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Stope wall convergence-based design for narrow vein orebodies

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Abstract

The major issue in mining narrow veins is the challenge of keeping dilution at acceptable levels. The definition of a narrow-vein orebody is not unique and remains controversial. The definition of a narrow-vein orebody should be both geometry and technology dependent. The width of a narrow-vein orebody and the equipment used to mine it govern how much planned and unplanned dilution is encountered in the extraction in its extraction given good ground conditions. To date, narrow vein mining stope design practices are based on overbreak predictions for dilution estimation and ground support. These practices are empirical in nature, based on experience and observations. The fundamental assumptions behind these approaches are that the overbreak is structural and stress-induced brittle failures. The stope analysis assumption is often based on rock mass elastic behavior. The brittle failure mechanism assumption is clearly reflected in the empirical methods of narrow vein open stope design such as the stability graphs. There is little experience with narrow veins mining of subvertical tabular excavations governed by stope wall closure rather than brittle failure mechanisms. This paper examined narrow vein mining stope design based on stope wall convergence in high stress conditions using numerical modelling. The results show that stope wall convergence and damage increase with depth. Higher K values and depths lead to greater displacement and decreased strength, causing significant stress damage and wall closure that can obstruct ore flow and affect blasting efficiency. Larger stopes experience less wall convergence. It's vital to consider stope width and stress conditions to control narrow vein stope wall displacement effectively foe efficient productivity.

Keywords

Narrow vein orebodies, stope wall convergence, numerical modeling, open stope design, horizontal displacement

1 Introduction

1.1 Background

Narrow vein mining involves the extraction of tabular orebodies in a single or in a complex fracture system An et al. (2018) note that narrow vein orebodies are common sources of precious minerals such as gold. For example, in China, the reserves of narrow vein orebodies account for 50% of the proven gold reserves and 90% of proven tungsten reserves respectively. It is difficult to estimate reserves in narrow-vein mines because of the complicated geology and different ore grades. Efficiency in estimation of narrow vein ore deposit sizes is further limited by operators' challenges with low stope tonnage ratios, considerable wall rock dilution, and constrained tonnages. Furthermore, large-scale automation is not a good fit for narrow-vein mining, especially for in-stope operations (Dominy et al. 1998). The concept of narrow-vein orebodies is not standardized; instead, it is impacted by regional, national, or author preferences, according to Suorineni (2010) study of the literature descriptions of these orebodies. The range of thickness that is deemed typical for an orebody with thin veins is 2 to 10 meters. According to Suorineni (2010), a narrow-vein orebody geometric properties and the technology used in mining it should both be considered in defining narrow vein, as a result an orebody with a width of less than two meters can be classified as narrow-vein. This emphasizes the significance of considering both geometric and technical considerations when classifying such orebodies in the context of mining. One of the significant issues related to narrow-vein mining is finding the balance between dilution and economic aspects of a mine.

1.2 Problem statement

Narrow vein mining is an essential practice for extracting high-value minerals from tabular orebodies; however, it presents significant technical and economic challenges. The major issue in mining narrow veins is the challenge of keeping dilution at acceptable levels. Existing stope design methodologies, such as the stability graph method (Mathews et al. 1981) and the Equivalent Linear Overbreak Slough (ELO) method (Clark & Pakalnis 1997), rely heavily on empirical approaches that were developed from databases specific to either wide or narrow ore bodies. This lack of adaptability often results in the misuse of these tools, leading to inefficient designs and operational issues in narrow vein mines, particularly at greater depths (Suorineni 2024; Feng et al. 2017). Saiang (2023) examined the stability of narrow vein mine stopes in operating mines with orebodies of widths between 0.7 m and 1.5 m dipping at 70º to 85º. This author assumed in his analysis that high walls of open stopes in underground mine stopes can be considered to behave in a similar manner to open pit slopes if stability is largely controlled by geological structures, and hence the kinematic method of analyses can be used to assess the stability of the footwall, hangingwall, roof and floor of a narrow vein open stope. Thus, current design practices frequently assume brittle rock mass behaviour and fail to account for inelastic deformation mechanisms, which become increasingly dominant in deep mining scenarios. Consequently, these methodologies are insufficient for addressing the challenges posed by wall convergence and stress-induced failure in subvertical narrow vein stopes, where stope strike lengths often significantly exceed the width stope widths. The alternative is to increase stope heights to the equivalent of stope strike lengths to meet production targets.

High stress conditions exacerbate the challenges of narrow vein mining by inducing significant wall closure and reducing stope stability. These issues are poorly addressed by empirical methods, which assume elastic rock mass responses and disregard the role of confinement and deformation in controlling stope wall behaviour (Suorineni 2010). Moreover, the lack of comprehensive, systematic guidelines for narrow vein stope design has led to reliance on trial-and-error approaches, as evidenced by studies conducted in Canada, Australia, and other regions (Dominy et al. 1998; Suorineni 2024). These deficiencies result in overbreak, underbreak, and material flow issues, reducing operational efficiency and increasing dilution and ore loss. The need for innovative, stress-sensitive design methodologies that incorporate numerical modelling and address wall convergence mechanisms is critical to advancing narrow vein mining practices and ensuring the safety and economic viability of mining operations.

2 Hypothesis

The current stope design methodologies in narrow vein mining assume elastic rock mass behaviour and brittle failure mechanisms, which inadequately address the realities of deep mining operations. In this paper it is hypothesized that in subvertical narrow vein stopes, wall closure and displacement dominate failure mechanisms rather than stress-induced brittle failures, particularly at depths where inelastic deformation becomes significant (Suorineni 2024). As stope lengths are often much greater than their widths in narrow vein stopes, the stability of these excavations is more significantly influenced by wall convergence under varying stress conditions. The work of Hoek et al. (1995) supports this conventional approach by elaborating that a critical damage index, defined as the ratio of the maximum tangential boundary stress to the unconfined compressive strength in the laboratory, surpassing a threshold of approximately 0.4—predicts the onset of brittle failure in underground openings across various rock mass types (Fig.1). Fig 1 shows that for σ_1/σ_c>0.4 the failure is excessive displacement of excavation walls. The wall failure mode is hypothesized to be the dominant failure mode at depth suggest that stope design under these conditions should be stope wall displacement based rather than stress-induced brittle and structurally controlled failure.

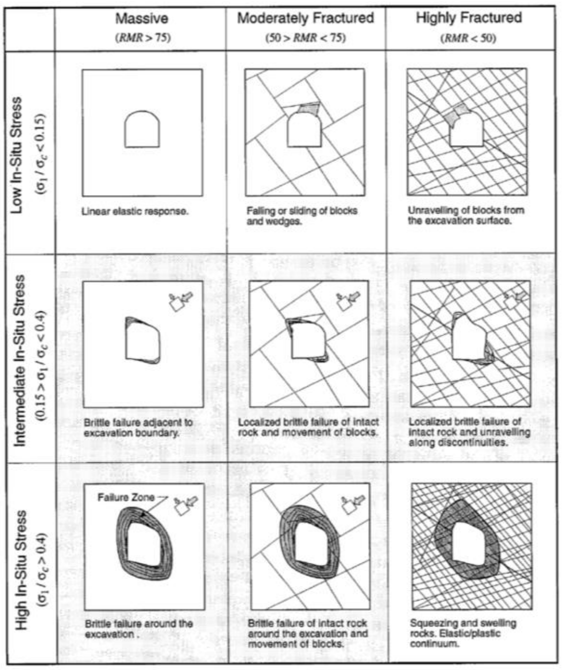

Fig. 1 Excavation instability and brittle failure as a function of RMR and the ratio of the maximum far-field stress to the unconfined compressive strength modified from Hoek et al. (1995)

This research postulates that high stress conditions, characterized by horizontal to vertical stress ratios (K_o) greater than 1, induce significant wall convergence, particularly when the major principal stress is oriented perpendicular to the stope strike. The hypothesis further suggests that stope width and the effective stress ratio critically influence wall stability, with narrower stopes exhibiting higher closure rates.

Numerical modelling is proposed as an effective approach to validate these hypotheses, emphasizing the need for stress- and geometry-sensitive design methodologies to optimize safety and operational efficiency in narrow vein mining. Furthermore, the results will confirm whether the research hypothesis is valid, and identify the dependencies between geomechanical properties, stress ratio (K_o), stope geometry, and stope wall convergence. Hypothetical schematics of the wall convergence is shown in Fig 2.

3 Methodology

3.1 Numerical modeling

Numerical modelling is a valuable tool in geomechanics, with which the engineer and scientific researcher can undertake the modelling of complex geo-processes and their interactions, which is hardly possible to be studied by sole direct observation, physical laboratory experimentations and closed form analytical solutions (Cundall and Hart 1992).

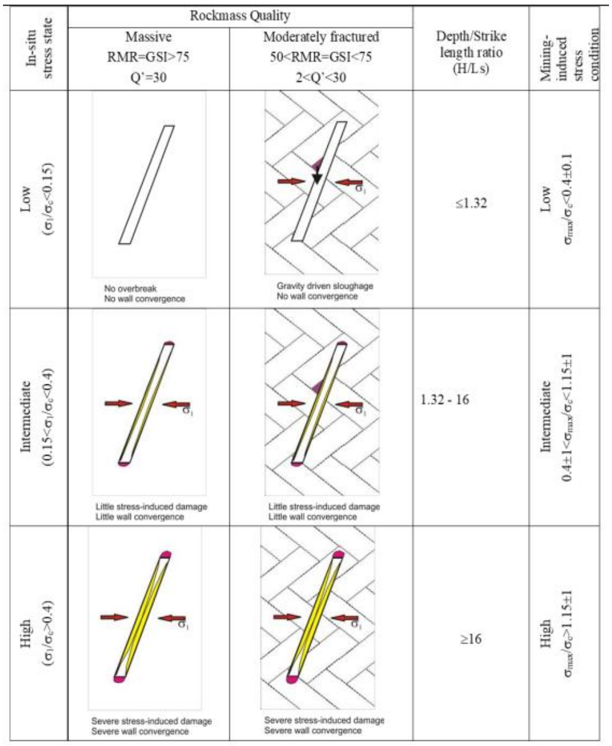

Fig. 2 Hypothetical schematic of conditions of narrow vein stope wall convergence (Suorineni 2024; modified from Hoek et al. 1995)

The Finite Element Method (FEM) employed in this study divides a continuous system into smaller, discrete components called finite elements connected at nodes. Using differential equations, it characterizes the behaviour of each element, and the total solution is obtained by adding these individual solutions. Decreasing the size of the elements improves accuracy. Modern FEM software, like RS2, optimizes the arrangement of equations for faster and more user-friendly solutions (Singh et al. 2010).

RS2, developed by Rocscience, is a powerful two-dimensional Finite Element Program for structural analysis, particularly in geotechnical applications like excavation, slope, tunnel design, and mine stability analysis. It models the mechanical behaviour of soils and rocks, allowing observation of stress, deformation, and failure distribution within geotechnical structures (Rocscience n.d.).

RS2 is chosen for modelling open stopes in narrow vein orebodies due to its reliability and accuracy in geotechnical modelling. More importantly, based on the hypothesis of the study, the narrow stope lengths far exceed the stope lengths to justify the use of 2D numerical modelling. RS2 is also user-friendly and provides easy-to-understand results. The software is also available in educational settings with vendor support.

3.2 Model input parameters

The input data for numerical modelling includes geological information (rock types), hanging wall and footwall properties, stope geometries, and in situ stress states, collected from various sources and the literature. Parameters such as rock strength, rock mass quality, and stress magnitudes will be used in numerical models to investigate stope behaviour in narrow veins. The thesis aims to advance understanding of stope failure mechanisms and contribute to safer mining practices.

The model was created in RS2 based on representative stope geometries identified in the literature and the definition of narrow vein orebodies. Following the guidelines in RS2 modelling, external boundaries, orebody geometries, and stope dimensions were constructed. This helps in establishing a realistic baseline for simulations. The model setup is shown in Fig. 3. Plastic analysis is conducted. The following different scenarios will be examined.

Simulating Different Stress Conditions: Simulation of various stress conditions, including varying the direction of the major principal stress relative to the orebody strike, will be conducted in the numerical modelling. This can help in understanding the impact of stress on stope walls convergence.

Analysing Stope Stability: Utilize the model to assess wall convergence under different conditions, focusing on the impact of stope width and different stress conditions. This involves understanding how the exposed hanging wall and footwalls react to the stress conditions as depth increases, which is central to the hypothesis of the study.

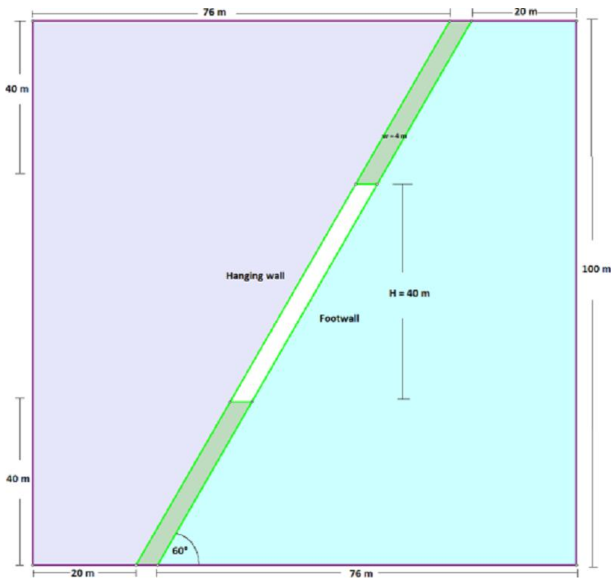

Fig. 3 Model in RS2 (Cross-section view)

As can be seen from the Figure 2, the orebody is dipping at 60°, the stope width is 4 m, and the stope height is 40 m. The mechanical properties for hanging wall, footwall, and orebody are set according to Table 1:

Table 1 Mohr-Coulomb input parameters (Abdullah et al. 2019)

Parameter	**Orebody**	**Hanging wall**	**Footwall**
Poisson's Ratio	0.26	0.25	0.18
Young's Modulus(GPa)	20	25	40
Unit weight (MN/m^3)	0.045	0.028	0.030
UCS (MPa)	90	90	172
Tensile Strength (MPa)	0.31	0.11	1.52
Cohesion (MPa)	10.2	4.8	14.1
Friction angle (°)	43	38	42
Porosity value	0.04	0.05	0.03

4 Results and Discussion

4.1 Hypothesis check

Case 1: depth = 65 m; $\frac{\sigma_1}{\sigma_c} = 0.14$:

As can be seen from the above figures, as depth of mining increases, and in-situ stress state increases, more damage, deformation can be observed. In particular wall closure becomes the dominant mode of failure as depth increases as expected.

In case 1, depth is shallow, and the ratio of principal stress to UCS of the rock is less than 0.15, which means that the rock's strength is high, we do not observe wall convergence (horizontal displacement observed is 0.001 m in hanging wall, and 0.0008 m in footwall) as shown in Figure 3, and Figure 4 illustrates that around the stope the strength factor is higher than 1, meaning stable rock conditions.

In Case 2, depth is 750 m, and a UCS of rock higher than in Case 1, but the ratio of the maximum tangential boundary stress to the laboratory unconfined compressive strength is between 0.15 and 0.4, meaning that major principal stress is higher and affects the stope in this case. Here, little stress induced damage (Figure 5 shows strength factor around the stope is between 0.32 and 0.63, and we can observe damage in hanging wall and footwall), and little convergence (Figure 6 shows horizontal displacement: in hanging wall 0.032 m, in footwall - 0.022 m).

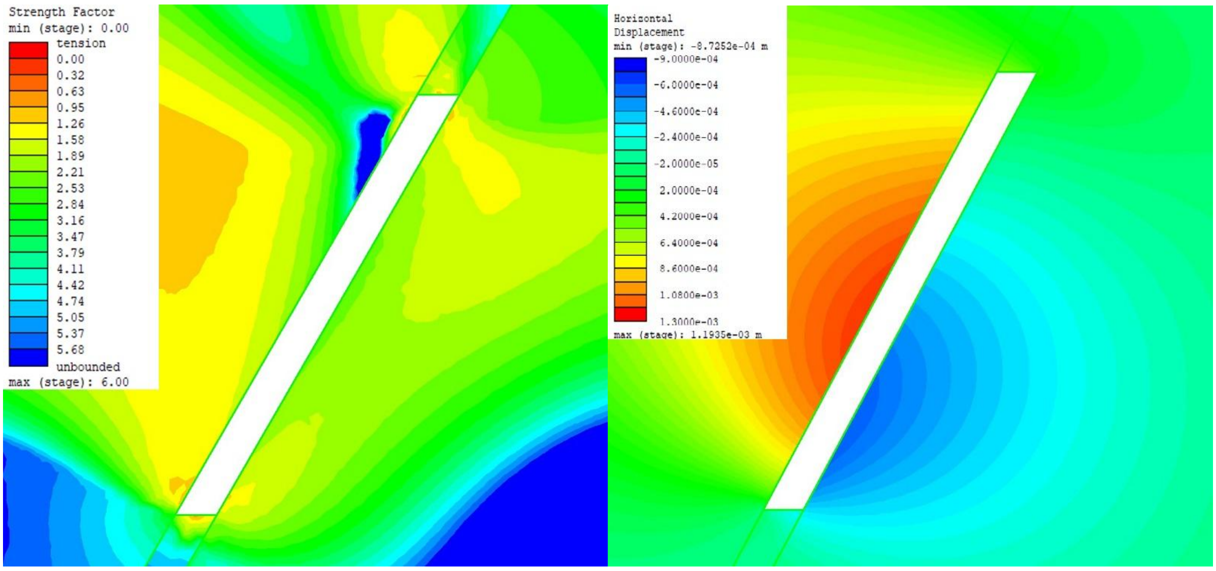

Fig. 4 Strength factor and Horizontal displacement (Case 1)

Case 2: depth = 750 m; $\frac{\sigma_1}{\sigma_c} = 0.4$:

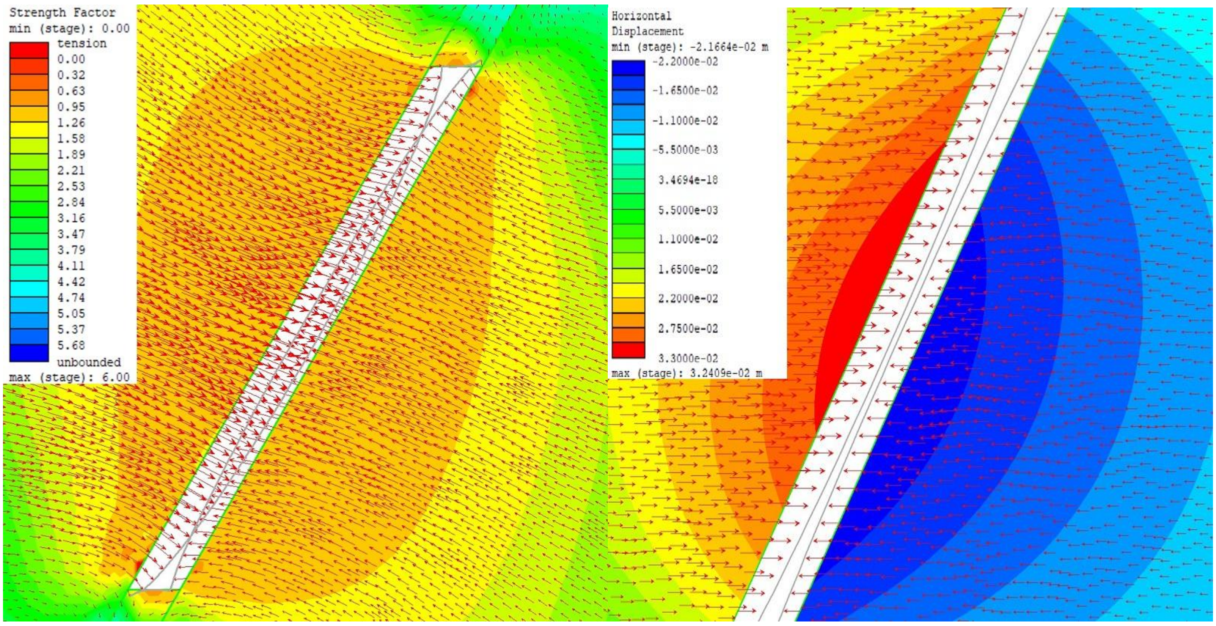

Fig. 5 Strength factor and Horizontal displacement (Case 2)

Case 3 analyzes the rock under 1500 m, where the ratio of principal stress to UCS is more than 0.4, meaning high stress concentration. Figure 7 shows severe stress induced damages around excavation in both hanging and footwall. Horizontal displacement in the hanging wall is 7.15 cm, in the footwall - 4.65 cm, meaning that walls are converging, and the deformation of walls was significant.

In summary, the results obtained from RS2 simulations show that stope wall closure becomes a more important consideration than brittle stress-induced and structurally controlled damage in narrow-vein open stope design at depths over 1000 m.

Case 3: depth = 1500 m; $\frac{\sigma_1}{\sigma_c} = 0.6$:

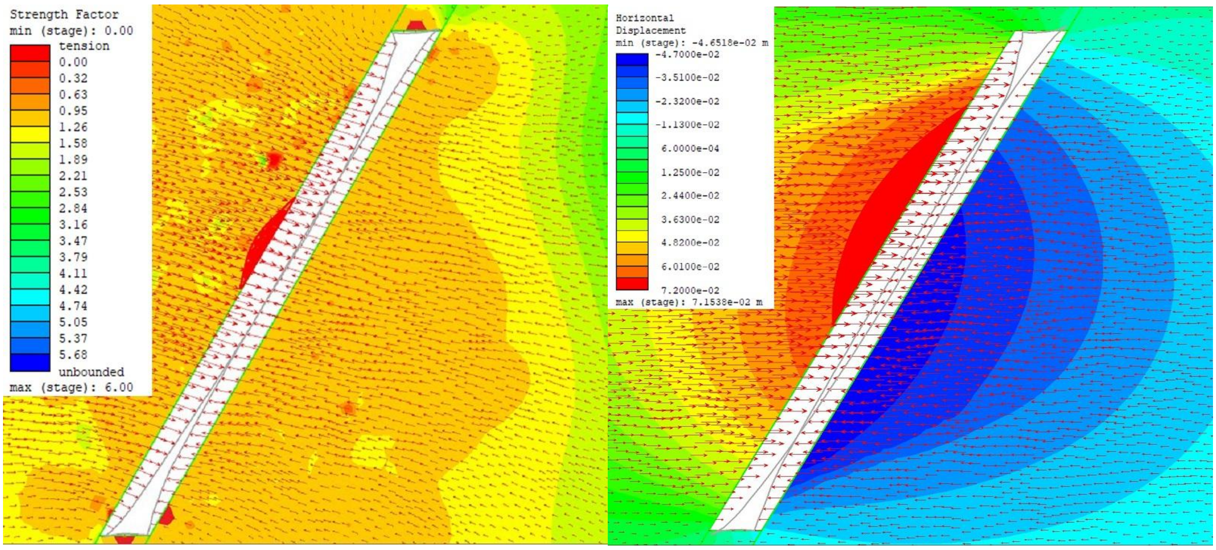

Fig. 6 Strength factor and Horizontal displacement (Case 3)

4.2 Stope width and wall closure

The impact of the stress ratio (K_o) and the width of stope on stope wall closure was analyzed. The study's main conclusions include the inverse relationship between stope width and the horizontal displacement of the hanging wall and footwall as well as the direct association between the stope walls' horizontal displacement and the stress ratio (K_o). There is a reduction in horizontal displacement of the hanging wall and footwall with increasing stope width as the wall displacements are far less compared to the stope widths. This observation confirms the issues raised in this research on the appropriate use of tools designed for wide stopes (Mathews et al., 1981) for the design of narrow vein stopes and vice versa. On the other hand, the study shows that the closure of stope walls increases with increasing K_o ratio. This effect is more noticeable in settings where the horizontal stress is much greater than the vertical stress and is parallel to the orebody. The results highlight the intricacy of geotechnical reactions in underground mining operations, where the stability and safety of excavations are largely dependent on the geometric features of the stope and the dominant stress regime, and that rocks under high stress conditions may deform in a plastic manner rather than brittle or structually controlled manner. Fig. 7 shows the relationship between stope wall closure and stope widths for various K_o. The figure shos that as width increases stope wall closures approach is a constant value for different K_o ratios.

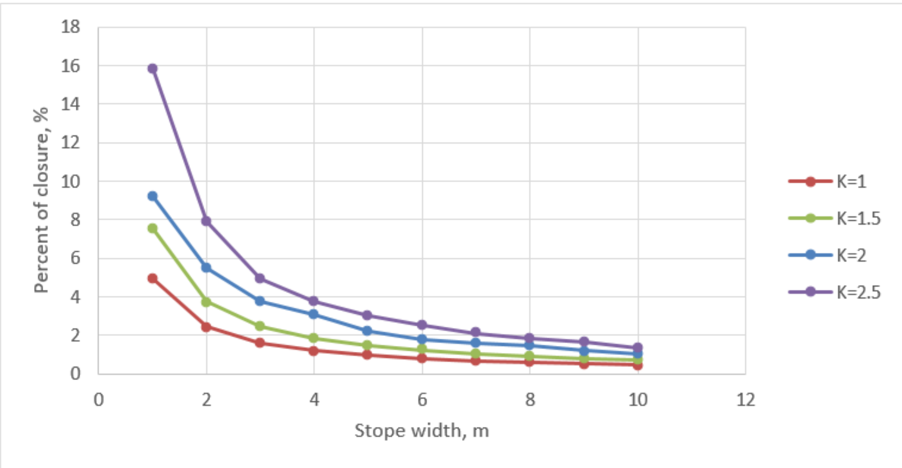

Fig. 7 Plot of percent of closure against stope width for different K-ratios

5 Conclusion and Recommendation

The main goal of this paper was to investigate stope wall convergence in narrow vein mining as a means for design of such stopes. This research used RS2 for inelastic 2D numerical modeling to simulate wall deformations under various stress conditions. The results show that deformation of stope walls increases with an increase in mining depth. At shallow depths the wall convergence is low, indicating stable mining conditions a potential brittle failure. For mining safety and efficiency, significant wall deformation caused by large stress concentrations over 1000 meters calls for increased support and monitoring. According to the study's findings, at depths larger than 1000 meters, inelastic failure, which is characterized by severe wall displacement and stress-induced damage, becomes a crucial element in forecasting the stability of narrow vein stopes. Wider stopes are shown to be less affected by wall closure. These results highlight how crucial it is to take stress conditions and stope width into account when designing narrow vein stopes.

It is recommended to increase the number of simulations up to 15 m wide open stopes and collect data from existing narrow vein mines to better understand the closure of hanging walls and footwalls to help define what a narrow really is.

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