CIM

Technical Paper

Rock Mechanics

▲ Determination of the strength of hard-rock mine pillars

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KEYWORDS: Rock Mechanics, Hard-rock mine pillars, Pillar strength, Underground mining.

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ABSTRACT

This paper presents the results of research that has been undertaken in order to develop an improved method of determining the strength of hard-rock mine pillars. Pillars are found in various shapes and sizes in all underground mining operations. Prudent engineering design requires that if pillars are to perform as desired, both the pillar strength and the pillar stress must be determined. A detailed pillar stability study has been combined with an extensive database of published pillar case histories (178) resulting in a new "hybrid" pillar strength formula, "The Confinement Formula", that utilizes classic strength of rock methods combined with empirical methods. "The Confinement Formula" utilizes a "mine pillar friction term" calculated from the average minor/major stress ratio within the pillar core. Statistically, the new formula provides better results at predicting pillar strength for the combined database than the best empirically fit pillar methods that currently exist. "The Confinement Formula" allows for the determination of the strength of mine pillars with an increased level of confidence over previously applied methods.

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Introduction

This paper presents a new method, "The Confinement Formula", to be used for determining the strength of hard-rock mine pillars. The method was developed through a combination of detailed research at Westmin Resources Ltd. and the assimilation with all available published hard-rock pillar case histories. The total combined database contains 178 case histories that represent pillars that are classified as stable, unstable or failed.

Traditional pillar strength formulations were reviewed and "The Confinement Formula" represents an advancement in pillar design methodology that takes into account the factors more common when dealing with the strength of rock. Empirical strength formulae developed to date have generally used the pillar width/height ratio as a primary input factor for pillar strength determination. This is in contrast to conventional strength of rock methods, whereby the primary input factors are the major and minor principal stresses on a sample. This paper presents the most common historical methods, a summary of the databases used, and the methodology used to develop "The Confinement Formula".

Historical Methods

The strength of mine pillars has been the subject of extensive research work in the past. The primary focus has been for coal mining operations, where large regular arrays of pillars are developed during the mining of coal seams. In hard-rock mining, research has been much more limited. The most notable works are that of Hedley and Grant (1972) and more recently, the work of Hudyma (1988). The limited amount of work on pillar strength determination for hard-rock mining has given an insight into pillar strength behaviour, however no methods that can be used with a high degree of confidence have been developed.

The empirical strength formulae developed to date have generally taken one of two forms: (1) the "Shape Effect Formula"; or (2) the "Size Effect Formula". Equation 1 is the general form of the equation that these strength formulae follow.

$$Ps = K \bullet [A + B * \left(\frac{w^a}{h^b}\right)] \quad \ldots\ldots\ldots\ldots\ldots (1)$$

where,

Ps = Pillar strength (Mpa)
K = Strength constant related to pillar material (Mpa)
w = Pillar width (m)
h = Pillar height (m)
A, B = Empirically derived constants which when added equal 1. In the case of the "Size Effect Formula", A is equal to 0 and B is equal to 1
a, b = Empirically derived power constants. In the case of the "Shape Effect Formula", a and b are equal

The "Shape Effect Formula" infers that for a given rock type, a pillar of a given shape (pillar width/height ratio) will have a constant strength, independent of change in size of the pillar. There are two variations of the "Shape Effect Formula". The first utilizes a linear relationship between pillar stress and pillar width/height ratio. The second utilizes a power relationship between pillar stress and pillar width/height ratio.

The "Size Effect Formula" infers that for a given rock type, a pillar of a given shape will have reduced strength as the size of the pillar increases. This formula is a modified power formula where the pillar width and the pillar height are subject to differing power terms. The use of a "Size Effect Formula" was adopted due to the belief that samples of increasing size would have a lower rock mass strength due to the increased number of structural features within a sample. It has been shown, however, that above a sample size of a side length of 1.0 m to 1.5 m, the resultant decrease in sample strength due to increasing sample size becomes negligible (Hoek and Brown, 1980).

Empirical strength methods for hard-rock pillars have been developed and can be fit to the existing pillar case histories. To some degree, this is accomplished with ease due to the limited number of case histories available, and the narrow range of pillar shapes in each database. The detailed compilation of the pillar databases presented here allows for the development of a more detailed strength formula covering a broad range of pillar shapes.

Database

This section presents the pillar databases that were used in the development of "The Confinement Formula". The databases have been analyzed both individually and as a group for this study. Five of the seven databases occur within massive sulphide orebodies and all occur within a good to very good quality rock mass. Combined, these databases represent the accumulated state of knowledge for hard-rock mine pillars. The work of Lunder (1994), Hudyma (1988), Hedley and Grant (1972), and Von Kimmelman et al. (1984) is presented in summary form below.

A research project was undertaken at Westmin Resources Ltd.'s Myra Falls Operations as a cooperative effort between Westmin Resources Ltd. and CANMET. Information was collected representing pillar geometry, pillar stability, and geological conditions. Pillar stability was classified on a five-level scale ranging from "5", failed to "1", stable. Pillar stresses were calculated using three-dimensional boundary element techniques and calibrated to existing mine conditions. The unconfined compressive strength of intact pillar material was determined to be 172 MPa. A total of 32 case histories were collected.

Hudyma (1988) presented pillar stability data collected from 13 Canadian mining operations as a M.A.Sc. thesis. Pillar geometry and a three-stage pillar stability classification were used to develop what Hudyma terms the "Pillar Stability Graph" method of designing rib pillars for open stope mines. Pillar stresses were calculated using two-dimensional fictitious force and displacement discontinuity boundary element methods. The unconfined compressive strength of intact pillar material of the pillar case histories varied between 70 and 316 MPa. There were 47 case histories.

Hedley and Grant (1972) presented a pillar strength formula based upon observation of pillar stability from the Elliot Lake mining district in Ontario, Canada. There were a total of 28 pillar case histories, of which three represented failed pillars. The pillar strength relationship was presented in the form of a "Size Effect Formula" based upon the work of Salamon and Munro (1967). The unconfined compressive strength of intact pillar material was in the range of 210-275 MPa.

Von Kimmelman et al. (1984) presented data collected from the Selbi-Phikwe Mine of BCL Ltd. located in Botswana. Pillar stress was calculated using two-dimensional displacement discontinuity methods. The unconfined compressive strength of intact pillar material was 94 MPa. There were a total of 47 case histories.

Pillar stability data of a more limited nature was used from the three following sources:

- Krauland and Soder (1987) from the Black Angel mine in Greenland;
- Sjoberg (1992) from the Zinkgruvan mine in Sweden; and
- Brady (1977) from Mt Isa Mines in Australia.

The method used to determine pillar stress can play an important role in the assessment of pillar strength. Methods vary between the relatively simple method of tributary area theory/extraction ratio method to more complex methods such as two and three dimensional modelling. The databases represented here have used all used one of these stress determination methods. While each method uses a different means of determining pillar stress, it is the authors' opinion that the resulting values are comparable. What is important is not necessarily the stress determination method used, but that the method can be calibrated the other case histories in the combined database and the fact that the method used accurately represents the pillar stresses within the mine in question.

Fig. 1. Schematic illustration of pillar stability classification method used at Westmin Resources Ltd. and the common pillar stability classification.

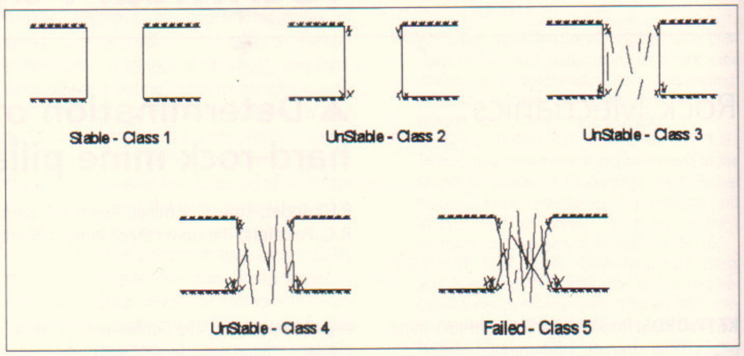

Table 1. Pillar stability classification criteria used at Westmin Resources Ltd.

Pillar stability classification	Observed pillar conditions
1	No sign of stress induced fracturing
2	Corners breaking up only
3	Fracturing in pillar walls
	Fractures <½ pillar height in length
	Fracture aperture <5 mm
4	Fracture >½ pillar height in length
	Fracture aperture >5 mm, <10 mm
5	Disintegration of pillar
	Blocks falling out
	Fracture aperture >10 mm
	Fracture through pillar core

Pillar Stability Classification

As a pillar progresses from a stable state to a failed state, there is increased visual evidence of pillar degradation. Increased jointing, blocks being released, and the need for additional ground support are all evidence of a pillar undergoing failure. A detailed stability classification method has been used at Westmin Resources with a high degree of success, to quantify the relative level of pillar instability. Each of the additional databases used similar stability classification methods.

Figure 1 is a schematic illustration of the pillar stability classification method used at Westmin Resources Ltd. Table 1 is the descriptive method used to classify pillar stability. Table 2 lists the pillar stability classifications used for each of the databases in the combined database and the "common pillar stability classification" that was applied to all of the databases. The stability level that has the greatest scope for

Table 2. Common pillar stability classification for combined database with corresponding individual database classifications

Combined database	Westmin Resources	Hudyma (1988)	Von Kimmelman et al. (1984)	Hedley and Grant (1972)
Failed	Class "5"	Failed	Class "C"	Crushed
Unstable	Class "2"-"4"	Sloughing	Class "B", "B/C"	Partially failed
Stable	Class "1"	Stable	Class "A"	Stable

Table 3. Distribution of pillar stability classifications for pillar case histories in the combined and individual databases

Pillar stability classification	Combined database	Westmin Resources	Hudyma (1988)	Von Kimmelman et al. (1984)	Hedley and Grant (1972)	Others
Failed	68	18	12	29	3	6
Unstable	52	11	9	11	2	19
Stable	58	2	26	7	23	0

interpretation is the "unstable" classification. This classification can also been referred to as the transition zone from stable condition to failed condition.

Table 3 shows the distribution of the case histories according to the "common pillar stability classification" for each of the databases that make up the combined database. There is a good distribution of pillars in the three pillar stability classes from each of the databases with the exception of Hedley and Grant (1972) which had only three failed and two unstable pillars.

Pillar Strength Determination

As shown in the previous sections, pillar strength has been assessed using empirical relationships that relate the pillar width/height ratio and a rock mass strength term. The computed strength is then compared to the predicted pillar stress in order to assess actual or predicted pillar performance. Conventional rock strength methods (Mohr-Coulomb, Hoek Brown), however, make use of the applied and confining stresses on a sample when determining sample strength. "The Confinement Formula" combines these two approaches to develop a "hybrid" strength formula that utilizes a "mine pillar friction term" and empirical strength constants. The empirical constants were determined in order to "best fit" the strength curves for the case histories in the combined database.

The method presented here, like those that have preceded it, represents pillar strength with two multiplicative terms, one representing the in-situ rock mass strength and the other that accounts for the variation of pillar strength as a result in the change in pillar shape. This is generalized by Equation 2.

$$Ps = Size \bullet Shape \quad \ldots\ldots (2)$$

where,
Ps = Pillar strength (MPa)
Size = Strength term that incorporates the "size effect" and strength of intact pillar material
Shape = Geometric term that incorporates the "shape effect" of the pillar

The development of each of the terms in "The Confinement Formula" is discussed in the following sections. The general form of "The Confinement Formula" is represented by Equation 3.

$$Ps = (K * UCS) \bullet (C_1 + C_2 * kappa) \quad \ldots\ldots (3)$$

where,
Ps = Pillar strength (Mpa)
K = Rock mass strength size factor
UCS = Unconfined compressive strength of intact pillar material (MPa)
C1, C2 = Empirically derived constants
kappa = Mine pillar friction term

Pillar Size Strength Term

The only common strength data available for the combined database were the unconfined compressive strength (UCS) of intact pillar material. It was determined that the "size term" in Equation 2 could be replaced by product of the "rock mass strength size factor", "K", and the unconfined compressive strength of intact pillar material. Detailed analysis of the individual databases was performed and the ranges of the "K" values for each of the databases was determined. These values ranged between 30% and 51%. The results of this analysis led to the definition of the average "rock mass strength size factor" to be 44% of the unconfined compressive strength of the intact pillar material.

Pillar Shape Term

The "shape term" in "The Confinement Formula" makes use of a new term to represent pillar shape called the "mine pillar friction term", kappa. Kappa is determined from what we have termed the "average pillar confinement" which is used in place of the pillar width/height ratio for the purposes of assessing "pillar shape". The "average pillar confinement" is defined as the ratio of the average minor and average major principal stresses at the mid-height of a pillar. Empirical constants have been applied to Equation 3 after a detailed analysis of the combined database. The method used to develop the "average pillar confinement" and the "mine pillar friction term" is discussed in the following sections.

Average Pillar Confinement

A means of utilizing the "average pillar confinement" in a pillar strength formula has been investigated. Numerical modelling using different rock mass failure criteria show that the mid-height of a pillar is the first point at which the factor of safety against pillar failure drops below one. A two-dimensional boundary element modelling exercise was undertaken to determine the relationship between pillar width/height ratio and the "average pillar confinement". The results of this modelling exercise showed that a relationship between pillar width/height and the "average pillar confinement" does exist. Equation 4 was found to relate pillar width/height ratio and the "average pillar confinement" with a good degree of accuracy at a modelled mining extraction ratio of 75 %.

$$Cpav = 0.46 \bullet \left[\log\left(\frac{w}{h} + 0.75\right)\right]^{\frac{1.4}{(w/h)}} \quad \ldots\ldots (4)$$

where,
Cpav = Average pillar confinement
w = Pillar width (m)
h = Pillar height (m)

The advantages of using "average pillar confinement" in the place of pillar width/height ratio for strength determination may not be immediately obvious. Where pillars are of regular rectangular or square shape, the pillar width and height can be acquired readily and will accurately represent the shape of the pillar. However, where pillars are of irregular shape, or are confined on one or two sides, the "effective" pillar dimensions are not so easy to assess, Usually a best "guess" is made on what to use for pillar width/height ratio. Using the average pillar confinement as determined from numerical modelling allows for a correct assessment of the "shape term" in pillar strength.

Mine Pillar Friction Term

"The Confinement Formula" utilizes a term that resembles the effect of increasing the friction angle of a material. This "frictional" effect of mine pillars is determined from the "average pillar confinement". For a given "average pillar confinement" value, Mohr circle diagrams can be constructed and an effective friction term determined. As the average pillar confinement (and pillar width/height ratio) increases the slope of subsequent Mohr circle plots result in what would appear to be a decreased value of the friction term. Using the complementary value of the slope gives us the "mine pillar friction term" used in "The Confinement Formula". Equation 2 is the formula for the "mine pillar friction term". Figure 2 shows the relationship between the "mine pillar friction term" and the "average pillar confinement".

$$kappa = \tan\left[\cos^{-1}\left(\frac{1 - Cpav}{1 + Cpav}\right)\right] \quad \ldots\ldots (5)$$

where,
kappa = Mine pillar friction term
Cpav = Average pillar confinement

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NEWS IN BRIEF

ZIMINE '97

Zimine'97, Zimbabwe's second mining exhibition and conference, to be held in Harare, **November 10-13, 1997**, has attracted enormous interest from international exhibitors who are eager to stake a claim to Zimbabwe's resurgent mining industry and use the exhibition as a gateway to the metals and minerals exploration boom taking place north of the country's borders.

Heading the overseas rush for exhibition space in Zimine is Britain's Department of Trade and Industry which, as part of its intensive marketing campaign for Zimbabwe, is sponsoring a U.K. Pavillion for British companies.

Likewise, in a move to assist South African companies to market their products more aggressively on the international scene, South Africa's Department of Trade and Industry has increased its sponsorship of South African companies exhibiting at Zimine. They can now receive up to R40 000 in grants, R10 000 toward the transportation costs of exhibits and, in some instances, can qualify for a 70% allowance on air fares as well as R500 per day subsistence allowance.

Zimine is endorsed and supported by Zimbabwe's Chamber of Mines, the Association of Mine Managers of Zimbabwe, the Zimbabwe Drilling Association, the Association of Mine Engineers of Zimbabwe and the Association of Mine Surveyors of Zimbabwe. A biennial event, it is held in conjunction with Zimbex, the country's highly successful trade and business exhibition which, in just four years since its launch, has doubled in size in terms of both exhibitors and visitors, and now boasts more than 500 exhibition stands.

Adding his support to Zimine is Zimbabwe's Minister of Mines, Dr. Eddison Zvobgo MP. He states: "Zimbabwe has tremendous mineral potential and is noted for its variety of metals and minerals such as gold, coal, chrome, copper, lithium, graphite, nickel, asbestos and now, platinum. The industry is growing rapidly, accounting for 45% of the country's exports and contributing approximately 9% toward the Gross Domestic Product (GDP).

Zimine '97 is organized by Exhibition Management Services of South Africa, Thomson Publications Zimbabwe and Trade Fair Investment U.K. It takes place at the Tobacco Sales Floor, Harare from November 10 to 13, 1997. For more information, contact: Exhibition Management Services; Tel.: +27 (0) 11-783-7250; Fax: +27 (0) 11-783-7260.

NEWS IN BRIEF

5TH INTERNATIONAL SYMPOSIUM ON CONTINUOUS SURFACE MINING

A call for papers is issued for the 5th International Symposium on Continuous Surface Mining which will take place in Wroclaw Poland **May 26-29, 1998**. The symposium is organized by the Institute of Mining Engineering, Technical University of Wroclaw. The previous symposia of this series were held in Edmonton, Canada, 1986; Austin, U.S.A., 1988; Prague, Czechoslovakia, 1991; and Aachen, Germany, 1995. Although the focus of this symposium is on surface mining, papers on the application of continuous systems in underground mining will also be considered. The aim is to provide an opportunity to present and discuss the state of the art and future of world-wide continuous mining. The working language of the conference is English; presentations in Polish and German will be accepted. Simultaneous translation will be provided. Exhibition facilities will be provided for firms and organizations wishing to display products, services, software and literature relating to the themes of the symposium.

Intending authors are requested to submit an abstract in English (one to two pages, double-spaced, including names, addresses, telephone numbers, fax numbers, e-mail addresses of all authors) to the conference secretariat: Continuous Surface Mining, Instytut Gornictwa, Politechniki Wroclawskiej, pl. Teatralny 2, 50-051 Wroclaw, Poland; Tel.: (71) 3438684, (71)441201; Fax: (71) 448123; e-mail: paszkows@ins.ig.pwr.wroc.pl.

The chairman of the International Advisory Board is Professor Lech Gladysiewicz.