharp increase in pillar strengths after a pillar width to height ratio of 4 that can be attributed to increased pillar core confinement. Hence, the empirical pillar design charts do not capture the mechanics of pillar behavior.

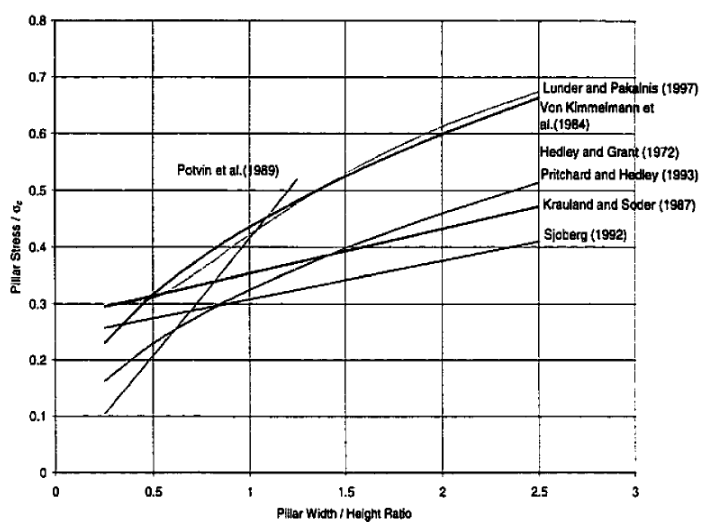


Figure 2: Combined pillar stability chart (after Maybee, 2000)

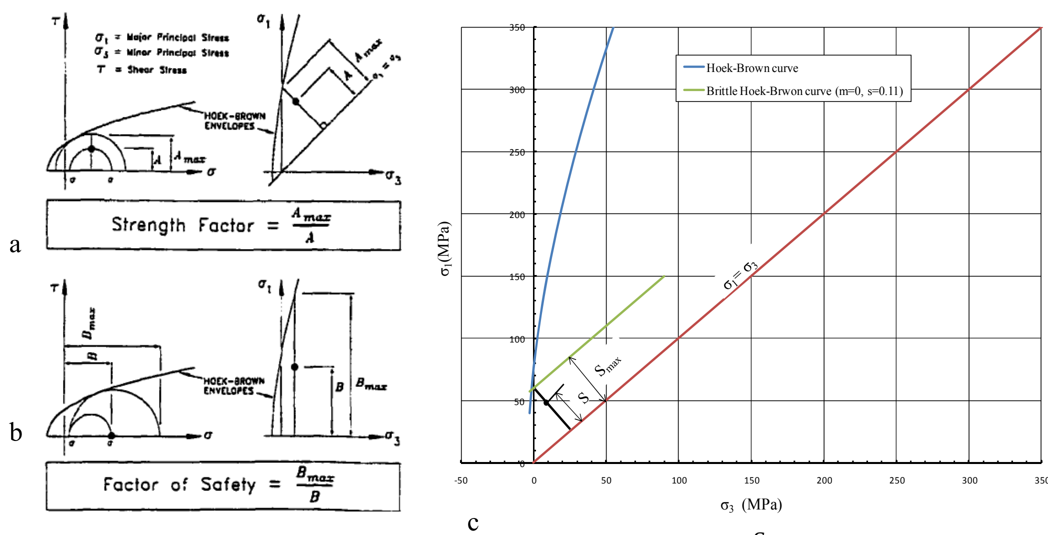
Numerical modeling of pillar failure mechanisms under shear loading

Modeling approach

Numerical methods enable stress and stability analyses to be applied to a wide range of rock engineering problems. With rapid advancements in computer technology, numerical methods have become popular and useful for solving engineering problems. Phase2 (Rocsience, 2007) finite element software was used to study failure mechanisms of orebodies under shear loading to be better understand their behavior. Failure mechanism describe the process taking place in the material in the course of loading and eventually leading to failure (Stacey, 1981). As noted by Bieniawski, (1967), this is distinct from failure criterion, which is a formula enabling the prediction of the stress level at which failure occurs.

While there are many failure criteria used to predict the stress levels at which the rock mass will fail, there are few criteria which can describe the process of failure mechanisms. The extension criterion (Stacy, 1981) and the brittle Hoek-Brown (Martin et al., 1999) are some of the failure criteria which have been observed to capture the failure processes in hard rock mines.

The empirical brittle Hoek-Brown failure criterion was selected in this paper to study the failure mechanisms of pillars under shear loading. For pillar stability analysis the factor of safety/strength factor is normally used. Figure 3 (a) and (b) show the definition of strength factor and the factor of safety. Figure 3 (c) shows the definition of strength factor as used in this paper based on brittle Hoek-Brown failure criterion.



$$\text{Strength Factor} = \frac{S_{\max}}{S}$$

Figure 3: (a) Strength factor (b) factor of Safety (McCreath and Diederichs, 1994) (c) definition of strength factor using Brittle Hoek-Brown parameters to be used in this thesis

In mining, there are different types of pillars for different functions. Depending on their geometrical arrangements, these pillars are loaded differently. This paper is mainly confined to rib pillar failure mechanisms thus justifies the use of two-dimensional modeling analysis. The ore deposit was assumed in this paper to have a thickness of 3 m.

For a geometrically uniform mining layout, the axial pillar stress is directly determined by the area extraction ratio. Thus, maintaining an extraction ratio for pillar stress determination using numerical modeling is very important in order to compare the pillars which are subjected to the same state of loading. A constant extraction ratio of 75% was assumed for sizing of rooms and pillars with the pillar width to height ratio varying from 0.5, 1, 1.5, 2 and 2.5. Figure 4 shows the layout of rooms and pillars that were implemented in Phase2.

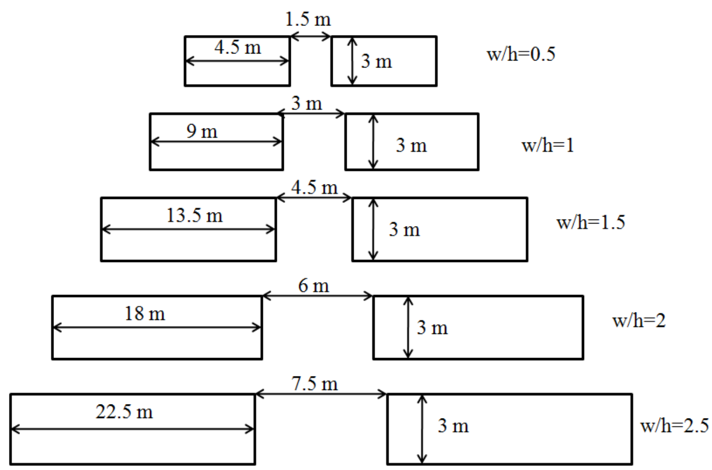


Figure 4: Room and pillar layout to achieve the extraction ratio of 75%

In order to avoid the problem of varying two parameters at the same time (i.e. k-ratio and principal stress orientation), the stope geometry was rotated while the k-ratio was kept constant. The stope geometries were rotated from 0° (i.e. base case) 10°, 15° to 40° in increments of 5° assuming that the horizontal orebodies can only be feasible to mine by room and pillar up to a maximum inclination of 40° (Titaya, 2005). A base case k-ratio of 1.5 was assumed. The rock mass properties used for modeling are those given in Martin and Maybee, (2000). Pillar loading was done by increasing or decreasing the depth below the surface. A pillar was assumed to be unstable when the strength factor was 1. In each run of the pillar model, the maximum principal stress at the core of the pillar, the confining stress and the depth at which the pillar was found to become unstable were recorded.

Model calibration

The models were first calibrated against case histories' in Lunder (1994). The ratio of maximum principal stress to minimum principal stress was set equal to 1.5. After each model run, the maximum core pillar stress was recorded. A strength factor of 1 and 1.4 meant unstable and stable pillars respectively. Pillar stability charts were generated and compared against Lunder and Pakalnis (1997) and Hedley and Grant (1972) (Figure 4). It can be seen from the figure that the model predicts very similar trends to other published data such as Martin and Maybee, (2000) and Kaiser et al.,(2000).

Pillar failure mechanisms under shear loading

There are a number of factors which govern pillar failure mechanisms. Mainly, the core pillar confinement, the strength of pillar rock mass, the mechanical behavior of the pillar-host rock and pillar end conditions. A uniaxially loaded pillar has symmetrical stress distributions across its long axis (Figure 5(a). Because of symmetrical stress distributions, these pillars have high confinements (Figure 5(c)) and energy absorption capacity. Failure of these pillars initiate in the wall propagating across the core.

An inclined pillar has combined compression and shear loading. These pillars have unsymmetrical stress distribution about the pillar axis (Figure 5 (b)). The addition of shear stress creates additional deformation to this pillar thus creating more energy liberation potential. Kvapil et al., (1989) states that when the load on a pillar changes from a uniaxial compressive load to one induced by a lateral shear force, destruction of the rock mass by bursting is visible in the upper corner of the pillar with the roof. It can be seen from

Figure 5(b) that the high stress concentration are in the opposite diagonal corners of upper footwall side and lower hanging wall side. Because of high stress concentration, rock mas fracturing initiates in these corners leading to slabbing and spalling of the pillars. Under high load the effective pillar size is reduced due to spalling of pillar walls, thus reducing confinments in the core of the pillar (Figure 5(d)). In that case, a small amount of seismic energy can create catastrophic failure, similar to what happened at Quirke and Campbell Mines.

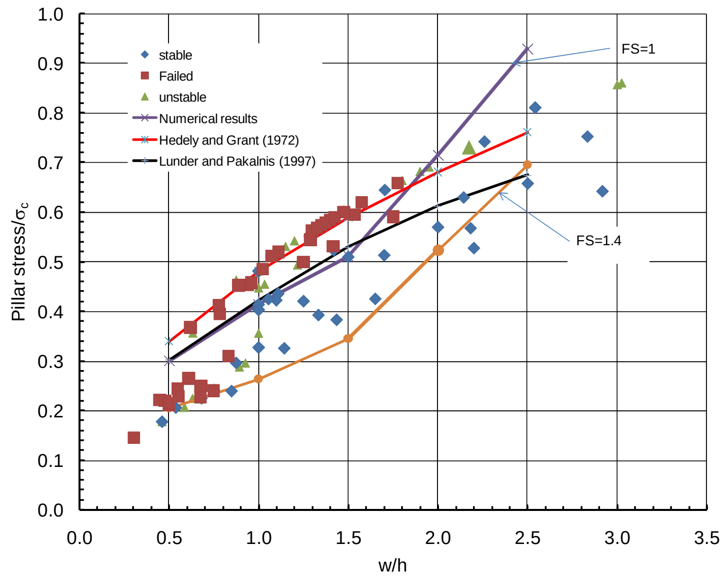


Figure 4: Model Calibration with case histories for generation of pillar stability charts

Pillar design charts

A series of elastic model was conducted to investigate the effects of principal stress inclination on the pillar stability. A combined pillar stability charts were generated for each orebody inclination and width-to-height ratio. Figure 5 (a) shows the pillar stability charts which were generated for each pillar inclination. It can be seen from the figure that the strength of pillar was increasing non-linearly in an upward curvature as the width-to height ratio increased. However, the pillar's load-carrying capacity was decreasing with an increase in orebody inclination. Based on this analysis, the minimum load carrying-capacity of pillar was found when the orebody was inclined at 40°. The effect of shear stress was pronounced after the orebody's inclination was about 15°. The pillar with w/h ratio of 0.5 and 1 was not affected by the orebody inclination. The capacity of pillars with w/h ratio >1 was highly affected by a change in orebody inclination. This explains why changing pillar geometry, which results in a change of loading mechanisms, can cause rockbursting.

Figure 6 shows a comparison of pillar stability charts plotted using brittle Hoek-Brown failure criterion for different orebody inclinations with Hedley and Grant (1972) and Lunder and Pakalnis (1997) empirical curves superimposed. It can be seen from the figure that, for orebodies dipping bewteen 0° and 15°, pillars are stronger and the empirical curves and modeled curves for pillars with width to height ratios less than 1.5 show similar trends. Beyond a width to height ratio of 1.5 there is significant difference between the modeled and empirical curves. Pillars dipping at angles greater than or equal 20° are conspicuously weaker than those at shallower dip angles, and do not show significant increases in strength with increasing pillar width to height ratios. It can be concluded that for these pillars there is no significant confinement effect on strength and explains the situation observed at Quirk Mine.

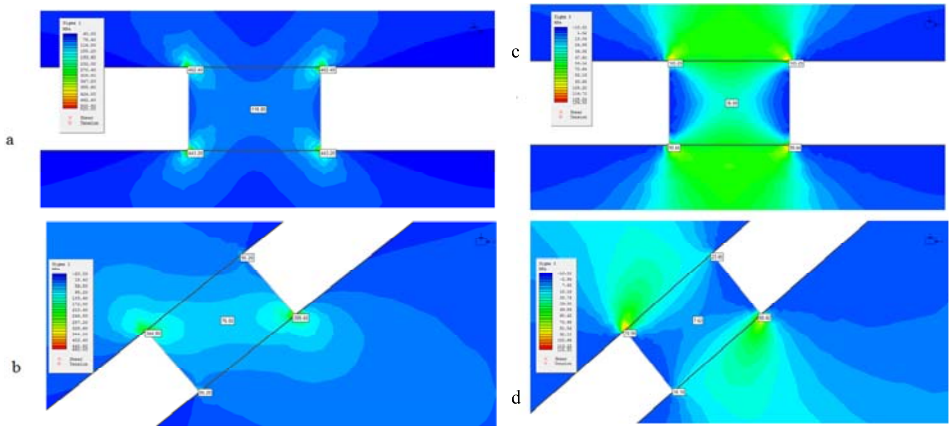


Figure 5: Contours of principal stress distributions in pillars: (a)&(c) maximum and minimum principal stresses respectively in horizontal pillar; (b)&(d) maximum and minimum principal stresses in inclined pillar respectively: 40°.

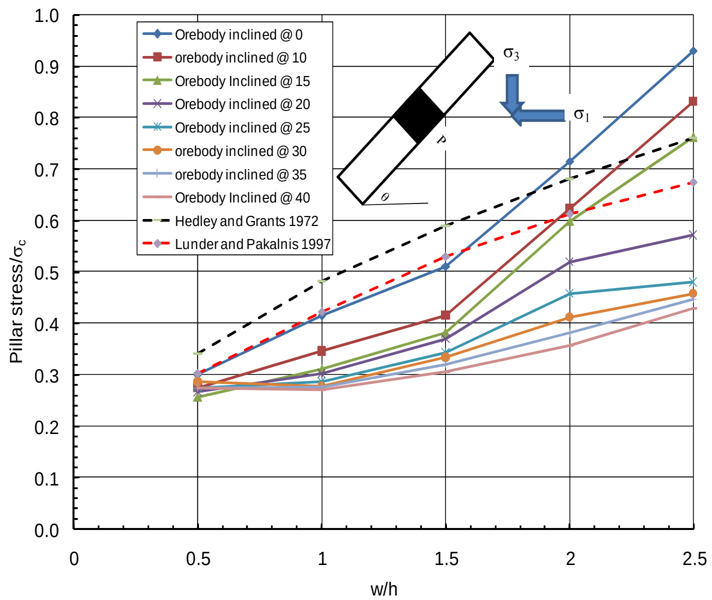


Figure 6: Comparison of pillar stability charts for different orebody inclinations (k=1.5, R=75%, FS=1)

Conclusion

Understanding the geometry of an orebody as it relates to maximum principal stress orientation is very important in pillar design. In inclined orebodies, pillars are loaded in compression and shear. Depending on principal stress orientation failure mechanisms of these pillars initiates in the upper corner of footwall side and lower corner of hanging wall in the opposite diagonal corners. The spalling resulting from these diagonal opposite corners reduces the effective pillar size in the pillar side walls, thus lowering confinements at the core of the pillar.

Empirical pillar design approach is important tools for estimating the strength of pillars. However these tools cannot properly estimate pillar strength in inclined orebodies. Application of these methods in inclined orebodies should be made with caution and that mine planning and design should take this into considerations. The pillar design chart developed in this paper can help to give guidelines on rib pillar behavior in different orebody inclination.

The conducted numerical analysis shows that the effects of orebody inclination on pillar design is more pronounced starting at an orebody inclination of 20°. For the orebodies inclined at an angle below this, the design approach can be made assuming as though they are loaded uniaxially. Wider pillars (i.e. pillars with w/h ratio>1) are most affected by orebody inclination than slender pillars.

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