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Stope wall convergence-based design for open stopes in 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 its extraction given good ground conditions. To date, narrow vein mining open 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. In numerical modelling it is often assumed the rockmass is elastic. 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 examines narrow vein mining open 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 in situ principal stress to vertical ratio values and depths lead to greater displacements, 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 for efficient productivity. The study has also given guidance as to what the definition of a narrow vein orebody should be.

Keywords

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

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1 Introduction

1.1 Background

Narrow vein mining involves the extraction of tabular orebodies in a single or in a complex vein 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. It is difficult to estimate reserves in narrow-vein mines because of the complicated geology and different ore grades. Efficiency in mining of narrow vein ore deposit sizes is further affected by operators' challenges with low stope tonnage ratios, considerable wall rock dilution, and blasting difficulties. Furthermore, large-scale automation is not a good fit for narrow-vein mining, especially for in-stope operations (Dominy et al. 1998). Suorineni (2010) notes that the definition of a narrow-vein orebody is not standardized, but depends on regional, national, or author preferences. The range of thicknesses that are deemed typical for an orebody to be described as a narrow vein varies from 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 its definition. Based on this, Suorineni (2010) proposed an orebody with a width of less than two meters should be classified as a narrow vein.

Narrow vein mining is an essential practice for extracting high-value minerals from tabular orebodies. However, its mining 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. 1981a) and the Equivalent Linear Overbreak Slough (ELOS) method (Figure 1b, Clark & Pakalnis 1997) are empirical approaches that were developed wide and narrow vein ore bodies, respectively. Unfortunately, these two tools are often used arbitrarily and independent of whether the orebody is wide and narrow vein orebody. This indiscriminate use 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).

The lack of comprehensive, systematic guidelines for narrow vein stope open design has led to reliance on trial-and-error approaches, as evidenced in studies conducted in Canada, Australia, and other regions (Dominy et al. 1998; Suorineni 2024).

1.2 Problem statement

The empirical methods for open stope design assume failure is structurally or stress-induced brittle failure. 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. The author assumed in his analysis that high walls of open stopes in underground mines can be considered to behave in a similar manner as open pit slopes if stability is largely controlled by geological structures. Hence, the author suggested kinematic 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, current approaches to assessing the performance of open stopes in narrow vein orebodies are insufficient for addressing the challenges posed at depth. At depth, stope wall convergence in subvertical narrow vein stopes become crucial, because stope strike lengths and heights often exceed the stope widths significantly and will converge in inelastic manner at depth to obstruct ore flow and cause blasting challenges. The increase in stope strike lengths or heights is often necessary in narrow vein open stope mining to meet production targets. The ELOS stability graph (Figure 1) database has 55% of stopes with widths less than 5 m and from an average depth of 800 m. Therefore, there is little experience in the performance of these stopes at depths greater than 800m with the lengths or heights required to meet production targets. Hence, there is need for innovative open stope design methodologies to address open stope design performance issues in narrow vein orebodies.

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. Similarly, Swan et al. (2005) define high stress as the ratio between the in-situ principal stress (1) and the mine rock intact strength (Figure 2). Based on this definition, deep mines can in low stress conditions and shallow mines in high stress conditions as shown in Figure 2.

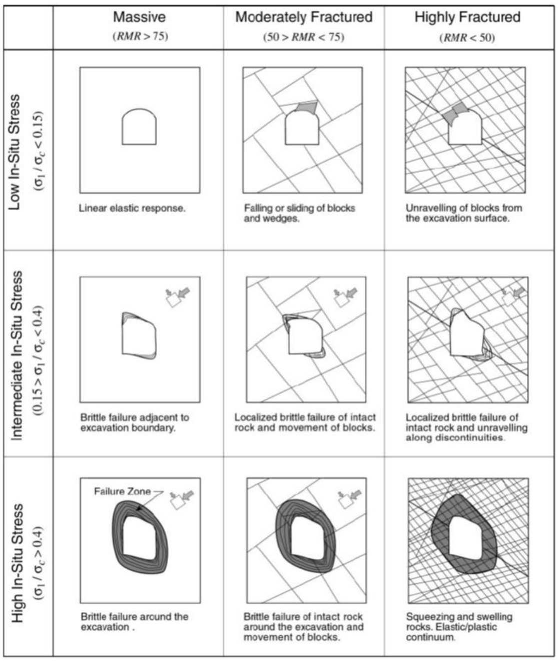


Fig. 1 Excavation instability and brittle failure as a function of RMR and the ratio of the maximum far-field stress to the unconfined compressive strength modified from Hoek et al. (1995)

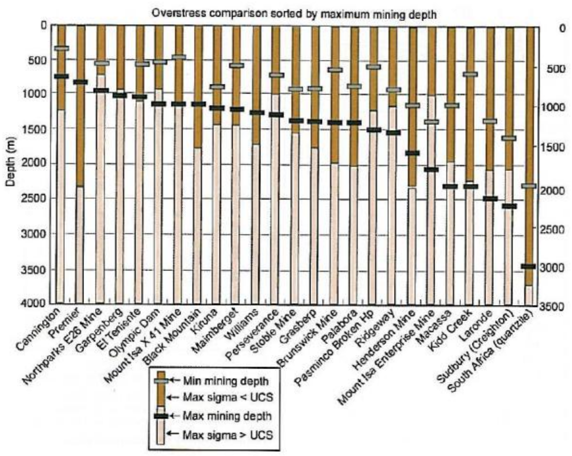


Fig. 2 Definition low and high stress as the ratio between σ_1 and rock intact compressive strength (UCS): This means deep mines can be in low stress conditions and shallow mines in high stress (Swan et al., 2005).

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 3.

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).

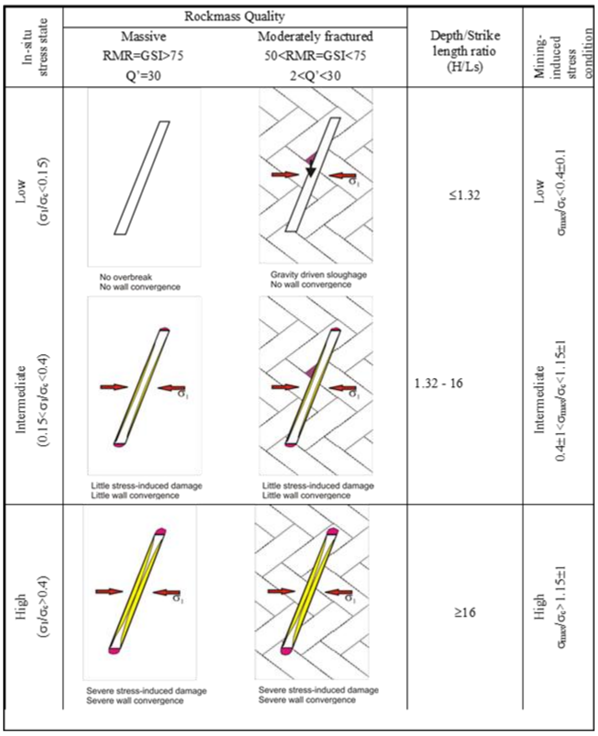


Fig. 3 Schematic of open stope wall closure with increasing depth

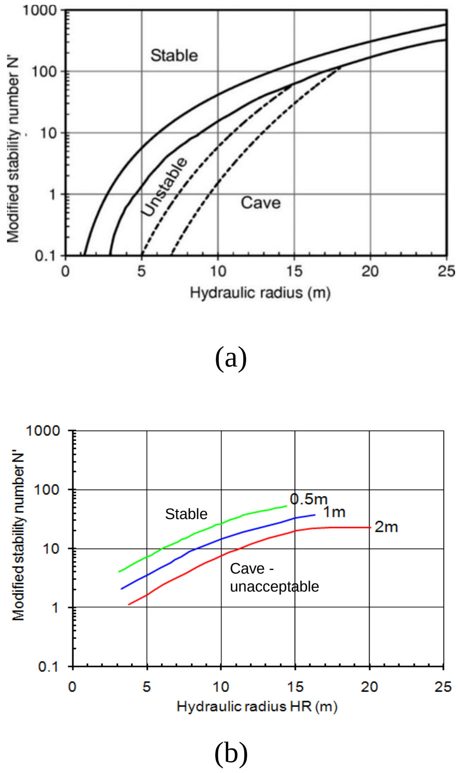


Fig. 4 Stability graphs (a) Modified stability graph (Nickson, 1992) and (b) ELOS Stability Graph (Clark and Pakalnis, 1997)

RS2 (Rocscience, 2024) is a powerful two-dimensional Finite Element Program for structural analysis, particularly in geotechnical applications such as excavation, slope and 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. This code 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 vein stope lengths far exceed the stope widths 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 setup input parameters

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. 5. As can be seen from the Figure 4, the orebody is dipping at 60°, the stope width is 4 m, and the stope height is 40 m. Three different rock types are considered in the model, namely hangingwall rock, Footwall rock and the orebody. The plastic analysis option was used since displacements are crucial in evaluating the extent of the stope wall closure. The following different scenarios are examined.

Simulating Different Stress Conditions: Simulation of various stress conditions, including varying the direction of the major principal stress relative to the orebody strike. This helped in understanding the impact of stress with increasing depth on stope wall 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.

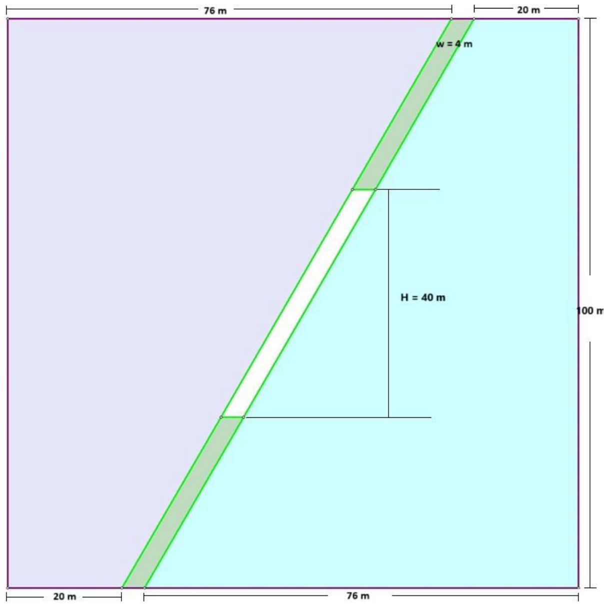


Fig. 5 Model setup in RS2 (Cross-section view)

The input data for numerical modelling includes geological information, namely: hangingwall, orebody and footwall properties; stope geometries, and in situ stress states. The data is compiled from various sources in the literature. Table 1 provides a summary of the rock properties.

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

Parameter	**Orebody**	**Hangingwall**	**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

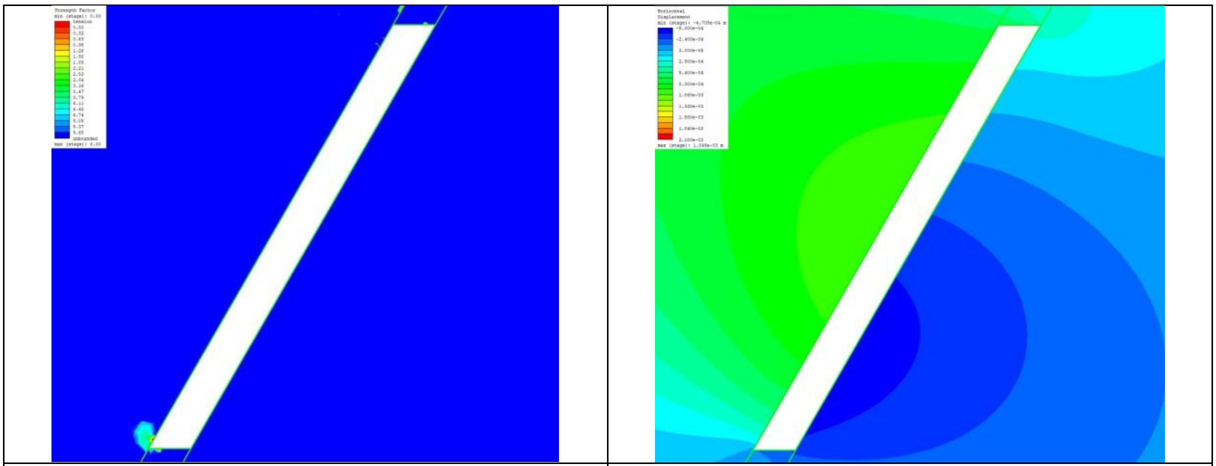
4.1 Proof of concept

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

In case 1, the depth is shallow, and the ratio of virgin principal stress (σ_1) to UCS of the rock is less than 0.15. This implies that the intact rock strength is high compared to the in situ stress. For this condition the orebody is in low stress environment acording to Hoek et al. (1995) and Swan et al. (2005) (Figures 1 and 2 respectively). In this case, there is no stope wall damage as shown in the strength factor plot in Figure 6a where the strength is greater 1, and stope wall closure is negligible, (horizontal displacement observed is 0.001 m in hanging wall, and 0.0008 m in footwall) as shown in Figure 6b. Hence, Figure 6 shows that the stope is stable rock for the assumed parameters.

In Case 2, the depth is 750 m below surface, the ratio of the maximum tangential boundary stress to the laboratory unconfined compressive strength is between 0.15 and 0.4. Figure 7 shows the strength factor around the stope is between 0.32 and 0.63 (Figure 7a), and we can observe damage in hangingwall and footwall. Figure 7b shows the horizontal displacement in the hangingwall and footwall are 0.032 m and - 0.022 m respectively and can be described as moderate.

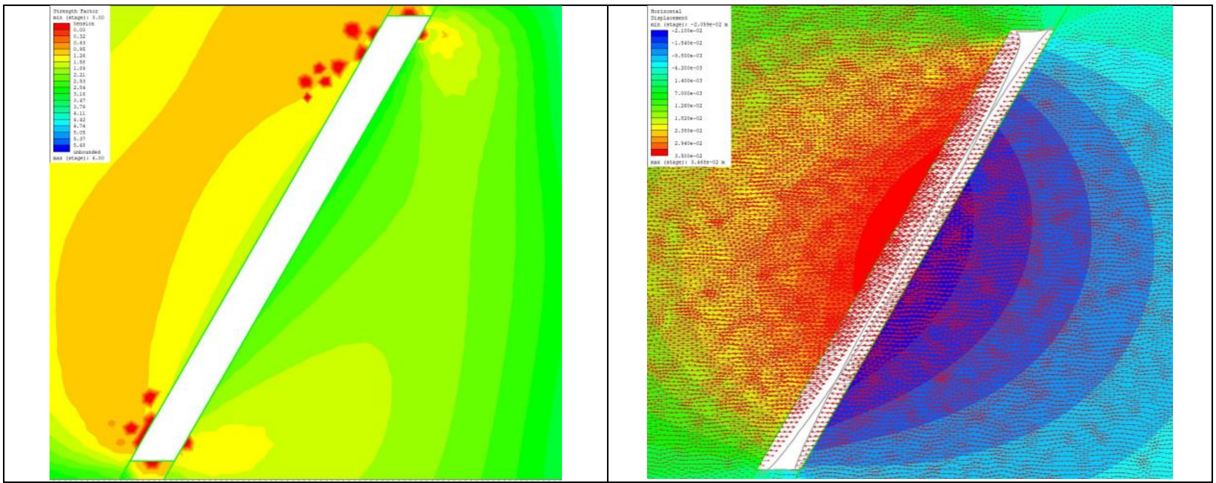
Case 3 analyzes the orebody at a depth 1500 m below ground surface, where the ratio of principal stress to UCS is 0.6, meaning high stress conditions. Figure 8a shows significant stress induced damage around the stope in both the hangingwall and footwall. The horizontal displacement in the hangingwall is 7.15 cm, and in the footwall - 4.65 cm (Figure 8b), meaning that walls are converging, and the displacemnet of stope walls are high.



(a) (b)

Fig. 6 Stope performance for Case 1: (a) Strength factor and (b) Stope wall closure - Horizontal displacement

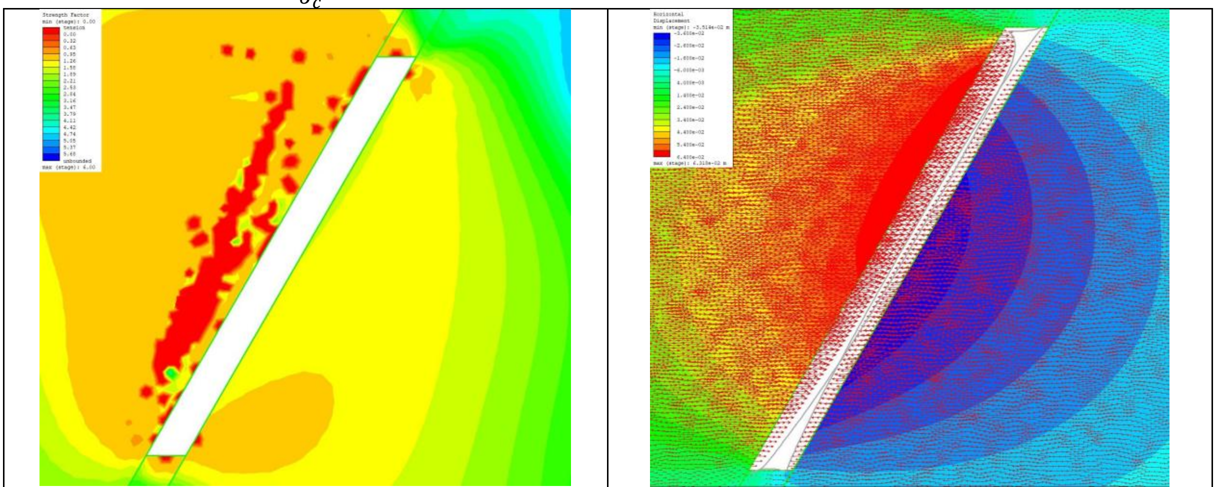
Case 2: depth = 750 m; $\frac{\sigma_1}{\sigma_c} = 0.4$:



(a) (b)

Fig. 7 Stope performance for Case 2: (a) Strength factor and (b) Stope wall closure - Horizontal displacement

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



(a) (b)

Fig. 8 Stope performance for Case 3: (a) Strength factor and (b) Stope wall closure - Horizontal displacement

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.

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. Figure 9 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.For a given K_o, stope wall closure decreases with stope size. On the otherhand, stope wall closure increases with increasing stope closure for a given stope width. These observations confirm the concerns raised in this research on the inappropriate use of tools designed for wide stopes (Mathews et al., 1981) for the design of narrow vein stopes and vice versa. Stope wall closure is more consequential in narrow stopes with didths less 3 m.

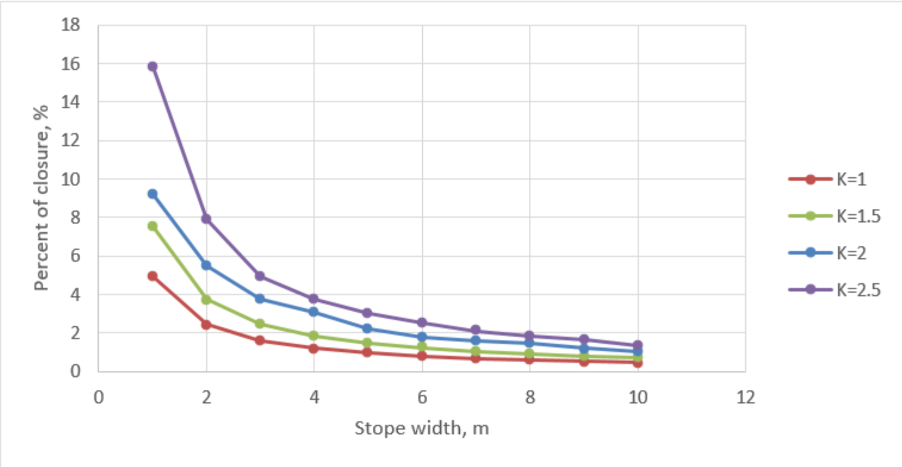


Fig. 9 Plot of percent of closure against stope width for different K_o-ratios

Figure 9 is significant for another reason. Suorineni (2010) based on literature showed that there is no consensus on the definition of narrow vein orebdies (Table 2). Based on Figure 9, the definition of a narrow vein orebody can be desciphered. From figure 9, for any given Ko-ratio, as the stope width increases the percentage stope wall closure decreases to a constant value of abot 4 m stope width independent of the K_o-ratio. For stope widths greater 4 m wall closure is not significant. Hence for orebody widths less than 4 m one is dealing with narrow orebodies, which confirms the Swiss definition of a narrow vein orebody.

Table 2. Definitions of narow vein orebody (Suorineni, 2010)

Country	Narrow vein orebody definition (Width of orebody)	Reference
Sweden	≤4m	Finkel et al. (1987, 2001)
Britain	2 – 3m	Brewis (1995a,b)
Australia	3 – 6m	Dominy et al. (1999); Dominy and Camm, 1996)
Canada	<2m	Lizotte (1993)
	<10m	Nicholas (1981)
	<5m	CANMET (1999)

5 Conclusion and Recommendation

The main goal of this paper was to investigate stope wall convergence in narrow vein mining as a means for designing open stopes in such orebodies. The results show that closure of stope walls increases with an increase in mining depth for given rock strength and K_o ratio. Fr a given Ko-ratio the closure decreases to a constant value as orebody stope width increases. At shallow depths the wall convergence is low, indicating stable mining conditions. According to the findings of study, at depths greater than 1000 meters depending on rock strength, 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. Stopes wider than 4 m stopes are less affected by wall closure.

The study is ongoing and simulations up to 20 m wide open stopes are planned.

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6 References

Abdellah, W. R., Hefni, M. A., & Ahmed, H. M. (2019). Factors Influencing Stope Hanging Wall Stability and Ore Dilution in Narrow-Vein Deposits: Part 1. Geotechnical and Geological Engineering, 38(2), 1451–1470.

Brewis, T., (1995a). Narrow vein mining, 1 – Steep veins, Mining Magaz. (1995), pp. 116–129.

Brewis, T., (1995b). Narrow vein mining: 2 – Flat-lying veins, Mining Magaz. pp. 129–133.

Canada Centre for Mineral and Energy Technology (CANMET), Narrow-vein mining project, 1999.

Cundall, P. A., & Hart, R. D. (1992). Numerical modeling of discontinua. Eng. Computations, 9(2), 101-113.

Clark, L M and Pakalnis, R C, 1997. An empirical approach for estimating unplanned dilution from open stope hangingwall sand footwalls, in Proceedings 99th Annual General Meeting, 33 p (CIM: Vancouver).

Dominy, S.C., & Camm, G.S. (1996). The nature and exploitation of narrow tin veins: A case study from South Crofty mine, Cornwall, U.K. British Mining. 57, pp. 150–170.

Dominy, S.C., Annels, A., Camm, G.S., Wheeler, P., & Barr, S.P. (1999). Geology in the resource and reserve estimation of narrow vein deposits. Explor. Geol. 6 (1999), pp. 317–333.

Feng, F., Li, D., Li, X., Guo, Z., Wang, S., & Chen, Y. (2017). Novel underhand cut-and-fill stoping method and mechanical analysis of overlying backfill. International Journal of Geomechanics, 17(7), 04017004.

Finkel, M., Olsson, M., Thorshag, H., Wernstrom, J., & Johannson, G. (2001). Narrow ore mining in Zinkgruvan, Sweden, in Underground Mining Methods – Engineering Fundamentals and International Case Studies, W.A. Hustrulid, and R.L. Bullock, eds., SME, Colorado, 2001, Chapter 23, pp. 221–227.

Finkel, M., Olsson, M., Thorshag, H., Wernstrom, J., & Johannson, G. (1987). Swedish Rock Engineering Research (SveBeFo) report on narrow ore mining in Zinkgruven, Sweden.

Hoek E. Kaiser P. K. and Bawden W. F. (1995). Support of underground excavations in hard rock. Rotterdam, Netherlands: A. A. Balkema Publishers.

Hammah, R. E., Curran, J. H., Yacoub, T. E., & Corkum, B. (2007). A comparison of finite element slope stability analysis with conventional limit-equilibrium investigation. Proceedings of the 2007 International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering.

Lizotte, Y.C., (1993). Narrow vein blasthole stoping: Current drilling and blasting technology. Project Report Submitted to the Canada Northwest Territories Mineral Development Agreement.

Mathews, K.E., Hoek, E., Wyllie, D.C., and Stewart, S.B.V., 1981. Prediction of stable excavation for mining at depths below 1000 m in hard rock. CANMET Report. DSS Serial No.OSQ80-00081, DSS File No. 17SQ. 23440-0-9020. Ottawa.

Nicholas, D.E. (1981). Method selection – A numerical approach, in Design and Operation of Caving and Sublevel Stoping Mines, D. Stewart, ed., SME-AIME, Symposium on Mine Mechanization and Automation, South African Institute of Mining and Metallurgy, New York, pp. 39–54.

RocScience. (n.d.). RS2 (Phase2 9.0) - Finite Element Analysis for Excavations and Slopes. RocScience Inc.

Suorineni, Fidelis & Kaiser, P. & Mgumbwa, Juma & Thibodeau, D., (2011). Mining of orebodies under shear loading Part 1 - Case histories. Trans. IMM, Section A: Vol 120 no 3 137.

Suorineni, FT., 2010. The stability graph after three decades in use - Experiences and the way forward. Int. Journal of Mining, Reclamation and Env. Vol. 24 (4), pp. 307-3392.