

**QUANTITATIVE ASSESSMENT OF IN-SITU
STRESS IMPACTS ON ROCK MASS
CAVABILITY IN BLOCK CAVING MINES**

by

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Thesis submitted to the School of Mining and Geosciences of
Nazarbayev University in Partial Fulfillment of the Requirements for the
Degree of

Bachelor of Science in Mining Engineering

Nazarbayev University

1st April 2025

ORIGINALITY STATEMENT

I, Molshylyk Almakhan, hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at Nazarbayev University or any other educational institution, except where due acknowledgement is made in the thesis.

Any contribution made to the research by others, with whom I have worked at NU or elsewhere is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.

Signed on 15.04.2025

ABSTRACT

Block caving is a large-scale mining method that has been favored due to its ability to achieve high productivity and low operating costs. Especially in recent years, when more low-grade and large ore bodies are discovered, and its extraction is only economically feasible under the low-cost extraction method.

Rock mass caving ability—the capacity of rock to propagate vertical failures—is primarily influenced by lithology, rock mass properties, and the hydraulic radius of the undercut level. However, recent studies on the effects of in-situ stress fields have presented conflicting views on the significance of stress evaluation in caving behavior.

This study investigates the influence of in-situ stress fields using an advanced numerical modeling technique based on the finite element method (FEM). A model built on a real-world mine example was used to analyze the influence of the in-situ stress fields and stress ratios on the cavability of the block. Cave propagation and ore body failure mechanisms were examined under a broad range of varying stress conditions.

Three distinct in-situ stress ratio (k) domains were identified, each exhibiting significantly different caving behaviors in terms of yielded rock and caved material. Additionally, stress redistribution patterns were analyzed with a focus on workplace stability, and recommendations for improving operational efficiency were provided.

DEDICATION

I dedicate this dissertation to the mining engineering community and the many experienced mining engineers from my hometown, especially my mother, her friends and colleagues whose discussions about mine and plant work from an early age sparked my interest in this field.

I also express my deep gratitude to the professors of our university, especially Dr. Ali Mortazavi for his guidance, patience, and invaluable advices, which helped me a lot throughout this research. I am also deeply thankful to Dr. Fidelis Suorineni for sparking my interest in this field and for providing the necessary materials that contributed to this work.

In addition, I thank my classmates from my department for the healthy competition and friendly atmosphere that provided motivation and desire to learn throughout my years of study at the university.

ACKNOWLEDGMENT

I express my sincere gratitude to Nazarbayev University for providing the necessary technology and access to numerous software programs essential for conducting this study.

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1. INTRODUCTION

1.1 Background/Problem Definition

In addition to the numerous advantages of the Block caving mining systems in terms of operating costs and production rates, it requires precise geotechnical investigations and ongoing monitoring of the cave, given the complexity of its caving mechanism. Method primarily depends on the ability of the ore body to propagate vertical failures which will be addressed as "cavability". This propagation results either from structural failures under gravity (tensile failure) or from stress-induced conditions, where the rock mass is subjected to a stress greater than its own strength (Liu et al., 2022). Which primarily depends on the stress distribution at close proximity to the ore body.

Numerous approaches for assessing caving behavior have been proposed since the first use of block caving in 1895 (Alipenhani et al., 2023). The prediction of the rock mass cavability is achieved by implementing empirical and numerical methods. The most popular empirical method for predicting caving behavior is the Laubscher stability graph, which uses the hydraulic radius of the undercut roof and the characteristics of the rock mass. Stability graphs developed based on the statistical distribution of the data collected from mine sites. Stability graphs are developed using statistical distributions derived from data collected at mine sites. Although some authors (Alipenhani et al., 2022; Saadat et al., 2024; Suzuki Morales et al., 2024; Rafiee et al., 2018; Suorineni, 2014) have raised concerns about the reliability of the input data and the assumptions underlying these graphs, they remain a useful tool - particularly during initial feasibility studies for providing a preliminary approximation of cavability. However, since empirical methods do not offer estimates of caving rates or the stability of operational levels, numerical modeling techniques are generally preferred in the later stages of mine planning due to their enhanced accuracy and predictive capabilities.

Numerical methods are considerably more reliable and can take into account many influential parameters (e.g., major faults, joint locations, and stress redistribution) thanks to the availability of sophisticated computer codes. However, other problems are the lack of reliable data from mine sites for construction of model and the sensitivity of the model to a variety of inputs, which can lead to incorrect results and incorrect predictions in case of minimal input error. To successfully simulate failure propagation, a representative model should be built that

takes into account the most influential input parameters to obtain the target result, rather than trying to recreate reality (Suzuki Morales, 2024).

Caving remains a complex and not fully understood process, as highlighted by operational challenges such as rapid hang-up rates at drawbells and mudrushes at the Cadia East mine (Castro and Cuello, 2018), the air blast incident at the E48 block, and extraction level damage at the E26 panels of the Northparkes mine (Shyman and Webster, 2022). These and other incidents underscore a lack of awareness, particularly in accurately assessing failure propagation mechanisms. Although numerous studies have examined cavability prediction (Alipenhali et al., 2023; Rafiee et al., 2018; Rafiee et al., 2016; Somehneshin et al., 2015), their findings often diverge, especially regarding the influence of in-situ stress conditions on caving behavior. A comprehensive overview of these differing perspectives is presented in the literature review. Complicating matters further is the high cost and significant uncertainty ($\pm 15\text{--}30\%$) associated with measuring in-situ stress (Suzuki Morales, 2024), which limits the ability to investigate its effects accurately. In light of these challenges, the present study aims to develop a mine model to assess the impact of in-situ stress on rock mass cavability more reliably.

1.2 Objectives of the Thesis

1.2.1 Main Objectives

The aim of this thesis is to systematically evaluate the impact of varying in-situ stress fields on the volume of the collapse zone and the progression of cave propagation, with the goal of enhancing the accuracy and reliability of modeling and prediction methods used in block caving operations.

1.2.2 Specific Objectives

- 1. Conduct a thorough review of existing research on the topic:** Conduct a study of existing research papers to gain an in-depth understanding of the topic and synthesize findings from recent research on the issue.
- 2. Use real-world data to enhance the accuracy of simulations and models:** Build a representative model using input variables and mine dimensions from an existing mine and gather geological observational data from technical reports and other reliable sources.

- 3. Analyze case study data to obtain relevant rock mass strength parameters:** As we use the Hoek-Brown failure criterion in the simulation, we must derive rock mass parameters from the reported data on intact rock and discontinuities within the rock mass. This can be achieved using RSData software.
- 4. Utilize numerical modeling to assess rock mass cavability under varying in-situ stress environments:** A 2D numerical modeling technique will be employed, as it offers a balance between computational efficiency and accuracy, making it suitable for simulating caving behavior across different stress conditions.
- 5. Interpret and analyze the results from simulations:** To derive the sensitivity of the caving rate to the in situ stress and evaluate how varying stress conditions influence rock mass fragmentation and failure zone.
- 6. Provide recommendations for further studies:** To propose future research directions that build on the findings of this study, with a focus on enhancing numerical modeling approaches and exploring additional stress-related factors influencing cavability.

1.3 Hypotheses

This thesis hypothesizes that in-situ stress conditions have a significant impact on rock mass cavability, influencing both the initiation and extent of cave propagation. It is expected that variations in stress fields will alter caving behavior, which can be effectively assessed through numerical modeling.

1.4 Justification of the R&D

In-situ stress parameters significantly affect the failure mechanisms that govern cave propagation. However, existing studies on prediction of cavability lack a specific assessment of the impact of these parameters. In addition, most simulations are conducted without considering site-specific geological characteristics, which limits their accuracy and applicability.

A major constraint in this field is the lack of geological parameters derived from field data that can be used in numerical modeling (Suzuki Morales, 2024). Therefore, the rationale

for this study is to address a significant knowledge gap in the field. This study aims to address this gap by integrating real geological data with numerical modeling.

By improving the understanding and modeling of in-situ stress parameters, this study will improve the prediction of rock mass behavior under excavation-induced stress. The incorporation of both empirical and numerical methods will contribute to improving mining safety by reducing the risks associated with cave roof collapse and unexpected ground failures. In addition, accurate stress modeling will lead to improved caving predictions, optimized production schedules, and resource extraction efficiency.

1.5 Scope of Work

This paper evaluates the effect of in-situ stress ratios on the cavability of underground block cave mines. The scope includes data collection from various reports on the Red Chris block cave mine to determine key parameters such as mining depth, undercut dimensions, major surface structures, and applicable geological settings as input parameters for numerical simulations. Additionally, the research involves the derivation of input parameters for rock mass characterization using geological data, including laboratory reports on intact rock properties and discontinuities. These parameters will be used in modeling and 2D numerical simulations to assess changes in cave propagation height under different in-situ stress conditions. Although the model is based on geological and geotechnical data from the Red Chris mine, major geological structures such as faults were excluded due to their strong influence on post-excavation stress field distributions. This decision was made to enhance the reliability of input parameters and the interpretability of results. The primary objective of the modeling is to observe general trends in caving behavior under varying stress conditions, rather than to produce highly case-specific outcomes. In addition, findings from existing studies in this field will be compared to validate the results and ensure the reliability of the analysis.

2. LITERATURE REVIEW

Caving relies on the natural unraveling of rock masses following undercut excavation, a process primarily governed by the structural characteristics of the rock mass and the surrounding stress field. The distribution and magnitude of in-situ stresses play a critical role in defining the extent and behavior of the caving zone, directly influencing both its volume and

fragmentation characteristics. Developing a comprehensive understanding of rock mass caving behavior is essential—not only for optimizing production planning but also for anticipating potential hazards and improving safety outcomes.

This review will examine case studies from major block caving operations to gain insights into industry practices and the operational challenges commonly encountered during caving. Additionally, studies focused on cavability assessment employing numerical modeling will be reviewed to explore effective modeling approaches and identify key parameters that require careful consideration. Ultimately, this literature review seeks to synthesize existing research on caving prediction, evaluate methodologies for estimating caving rates, and highlight research gaps that warrant further investigation.

2.1 Numerical Approaches to Caving and Fragmentation

The application of the finite element method (FEM) model was guided by a comprehensive review of previous studies (e.g., Alipenhani et al., 2020; Alipenhani et al., 2023; Vyazmensky et al., 2009), which support the method’s reliability in evaluating stress distribution and deformation scales. In contrast, several other studies (e.g., Ivars et al., 2011; Rafiee et al., 2018) employed the discrete element method (DEM), which explicitly incorporates fractures—such as joints and faults—based on field-mapped data or statistical distributions. DEM is particularly effective in capturing complex behaviors such as strain localization, bulking, dilation, and collapse—phenomena that are challenging to model using purely continuum-based approaches. Based on this comparison, FEM was selected for the current study. Furthermore, Alipenhani et al. (2023) also addressed the selection of appropriate failure criteria for simulating rock mass failure in two-dimensional FEM analyses. Additionally, the study introduced the use of RockData software, which derives rock mass properties from intact rock characteristics, fracture sets, and lithological data. These properties were subsequently integrated into the FEM model to enhance simulation accuracy.

2.1.1 Rock Mass Deformation and Caving Limits

The study by Alipenhani et al. (2022) focuses on comparing simulation results with empirical charts for predicting caving propagation. The modeling approach involved a step-by-step simulation of undercut extraction, during which cave height progression was monitored. The model incorporated the Mining Rock Mass Rating (MRMR) system and other lithological

properties of the rock mass. These parameters were also used to estimate caving height based on Laubscher's empirical chart, allowing for a direct comparison between numerical and empirical predictions.

The following elements are addressed in the methodology section of the model construction in research done by Alipenhani et al. (2022):

Calculation of Caving Height and Failure Criteria: Caving mechanics are typically characterized by a progression from caved rock to deformed rock, and finally to undisturbed rock, moving from the bottom upward. To accurately reflect this behavior, the model must incorporate elasto-plastic material properties, ensuring that the cohesion of the rock mass decreases upon failure. The authors highlight the inaccuracy of assuming vertical-only caving behavior, noting that such simplification can lead to misleading results. In their approach, the caved rock mass is defined as material that has undergone a total displacement exceeding 1 meter which was originally applied in the study by Sainsbury et al., (2012). Methodology outlines important steps for building a reliable model, such as setting appropriate boundary conditions and ensuring accurate mesh density. The paper presents a sensitivity analysis to undercut span and caving height, and provides an example of accurate failure criteria and input parameters used in practice. The results of the FEM models are compared with traditional empirical methods, such as the Laubscher failure table and the cave propagation factor (CPF). This comparison helps us to understand the differences between these approaches.

Geological Parameters: The authors incorporated the derivation of rock mass parameters using RSData, a specialized software tool that utilizes lithological characteristics and intact rock properties to compute strength parameters of the rock mass. This approach is presented as an optimal alternative to manual calculation methods

In addition, the paper reviews previous research done by the Basson et al., (2016) Duplancic et al., (1999) on failure analysis, provides a guide to useful references, and points out potential problems in existing methods. Overall, paper provided a clear framework for understanding and interpreting FEM results when analyzing how in-situ stress fields influence the failure propagation height.

2.1.2 Model-Based Analysis of Factors Affecting Caving

Rafiee et al., (2018) carried out the numerical simulation of rock mass caving in block caving operations using PFC3D software. The authors evaluate the influence of various parameters on the cavability of rock mass by assessing the impact of factors such as uniaxial compressive strength (UCS), joint orientation, joint persistence, joint density, confined stress, hydraulic radius, and friction angle on the rock's ability to fragment and collapse. The study specifically investigates how these factors influence cave initiation, propagation, and continuous caving.

Key findings highlight that the hydraulic radius and in-situ stresses have the highest impact on rock cavability. An increase in confined stress leads to a sharp decrease in the amount of ore extracted, while larger hydraulic radii significantly increase the efficiency of ore extraction. The results demonstrate that confined stresses can stabilize the rock mass and prevent cave propagation, while hydraulic radius influences the volume of caved material.

For our research on block caving, this paper offers valuable insights into the key parameters affecting rock fragmentation and provides a unique method to assess cavability through numerical simulations. This study will influence the development of our own model, which aims to simulate cavability in different depths.

Another research done by Alipenhani et al., (2023) focused on the influencing factors of cavability. It provides a comprehensive analysis of previous methods used to evaluate block cavability. Authors underline the use of the Mohr-Coulomb elastic failure criterion within the discrete element method (DEM), as cavability is significantly influenced by rock mass discontinuities. The primary indicator of caving considered was the Minimum Required Caving Span (MRCS) and its dependence on variables such as joint orientation, joint spacing, and others.

Alipenhani et al. (2023), in addition to evaluating influential parameters, highlighted the following key points:

- 3D modeling, while accurate, is computationally challenging due to the complexity introduced by numerous geological inputs. In contrast, 2D modeling is presented as a more

practical alternative, allowing for repeated simulations with varying input parameters and facilitating sensitivity analysis.

- Limitations of empirical methods, particularly the stability graphs developed by Laubscher and Mathews, due to incorrect assumptions that affected their results. Additionally, it references prior studies employing numerical methods to identify critical findings and points out gaps that require further investigation.

Building on this, our research aims to evaluate cavability on a broader scale, such as real-life mine dimensions, while focusing on the influence of stress ratio on cavability itself. Additionally, the insights gained from the 2D modeling implemented in this paper offer valuable guidance for developing our approach.

2.1.3 Influence of In-Situ Stress Field

Saadat et al. (2024) investigated how the stress field influences the cracking and collapse processes during continuous coal mining, specifically focusing on the overburden response as excavation progresses. While the study is centered on longwall mining and does not directly address block caving, it offers valuable insights into the role of stress redistribution in rock mass failure.

The research demonstrates how numerical simulations can capture the progressive fracturing of rock masses under stress, highlighting the formation of stress concentration zones that lead to large-scale fractures. It emphasizes that accurate modeling of stress redistribution is crucial for understanding rock mass behavior and predicting failure progression. These findings align with our work on block caving, where similar stress redistribution plays a key role in cave dynamics.

The study by Alipenhani et al., (2023) also evaluated the effect of the in-situ stress ratio on MRCS, finding a correlation. However, the results suggested that the stress ratio's influence on MRCS was negligible compared to other factors. This finding contrasts with previous research, such as that of Rafiei et al. (2018), raising a conflicting perspective on the subject. As highlighted in the review by Suzuki et al. (2023), results vary significantly due to the use of different methodologies and the subjective interpretations of various authors. This

underscores the lack of a standardized approach for conducting and interpreting numerical simulations in caving studies.

2.1.4 Interaction between Open Pit and Block Cave

The paper by Vyazmensky et al. (2009) investigates the interaction between block caving operations and open-pit slope stability. The method to simulate the interaction is carried out using a 2D hybrid finite element/discrete element (FEM/DEM) approach. Study simulates the upper level (Lift 1) block of the Palabora mine, where the failure of the crown pillar and pit slope took place due to the progressive caving of the block and the interaction of structural discontinuities and lithologies. The rock mass parameters were taken from case studies and appropriately implemented into the model with a sufficient degree of approximation. As a result, the model successfully replicated observed failure zones, demonstrating its capability to predict potential hazards in similar operations. The authors highlighted the importance of detailed structural inputs and validated numerical methods for understanding and mitigating risks during the transition from open-pit to block caving operations.

Study illustrates the process of inputting structural features into the numerical model, providing a clear example of the factors to consider and how to use them correctly. This report will be used to accurately derive input parameters for rock masses in 2D RS2 modeling and to inform the methodology of my study. It serves as a reference for implementing detailed structural data and validating the approach to better understand the effects of in-situ stress fields on caving propagation.

2.2 Case Studies

Stegman et al. (2018) provided an overview of key events spanning decades of block cave operations at Rio Tinto, examining research focused on the causes of key issues encountered during operations at Northparkes (E26 Lift 1 and 2; E48 Lift 1), Palabora and Argyle block cave mines. It also identifies five key lessons that should be applied to the Oyu Tolgoi block cave mine, which was undergoing feasibility study at the time.

The key issues include production rate stability issues, slow or erratic caving rates and dilution, also known as ‘throw-in’, caused by excessive cave extension and increased

seismicity. While the authors note that Rio Tinto has considerable experience in dealing with these issues when they are encountered, they emphasize the importance of addressing such risks at the planning stage as the most effective approach.

Overall, the study provides valuable insights into the broader understanding of the block caving industry. In particular, it provides background information and highlights knowledge gaps that need to be addressed to overcome the challenges encountered in the past. The conclusion highlights the need for further research in areas such as the interaction between field geological data and the stress field response to caving. It is mentioned that this knowledge is critical to successfully forecasting, planning and achieving mining strategy objectives, including production and processing rates.

2.2.1 Stress Redistribution and rapid Hang-Ups in PC2, Cadia Mines

In the context of block caving and underground mining, hang-ups refer to the accumulation of coarse or oversized rock fragments that become lodged in drawbells, obstructing material flow. These hang-ups often occur due to the interlocking of angular rock fragments, which prevents smooth gravitational flow of broken material. Castro and Cuello (2018) investigated the factors contributing to hang-up rates (HUR) at the drawbells of Cadia East, focusing on variables such as rock mass properties, lithology, and recovery rates. Their comparative model indicated that these geological and operational factors had only a minor influence on HUR, as the differences between the two panels, PC1 and PC2, were relatively small in terms of rock mass quality, lithology, and recovery performance.

Importantly, Castro and Cuello (2018) highlighted how a redistributed stress field between adjacent blocks can significantly influence ore recovery efficiency. Following the extraction of panel PC1, stress redistribution likely resulted in increased confining pressure in PC2. This elevated stress may have impeded the caving process and contributed to a higher frequency of hang-ups. Since hang-up rates are closely linked to rock fragmentation—governed by the size, shape, and breakability of rock fragments—a plausible hypothesis is that in-situ stress conditions directly affect both fragmentation behavior and ore extraction efficiency. In other words, changes in the stress field not only influence how the rock mass breaks apart but also affect the likelihood of fragment interlocking and the overall flow of the caved orebody.

2.2.2 Case Studies from Northparkes Mine Operations

Rockburst Hazards in Relation to Cave Propagation:

In recent years, the incidence of rock bursts in block caving operations has increased, primarily due to elevated in-situ stress levels associated with deeper mining. A key insight from Liu et al. (2022) is the critical role of caving rate in mitigating pillar bursts at the extraction level. Since pillars temporarily support the weight of the overlying caved rock mass, it is essential to synchronize the draw rate with the caving rate. Any imbalance—particularly when the caving front advances non-uniformly or exhibits anisotropic behavior—can result in uneven stress distribution and excessive loading on pillars, significantly raising the risk of sudden failure.

The study presents comprehensive geotechnical data from Northparkes mines, including in-situ stress conditions, mining depth, lithology, rock mass strength parameters, and detailed records of seismic activity. Notably, rock burst events at Northparkes were linked to challenges in predicting the cave propagation rate. This highlights the critical need for reliable cavability assessments to anticipate caving behavior and minimize operational hazards. The inclusion of recent and relevant references, such as Webster et al. (2020), enhances the value of Liu et al.'s work by offering not only technical insights for operational risk assessment and design strategies, but also a clearer understanding of the current challenges and practices within the deep block caving industry.

Inconsistencies in predicted caving rate and extent:

The paper by Snyman and Webster (2022) presents a comprehensive analysis of the rapid collapse observed in the E48 block cavern at Northparkes Mine, Australia. The study attributes this behavior to moderate in-situ stress conditions and the use of hydraulic fracturing as a pre-conditioning for caving propagation measure. Interestingly, similar applications of hydraulic fracturing in other mines have not produced the same results (Castro and Cuello, 2018), highlighting the significant influence of stress conditions on caving behavior.

Using the ideas from the paper by Snyman and Webster (2022), one can develop the hypothesis that higher horizontal principal stresses act as a constraint, counteracting gravitational fragmentation and slowing down caving propagation. To test this hypothesis,

numerical simulations as an analysis of how changing stress conditions affect caving dynamics will be conducted. This resource will also serve as a real-world example to discuss the impact of low to moderate horizontal stresses on caving behaviour, providing critical context for my conclusions.

A study by Webster et al. (2020) provides a comprehensive assessment of potential cave extensions in block caving at Northparkes Mines. The study focuses on key aspects such as maximum cave extension and optimum recovery rates, with particular attention to past experience with long-term block caving operations at the mines.

Webster et al. (2020) delves into the analysis of the undercut geometry of caves E48, E261L and E262L, highlighting how its structures affect caving and dilution. The paper also examines the undercut sequence and geometry in Block E26, offering valuable parameters to be used to model the 2D numerical model, improving its realism and accuracy. Block 26 has encountered a cave collapse (roof stabilization and stalled fragmentation). A possible cause is highlighted as the hydraulic radius of the initial undercut (43 meters), which can also be determined by proper modeling and the results can be compared.

2.2.3 Palabora Mine (South Africa)

Open pit - Block Cave interaction:

The Palabora Mine in South Africa represents one of the most prominent and instructive examples of the complex geotechnical interactions that can arise when transitioning from open-pit mining to large-scale block caving. This mine has served as a focal point for investigating the challenges of stress redistribution, slope stability, and the evolving understanding of cave-pit system dynamics.

Moss et al. (2006) conducted a seminal investigation into a significant slope failure event at Palabora, which occurred despite ideal geotechnical conditions. The open pit was developed in rock of exceptional quality—characterized by minimal jointing and high strength—allowing for the construction of some of the steepest pit slopes globally, with angles reaching up to 58°. Moreover, with a vertical separation of approximately 600 meters between the base of the pit and the initiation level of the block cave, the prevailing assumption had been

that interaction between the two operations would be minimal. However, a sudden failure in the northwest pit wall displaced approximately 100 million tonnes of rock mass, fundamentally challenging this assumption. The incident revealed a critical gap in the understanding of pit-cave interaction and highlighted the inadequacy of existing predictive models, particularly under conditions of complex stress redistribution.

Adding to this, Basson et al. (2016) presented a detailed geological framework of the Palabora deposit, identifying prominent fault zones and structural features that significantly influence local stress fields. These structures, they argued, could deviate in-situ stress orientations and concentrate loads in unexpected locations—especially critical when considering the combined effects of surface and underground excavation. Their analysis emphasized that geological complexity must be explicitly accounted for in both cave initiation planning and long-term stability assessments.

A notable concern in the early stages of Palabora's caving operation was the orebody's competent nature, which initially raised doubts about its cavability. Contrary to these concerns, the cave did propagate successfully, though not without revealing new challenges. The Palabora case highlighted that even with favorable rock mass conditions and considerable vertical offsets, dynamic interactions between mining levels can produce unanticipated failures. Furthermore, the role of structural anisotropy and dominant lithological units emerged as key factors in influencing cave geometry, stress redistribution, and the potential for pit wall destabilization.

Collectively, the work of Moss et al. (2006) and Basson et al. (2016) underscores the need for advanced, site-specific modeling approaches that incorporate geological structure, stress path evolution, and excavation sequencing. The Palabora Mine thus stands as a critical reference point for future designs where surface and underground operations coexist, and it serves as a reminder that high-quality rock alone does not eliminate the risks inherent in pit-to-cave transitions. For this reason, the Palabora case served as a motivation to include surface structures, such as the open pit, in our own numerical model. This allows us to explore how stress redistributes between the surface and the underground mine, and to better understand potential interactions during cave progression.

3. METHODOLOGY

3.1 Selection of Case Study and Modeling Approach

After careful consideration of various technical reports and case studies, it was decided to construct the model based on the Red Chris Mine in Canada. The primary criterion for selecting this mine was the availability of feasibility studies and technical reports online, facilitated by Canadian natural resource policies. These reports provided precise geological data, enabling the creation of a more representative model while minimizing computational errors. The ore body (porphyry copper) fairly uniform and hard with minimal discontinuities. In addition, the availability of reported average rock properties streamlined the data collection process.

3.1.1 Spatial Configuration of the Mine

Red Chris is an open-pit mine that has nearly reached its pit limit. Further extraction is planned to transition underground using the block caving method (see Figure 1.). The block caving operation has already passed feasibility studies, demonstrating positive economic value, and is expected to begin operation in 2026. The design consists of three panel raises, with undercuts MB1, MB2, and MB3 extracted sequentially to ensure a total productivity of 13.6 Mt/a. These undercuts have a combined footprint of approximately 750×400 m, covering a total area of about 271,000 m². Our model incorporates the MB1 undercut with dimensions of 400×260 m.

Table 1. Mine Geometry (Technical Report of Red Chris Mine, 2021)

Mine Section	Parameter	Value	Unit
Surface	Elevation	1500	mRL
East Pit	Depth	388	m
	Slope	34-46	°
	Width	1069	m
	Elevation of UPL	1112	mRL
Undercut (MB1)	Height	5	m
	Footprint	400×260	m

	Area	103,370	m ²
	Elevation	530	mRL

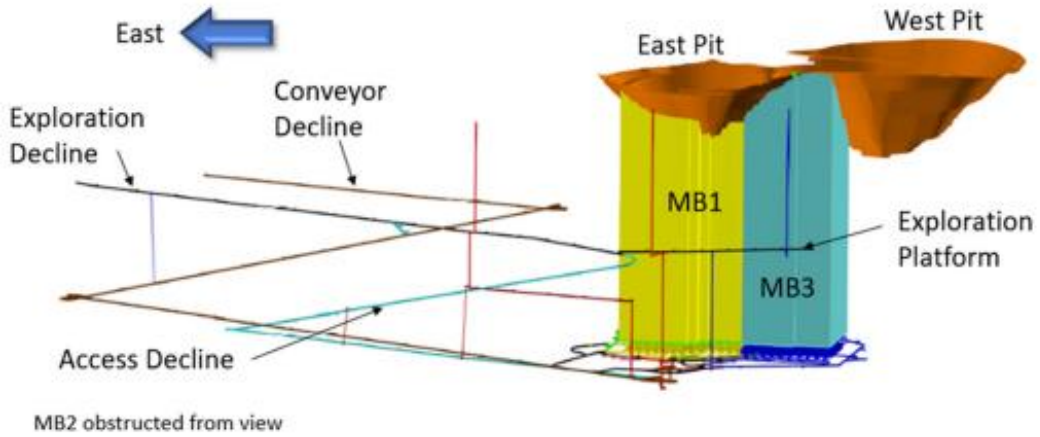


Figure 1. Underground Mining Design (Stewart et al., 2021)

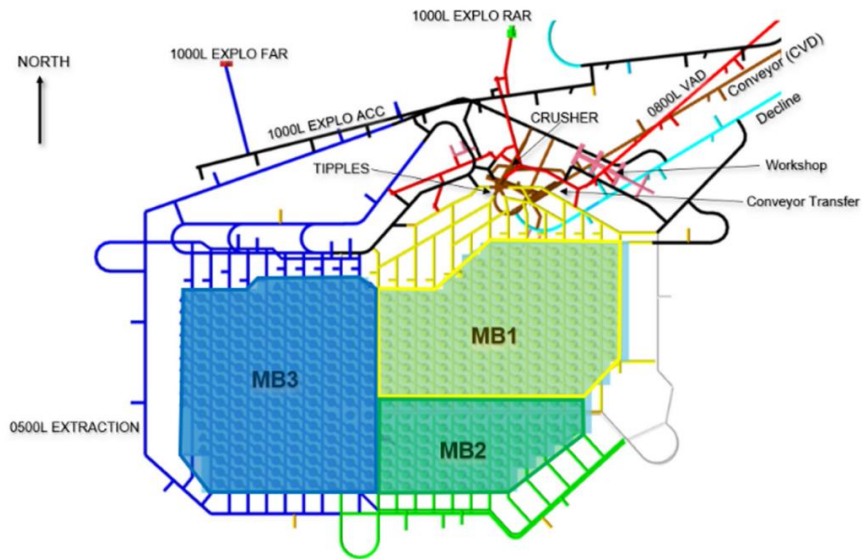


Figure 2. Extraction level layout with access declines (Stewart et al., 2021)

The design parameters of the pit and undercut were incorporated into the model construction process (see Figure 3). In 2012, the Red Chris pit operation was at Level 5, with plans to reach Level 7 by the end of 2026. The transition from open-pit mining to block caving is scheduled upon completion of the open-pit final phase.

The underground ore body differs from the previously mined sub-surface ore body (via open-pit mining) due to lower alteration and higher gold and copper grades. The most suitable mining methods considered were sublevel caving, sublevel open stoping, and block caving. Among these, block caving was selected as the optimal method, as it allows for higher resource recovery and favorable mining rates, ensuring economic feasibility and a higher project return rate.

Using the pit parameters reported in the technical report, the ultimate pit limit, final pit dimensions, and the distance between the pit limit and the undercut footprint, along with the final pit depth, were adapted to the RS2 model geometry. Overall, model dimensions are 1462 × 1200 m.

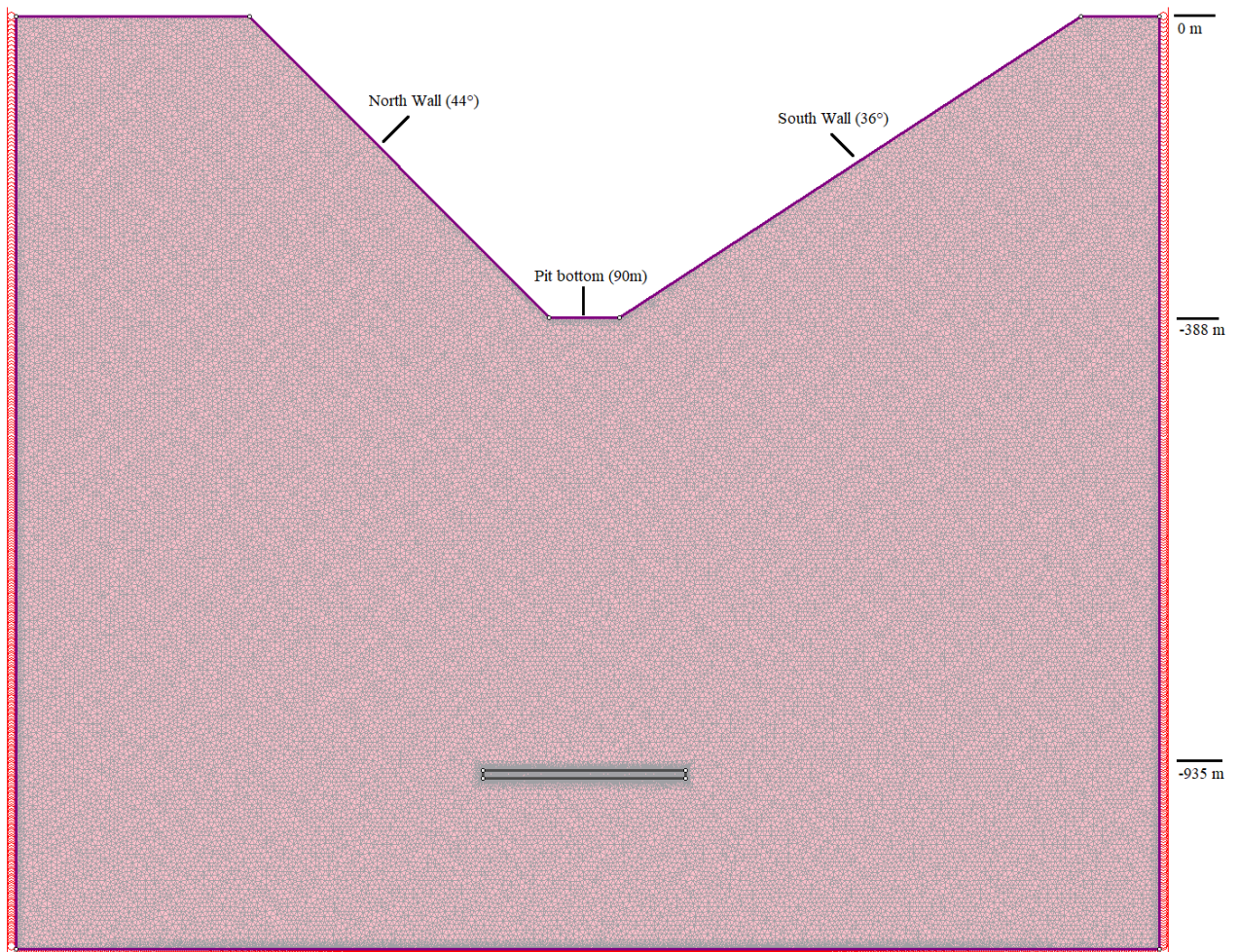


Figure 3. RS2 model of east pit and MB1 undercut section. Looking east

3.1.2 Geological Characterization and Derivation of Input Parameters

The Red Chris deposit is a copper porphyry ore body embedded in the Red Stock host rock mass, which is primarily composed of diorite and monzonite. The deposit has a planar elliptical shape, extending approximately 1.3 km in length, 0.3 km in width, and 3.4 km in depth. Its cross-sectional shape resembles an inverted cone, narrowing with depth. The ore body is located within the 'Stikinia' terrain zone, which has historically undergone folding due to tectonic movements associated with the formation of the northern mountains (Gillstrom et al., 2012).

The average rock mass strength parameters were adapted to the model from technical reports, specifically the National Instrument 43-101 reports (see Table 2). Primary fragmentation and caving are considered to be initiated and driven primarily by stress parameters and the strength of the ore body rather than by discontinuity sets (Stewart et al., 2021). The exclusion of the major fault heading southeast was necessary to achieve a target-oriented simulation and ensure accurate modeling of primary stress redistribution. Previous cavability simulations on Red Chris mine by Shapka-Fels (2023) indicated that primary sub vertical faults obstructed horizontal stress distribution within the caving zone. While this lithological consideration is critical for evaluating specific mine conditions, it is unsuitable for our study as it limits a proper assessment of the stress effect on caving behavior.

Table 2. Average Ore Body Parameters (Rees et al., 2015; Stewart et al., 2021)

Average Rock Mass Properties	Value
UCS	80 MPa
RMR	>90
RQD	75-95
Ground Condition	“very good”
Specific Gravity (dry)	2.78

RSData software was used to derive the deformation modulus and Generalized Hoek-Brown parameters from the available geological data. After defining the material properties by inputting GSI, UCS of intact rock, and m_i parameters, the software automatically calculates

the deformation modulus, Hoek-Brown failure parameters, and residual strength of the rock mass.

Since the Hoek-Brown criterion is an equation that utilizes empirically derived rock mass parameters, certain assumptions and approximations were necessary, requiring the application of engineering judgment to ensure realistic parameter estimation. The mesh size was chosen to range from 2 to 4 meters to accurately represent the average block size within the rock mass.

Table 3. Model-ready Input Parameters

	Parameters	Value	Unit
Hoek & Brown Parameters	mb	9.197	-
	s	0.061	-
	a	0.501	-
Rock Mass Parameters	UCS	19.692	MPa
	global strength	35.263	MPa
	modulus of deformation	11.498	GPa
	tensile strength	0.529	MPa

3.2 Computational Model Setup

3.2.1 Boundary Conditions

Boundary conditions for the RS2 model included full fixation of movement in both directions at the bottom to simulate a rigid foundation. Due to the nature of the caving simulation, horizontal movement was restricted at the lateral boundaries, while vertical displacement was allowed. The gradual increase of stress without interruptions throughout the simulation (see Figure 4.) validates the accuracy of the boundary settings, ensuring realistic stress distribution and model stability.

The initial element loading conditions included field stress and body force. Since the model assumes a geostatic stress condition, vertical stress remains constant at the undercut

area, while horizontal stress is the only varying parameter in the stress field. To simulate the influence of in-situ stress on cavability, we applied the empirical method developed by Hoek & Brown (1960) to predict the possible range of stress ratio (k) (see Figure 5). This method is particularly relevant to our study, as it was originally developed using data from deep hard rock mines, covering a broad range of possible in-situ stress ratios at a given depth (Hoek & Brown, 1978). In the original work, the authors highlight that horizontal stresses vary significantly depending on tectonic activity and other major geological features of the region, which explains the wide range of possible stress ratios.

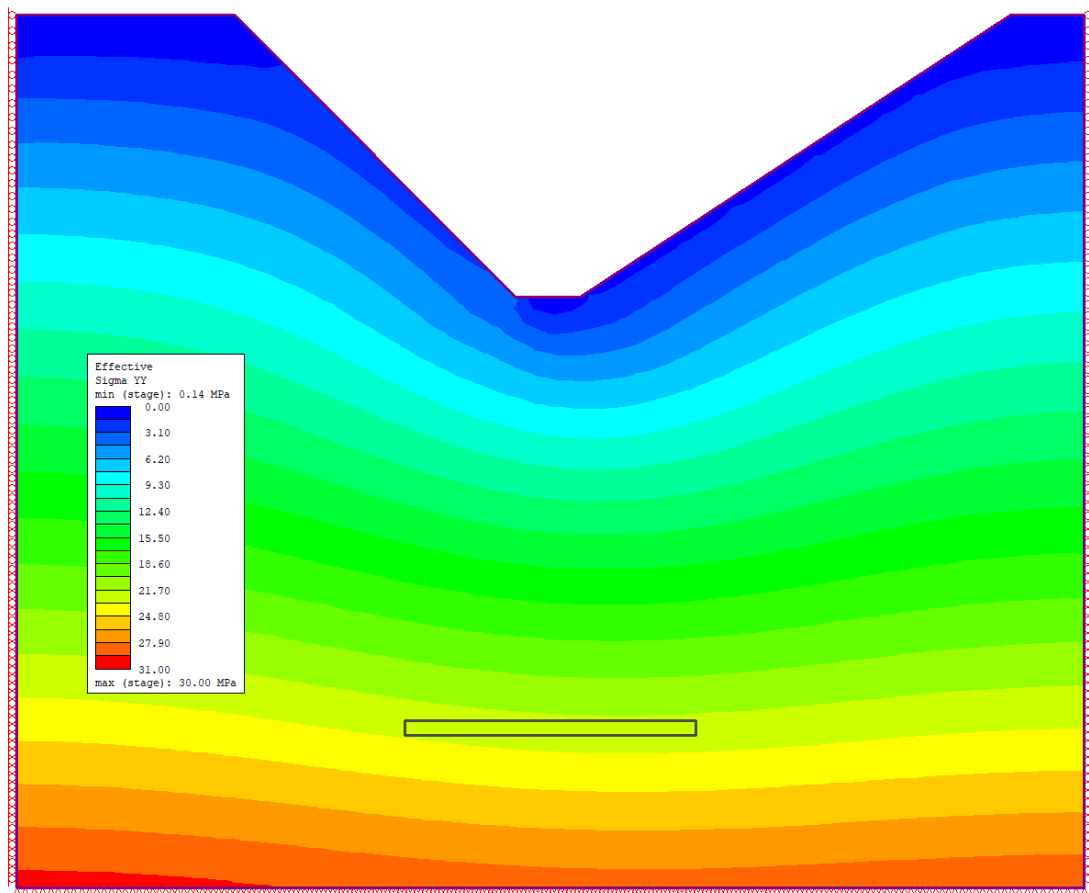


Figure 4. Initial Condition. Illustrates σ_{yy} = vertical stress gradient (along the Y-axis)

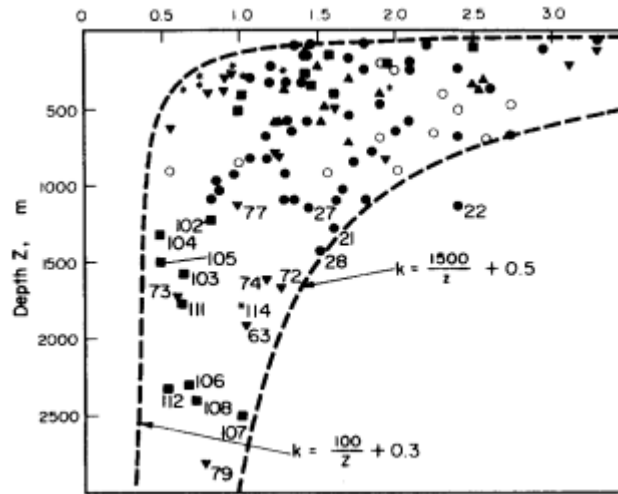


Figure 5. Empirical Range of In-Situ Stress Ratios as a Function of Depth (Hoek & Brown, 1978)

In general, in-situ stress ratios are determined by combining the geostatic stress assumption with a range of stress ratios derived from empirical method. Therefore, in our model, vertical stress is set as a constant value, while varying horizontal stresses are applied to evaluate their influence on cave propagation. In particular, due to the undercut depth of 935 m, the in-situ stress ratio (k) is expected to range from 0.4 to 2.1. For the simulation, a step interval of 0.05 was selected to ensure an adequate degree of precision in evaluating the sensitivity of cave propagation to varying stress conditions.

3.2.2 Failure Criterion

The Generalized Hoek and Brown (GHB) failure criterion was chosen for numerical simulation, please refer to Equation (1). This empirical method establishes a nonlinear relationship between the stress field and rock mass parameters (e.g., s , a , and m_b) to estimate rock mass failure, making it particularly effective for modeling progressive failure. Although the method is empirical, it has been widely validated and successfully applied in the mining industry (Hoek et al., 2002). Its application in caving propagation simulations is justified by its ability to account for overall rock properties and averaged parameters across rock masses with varying degrees of alteration.

$$\sigma_1 = \sigma_3 + \sigma_c \left(m_b \frac{\sigma_3}{\sigma_c} + s \right)^a \quad (1)$$

For simulating brittle hard rock behavior, it was necessary to define the deformation modulus of intact rock, which was then used to derive the rock mass modulus by application of its Geological Strength Index (GSI). However, triaxial test results for intact rock were unavailable. To address this, the modulus ratio (MR) method from RSData software was applied to derive the deformation modulus of intact rock. As previously mentioned, the Red Chris porphyry ore body is primarily composed of diorite, and therefore, the recorded MR value for diorite from publications of Hoek & Diederichs (2006) was used. This MR value was multiplied by the UCS of intact rock to estimate its deformation modulus.

Additionally, the model incorporated plastic behavior for the ore body, meaning that yielded rock retains residual strength parameters. This approach enables the evaluation of failure mechanisms and displacement behavior within the rock mass. The residual strength parameters were adjusted using the Geological Strength Index (GSI) of the yielded rock mass, ensuring a more realistic representation of post-failure behavior (Table 4.)

Table 4. Peak and Residual Parameters of the Rock Mass

Parameter	Peak	Residual
GSI	79 <i>(blocky structure and good surface condition)</i>	65 <i>(highly fractured rock with fair to poor surface)</i>
m_b	13.197	8.574
s	0.135	0.036
a	0.500	0.501

3.2.3 Result Interpretations

According to Duplancic & Brady (1999), caving propagation domain theoretically consists of four discontinuity zones:

Caved Zone – The region where the rock has fully disintegrated and collapsed due to gravitational forces.

Airgap – The void created by rock caving, influenced by the mining and cave propagation rate.

Yielded Material (Discontinuity Propagation Border) – The area where rock deformation occurs due to stress but without complete collapse. This boundary varies significantly depending on factors such as the post-peak behavior of the rock mass, stress redistribution, and other geological conditions in the surrounding undisturbed rock.

Undisturbed Rock– A stable region where stress remains low relative to rock strength, preventing stress-induced failure.

The caving initiates at the roof of the undercut, forming an arch-like structure that transitions into the yielded elements. These yielded elements are loosened and have acquired residual strength parameters but have not yet fully disintegrated. The caved zone is surrounded by yielded elements with significant total displacement, which can be considered a zone of loosening, as described in the conceptual model constructed by Duplancic & Brady (1999) (see Figure 6).

In our case, special attention was given to the yielded zone and the causes of failure, as it is primarily a stress-related phenomenon. We adopted the deformation scale previously used in finite element modeling (FEM) for caving prediction, this approach was validated by Sainsbury at Norhtparkes Mine and applied by Alipenhani et al. (2022). Specifically, we classified vertical displacement of 1 meters as the boundary between the caved zone and the yielded zone. This approach enabled us to represent the maximum extent of cave propagation and deformation front under different stress conditions (see Figure 7).

In the yielded zone above the caved area, the probability of further caving is assumed. The extent of material loosening provides insight into the likelihood of caving progression and the maximum naturally cavable area.

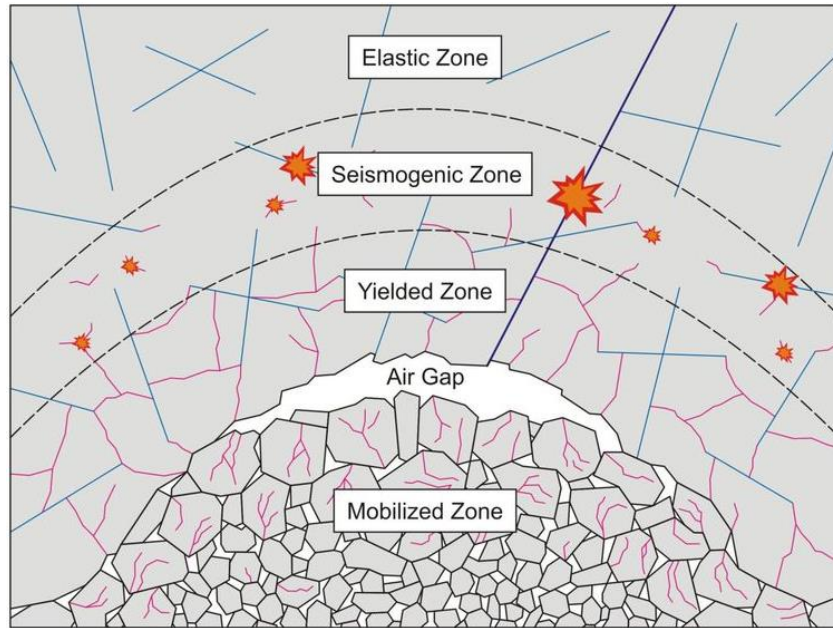


Figure 6. Caving Process Representation (Ivars et al., 2011)

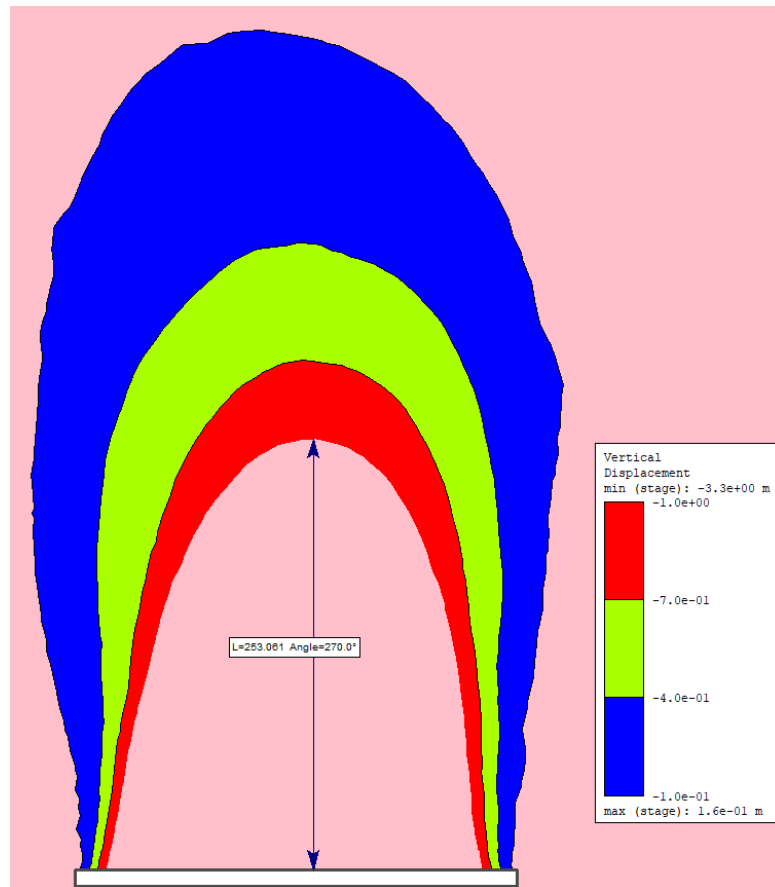


Figure 7. Example of Caved Roof Height from Simulation ($k = 1.5$)

4. RESULTS

To evaluate the influence of stress on caving behavior, 41 simulations were conducted, with the stress ratio (k) as the only varying parameter. The vertical stress remained constant based on the geostatic stress assumption, while the horizontal stress varied, resulting in stress ratios ranging from 0.4 to 2.1. Sudden changes in the caved zone and discontinuity propagation area occurred at the boundaries between three distinct domains rather than within them. Smaller interval steps for k were applied where significant differences in caved material volume were observed, ensuring a more detailed analysis of stress-dependent cave propagation.

After the sudden excavation of the undercut ($260\text{m} \times 5\text{m}$) in Stage 2, significant stress redistribution occurred. Stress tensor analysis revealed distinct vertical and horizontal stress flow patterns around the excavation. Due to the large undercut width, a substantial low-stress zone developed above it, acting as the primary driver for caving. This reduction in confinement weakened the rock mass, facilitating failure initiation and propagation.

4.1 Stress Field and Pit Interaction

Given the naturally low stress near the pit slopes, this complex interaction resulted in a widespread de-stressed zone. In our case, presence of the deep pit significantly altered horizontal stress distribution, acting as a stress-relief mechanism that reduced confinement and extended the stress path deeper into the rock mass. However, stress distributions at different in situ stress values exhibited three distinct patterns, each influencing the yielding behavior and maximum caving height. The domains, categorized by stress ratio ranges, are as follows:

- Low-Stress Ratio Zone ($0.4 \leq k \leq 0.6$)
- Moderate-Stress Ratio Zone ($0.7 \leq k \leq 1.2$)
- High-Stress Ratio Zone ($1.3 \leq k \leq 2.1$)

These distinct redistribution patterns highlight the complex interaction between stress conditions, yielding mechanisms, and overall cave development.

4.1.1 Stress Redistribution at $0.4 \leq k \leq 0.6$

In the zone of principal vertical stress and lower confining stresses, where k ranges from 0.4 to 0.7, significant horizontal stress was not observed until reaching the floor of the

undercut, except in the crown pillar zone, where stress concentration was evident. In contrast, vertical stress formed an extensive low-stress zone connecting the undercut to the surface, resulting from reduced vertical stress at the pit bottom and the undercut roof. Additionally, periodic vertical de-stressing with deviating stress boundaries was observed around the lower sections of the pit walls. These elongated low-stress zones extended to significant depths and gradually transitioned into higher-stress regions along the cave walls (see Figure 9).

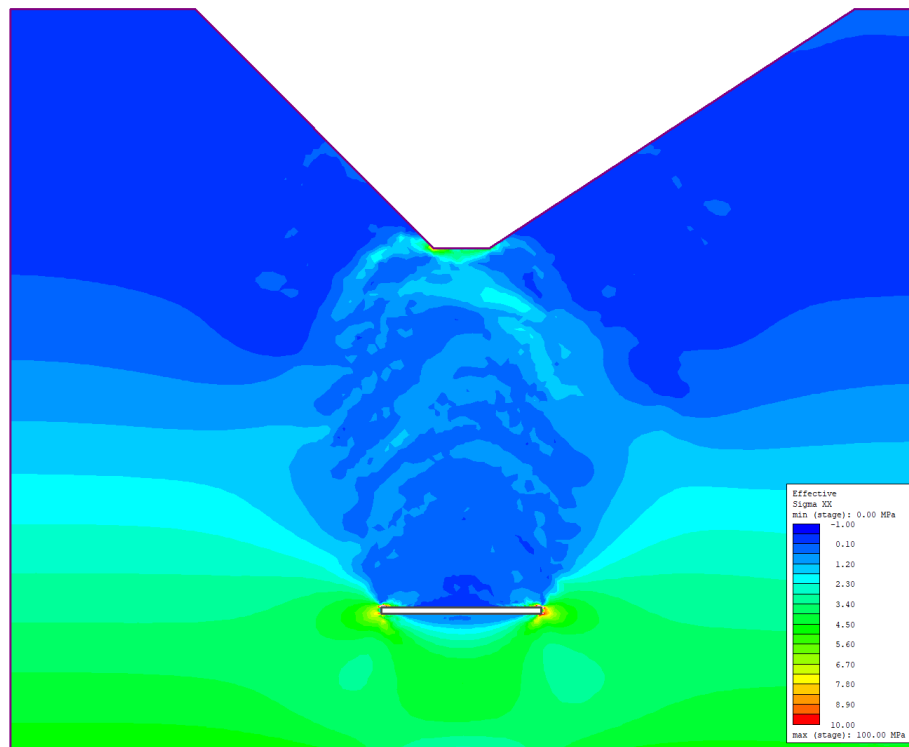


Figure 8. Horizontal Stress Following Undercut Excavation (k=0.5)

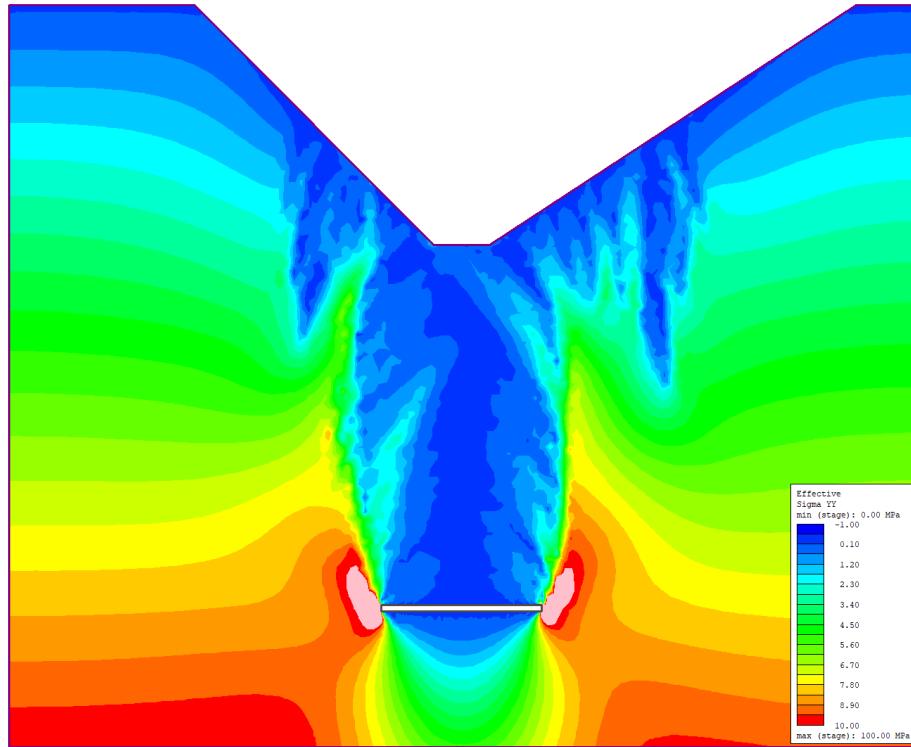


Figure 9. Vertical Stress Following Undercut Excavation ($k=0.5$)

4.1.2 Stress Redistribution at $0.7 \leq k \leq 1.2$

Maximum caving occurred within a stress ratio range of 0.7 to 1.2. In this domain, tensional vertical stress developed in the crown pillar zone, enabling cave propagation down to the pit bottom. Stress redistribution within this range remained consistent due to the destressed conditions in the pillar zone. As a result, the stress path in the x-direction shifted downward, expanding the low-stress region above the undercut. This interaction between the undercut and pit geometry played a crucial role in reshaping the overall stress field, directly influencing cave propagation and failure mechanisms.

Vertical stress significantly deviated following the undercut excavation, forming an elliptical-shaped tension zone between the undercut and the pit bottom. The location of the tensile zone was closer to the pit rather than directly above the undercut, which, when linked with failure zones at the undercut roof, contributed to a greater caving height. Additionally, the pit walls, which extend regions of minimal vertical stress, created a broad low-stress zone across the upper section of the model. The redistribution of vertical stress due to excavation also resulted in periodic low-stress regions extending from the pit bottom toward the model's lateral boundaries.

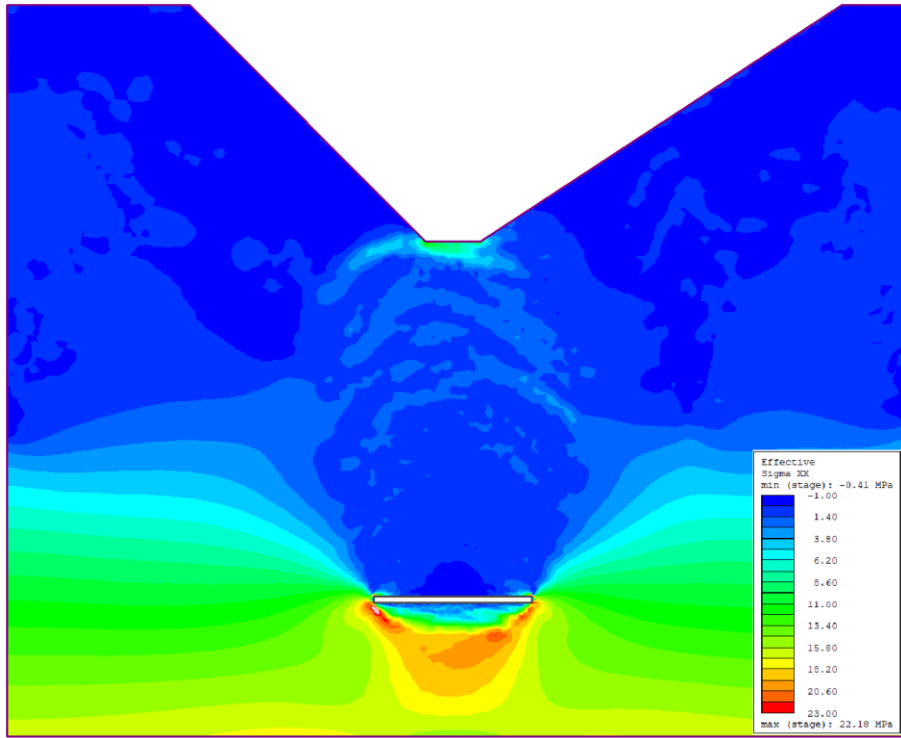


Figure 10. Horizontal Stress Following Undercut Excavation (k=1)

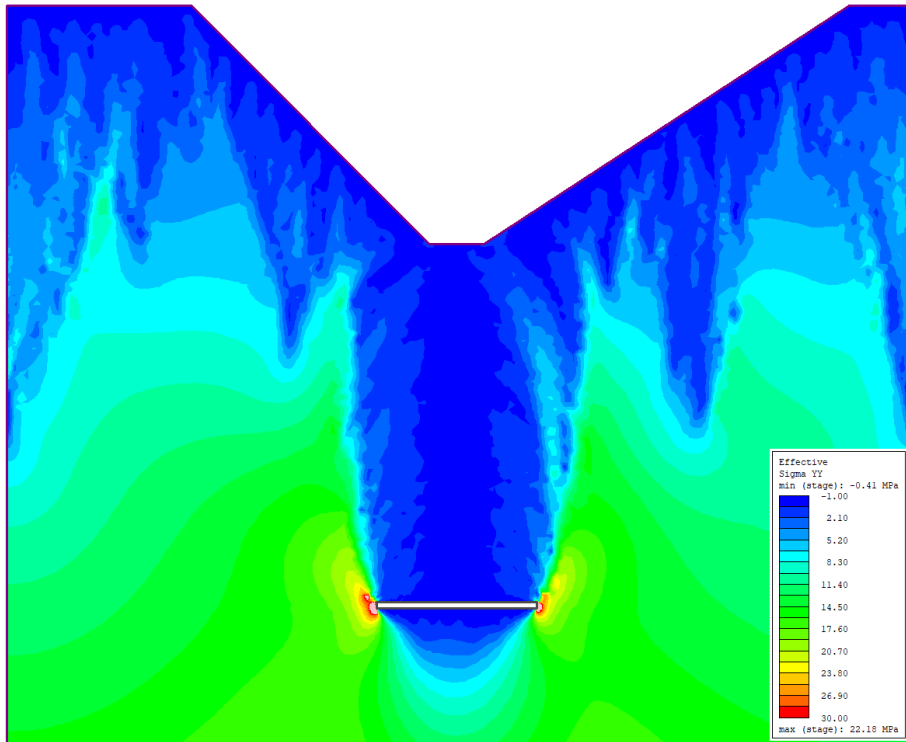


Figure 11. Vertical Stress Following Undercut Excavation (k=1)

4.1.3 Stress Redistribution at $1.3 \leq k \leq 2.1$

At this stage, high horizontal stress in the crown pillar zone expanded significantly, leading to substantial confinement, while low-stress concentration was primarily observed only at the top of the undercut. Additionally, for cases where $k \geq 1$, a significant accumulation of stress was observed in the lower part of the undercut, where the extraction level is expected to be located.

Zones of high vertical stress caused the separation of elongated tension forces extending from the pit bottom to the undercut. At this stage, high horizontal stress accumulated in the crown pillar zone, resulting in significant confinement, while low-stress concentration was primarily in circular shape at the top of the undercut.

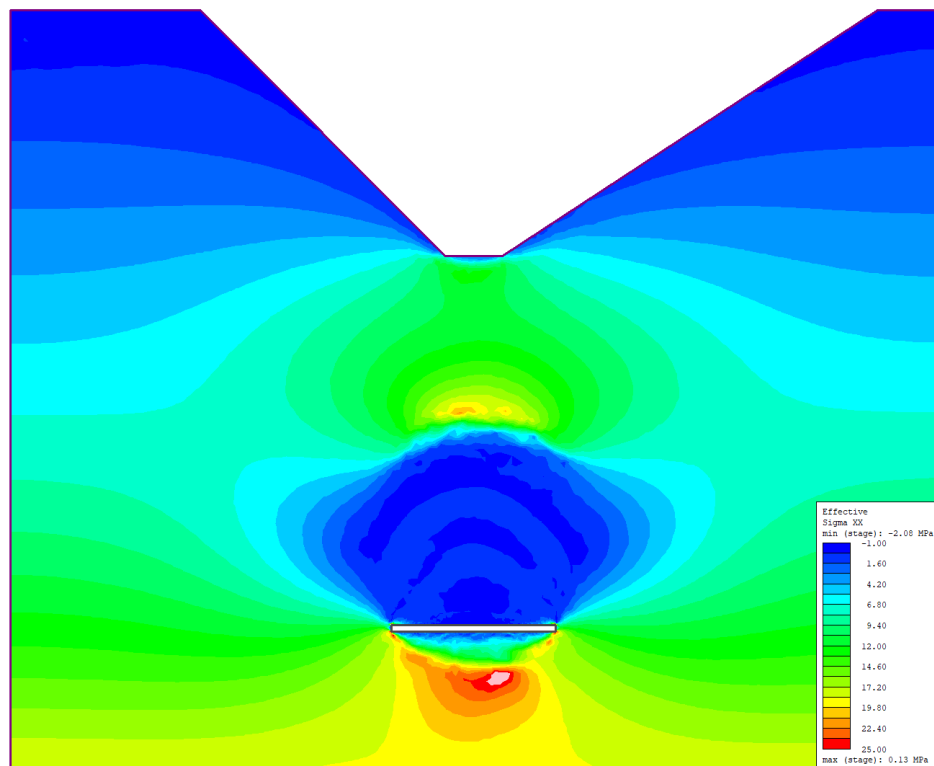


Figure 12. Redistribution of Horizontal Stress Following Undercut Excavation ($k=1.5$)

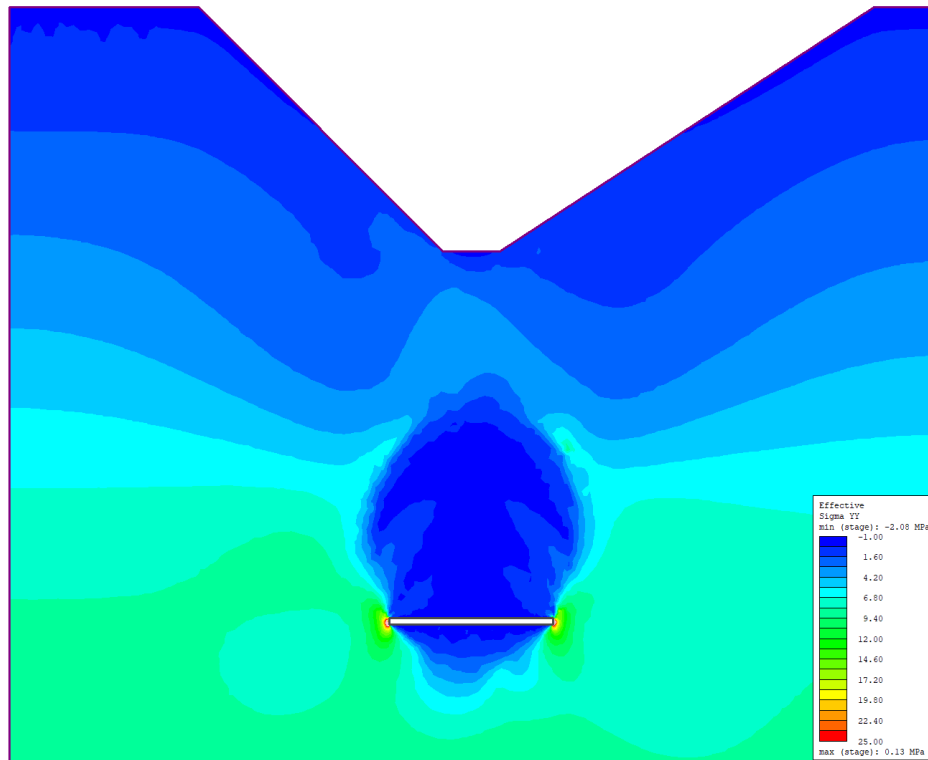


Figure 13. Redistribution of Vertical Stress Following Undercut Excavation ($k=1.5$)

4.2 Yielded Zone and Loosened Material

In RS2, an element "yields" when stress induced to it exceeds material strength limits, but not all yielded elements fail in the same manner. The two primary failure modes in yielded elements are:

Shear Failure: Occurs when shear stress surpasses the failure envelope, which is dominant in high-stress conditions.

Tensile Failure: Occurs when tensile stress exceeds the material's tensile strength, commonly observed in low-confinement areas.

Cave propagation was initiated through a combination of failures. Any initial failure led to a reduction in overall rock mass strength, making further movement easier than in the initial state. The simulations utilized an elastic-plastic material model, accounting for both elastic deformation and permanent yielding. In RS2, tensile failure automatically reduces shear strength by a factor of 0.1. As a result, any element that fails in tension subsequently undergoes shear failure. Similarly, elements that initially failed in shear due to excessive stress transitioned to a residual strength state. The associated reduction in deformation modulus within the yielded rock mass, combined with gravitational forces, further promoted tensile failure at adjacent nodes, driving discontinuity propagation.

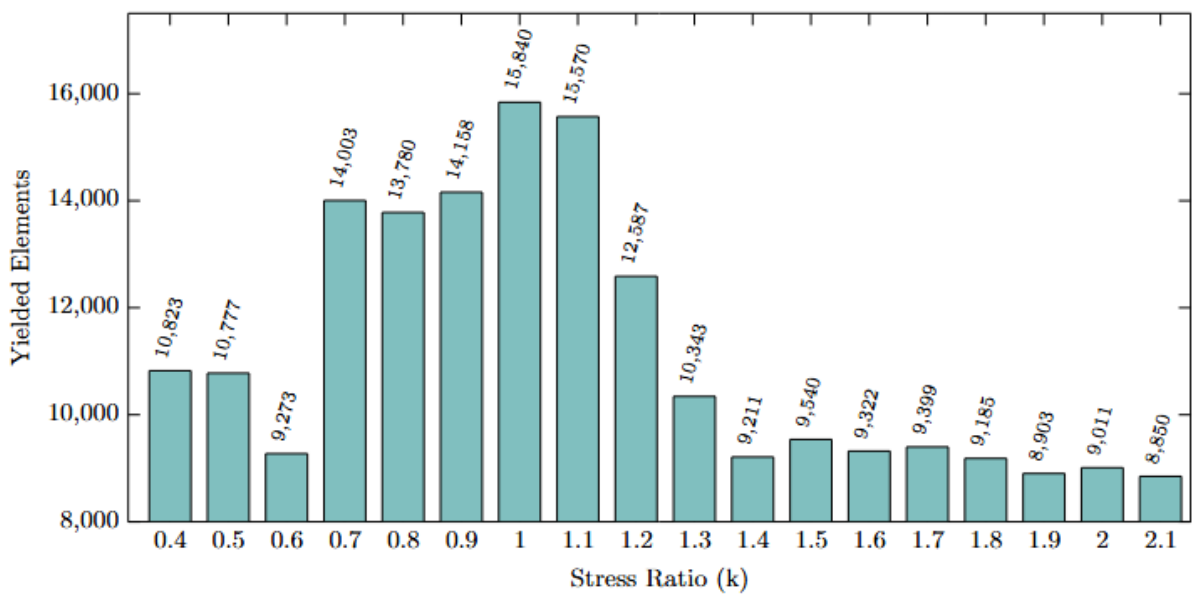


Figure 14. Number of Yielded Elements at Each Stress Ratio (k)

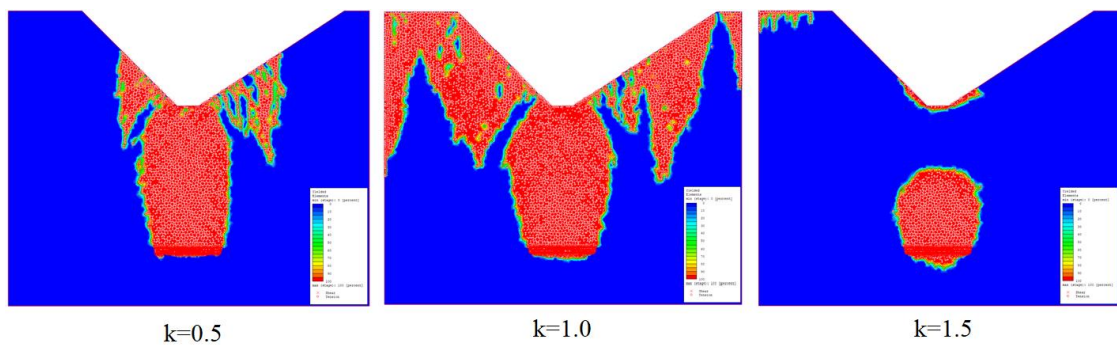


Figure 15. Distribution of Yielded Elements

Overall, the deformation zone also can be classified into three distinct modes, each differing significantly from the others. In the low-confinement stress zone, yielding propagated from the undercut to the pit but remained limited at the lower pit walls, resulting in a moderate failure zone. In the medium-confinement stress zone, a significantly large rock mass underwent yielding, leading to extensive deformation. In contrast, under high vertical stress conditions, yielding was concentrated around the undercut, forming a circular pattern. This suggests that instead of discontinuities propagating upward, failure expanded laterally, driven by a wide zone of shear failure surrounding the yielded elements. However, in this high-stress zone, discontinuity propagation remained confined within a strict boundary, indicating an overall smaller deformation zone compared to the other stress ratio zones.

4.3 Effect of Stress Ratio (k) on Cave Height

As discussed earlier, in FEM simulations, disintegrated (caved) rock is defined as material that has undergone solid displacement of more than one meter. In each simulation, rock exceeding this displacement threshold was recorded as fully caved material, and the maximum propagation height was documented.

At the lowest stress ratio, the caving height was measured at 212.7 meters. From this point, the propagation height gradually declined, reaching 115 meters at $k=0.65$. However, exactly at $k=0.7$, the cave suddenly expanded to its maximum height of 580 meters. Further increases in confining stress resulted in a gradual decline in caving height, decreasing to 500 meters at $k=1.2$.

The third zone, beginning at $k=1.3$, exhibited a sharp decrease in caving height to 237 meters. While the total caved mass in the low-confinement stress zone (0.4 to 0.7) was as same as in the high-stress zone ($k \geq 1.3$), a sudden reduction in roof height was observed as horizontal stress continued to increase. At the maximum horizontal stress ($k=2.1$), the cave roof declined further to 147 meters.

Despite significant differences in the extent of discontinuity-affected areas across each domain (see Figures 14 and 16), the total caved mass in the lower and higher stress zones

remained relatively similar. Which indicates the intensity of the failure occurred is higher rock masses with intense confining stresses.

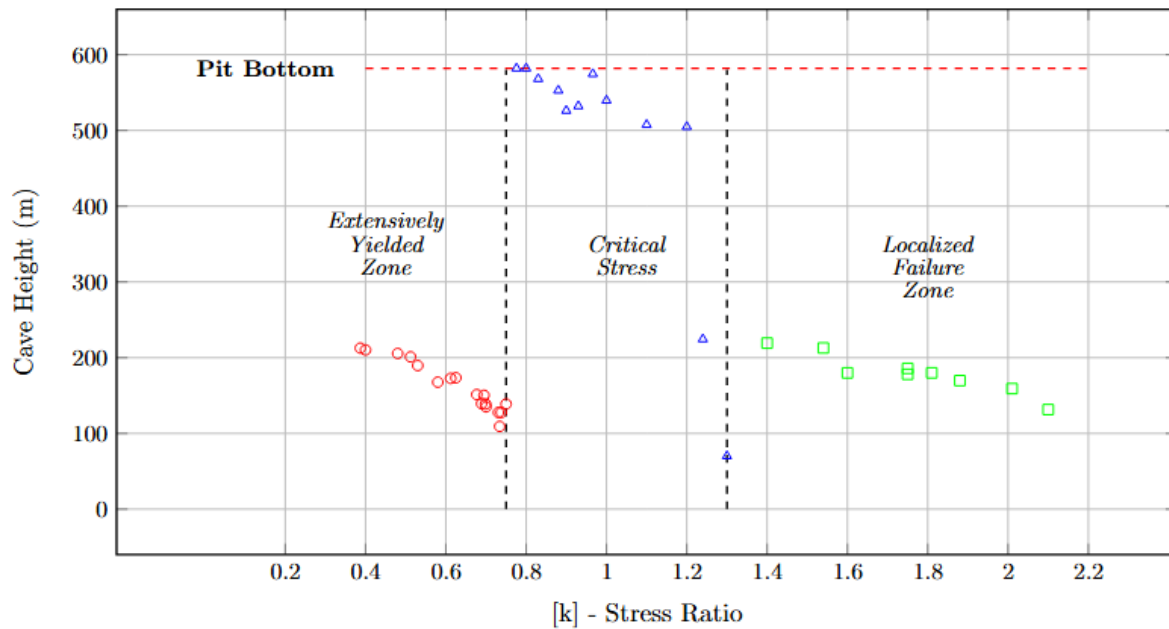


Figure 16. Stress Conditions and Cave Propagation

5. DISCUSSION

Simulation results revealed general trends in failure mechanisms under various stress conditions. Findings indicate that stress conditions can be categorized into three distinct domains, each differing in terms of overall failure extent and caving height.

Low Confinement Stress Zone ($k \leq 0.6$)

In this domain, the formation of an elongated tension zone resulted in a larger yielded area, extending toward the pit bottom. However, caving height remained moderate and declined towards the upper boundary of the domain as confining stress increased. These findings suggest that in tectonically active regions or areas influenced by major faults—where principal stress is vertical — moderate caving is more likely to occur. Additionally, low horizontal stress creates a stable stress environment for the extraction level and operational declines.

High Confinement Stress Zone ($k \geq 1.3$)

Higher stress levels led to increased stress accumulation in the crown pillar, resulting in the least amount of yielding. Discontinuity propagation formed a circular-shaped zone around the undercut, and caving height was relatively high compared to fracture propagation. This suggests that rapid caving following undercut development is likely in this domain, after which a stable, arch-like roof could form, slowing the caving rate. Implementation artificially created discontinuities, such as hydraulic fracturing, is recommended in this scenario to enhance mine cavability and ensure controlled failure progression. Furthermore, if a post-undercut extraction method is applied, the extraction level will be subjected to extreme high-stress conditions. High stresses in the floor of the undercut may contribute to operational challenges by causing drawbell damage and increasing hang-up rates. A relevant example of this scenario is the rapid cave propagation and operational difficulties observed in the E26 Lift 2 mine at Northparkes (Stegman et al., 2018). However, the in situ stress ratios of such mines are not well-documented or are subject to significant uncertainty, making it difficult to establish a precise cause-and-effect relationship.

Moderate Confinement Stress Zone ($0.7 \leq k \leq 1.2$)

The most unpredicted and extreme caving behavior occurred in this stress range. Large-scale cave propagation and rock mass failure were observed, extending even to the model boundaries. This was caused by periodic zones of high and low vertical stress, creating alternating stress states. These cyclic stress variations resulted in softening and vertical failure layers at the pit walls, with yielded zones separated by high-stress bands. Stress distribution in this zone may contribute to pit wall instability. The large-scale failure observed in the Palabora open-pit mine, where pit slopes collapsed above an active block cave (Moss et al., 2006; Basson et al., 2016), could be the demonstration of the failure in this simulation. Whereas in the higher stress region, the presence of the pit had little influence on caving, indicating that slope failures in the upper pit are unlikely in areas with high confining stresses. This large influence of stress on the overall cave performance could not be ignored in the mine planning or geotechnical assessments. However, the exact mechanics behind these periodically de-stressed vertical zones, particularly at the pit and border areas, remain unclear.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

This study evaluated rock mass caving behavior under different stress conditions. Previous research presented conflicting views on the influence of stress fields on caving behavior. While existing studies on block cave cavability prediction focused on various influencing parameters, this research specifically examined the impact of varying in-situ stress fields on the volume of the collapse zone and the progression of cave propagation.

The findings provided significant evidence supporting the hypothesis that rock mass caving is highly dependent on local stress distribution. Stress distributions at different in situ stress values formed three distinct patterns, each influencing the yielding behavior and maximum caving height. These variations in stress redistribution shaped the failure mechanisms and controlled how caving propagated through the rock mass.

Additionally, this study evaluated failure mechanisms and considered the potential for time-dependent cave propagation due to gravity-driven loosening of the rock mass. Notably, in the medium stress zone ($k = 0.7$ to 1.2), the most unpredictable and extreme caving behavior was observed. Large-scale failure and cave propagation extended even to the model boundaries, indicating a complex and unstable caving mechanism.

The identification of critical stress zones highlights a research gap that requires further investigation, particularly in understanding the mechanisms driving extreme caving behavior in medium-stress environments.

6.2 Recommendations

To generalize these findings on a broader scale, models of different mines should be developed to simulate caving behavior under varying stress states, mine geometries, and rock mass properties. For higher accuracy, future studies should base models on actual mine designs and officially reported geological characteristics. Additionally, stress influences should be analyzed with the inclusion of major lithology at the mine side using finite/discrete element methods.

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