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Numerical Modelling Analysis for Design of Optimum Stope and Pillar Geometry for Underground Mining of East Deposit of Kheratarla Wollastonite & Calcite Mine

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Abstract

This paper presents a comprehensive numerical modeling analysis aimed at designing optimal stope and pillar geometries for the underground mining of the East Deposit of Kheratarla Wollastonite & Calcite Mine. Using ITASCA's IMAT software powered by FLAC3D, the study constructs a detailed 3D model that simulates critical stress distributions within the rock mass, enabling a precise assessment of various stope geometries' stability. The results provide a robust framework supporting a safe and efficient transition to underground mining.

Keywords – Stope optimization, IMAT software, FLAC3D, mine planning, wollastonite mining, industrial mineral mining, underground mining

I. INTRODUCTION

Underground mining is essential for accessing valuable mineral deposits that lie beneath the Earth's surface, particularly when surface mining becomes economically or geologically unfeasible. As the global demand for minerals continues to rise, optimizing underground mining operations has become increasingly critical. This study focuses on the East Deposit of Kheratarla Wollastonite & Calcite Mine, transitioning from open-pit to underground mining to access deeper mineral resources effectively.

The design of stope and pillar geometry is central to underground mining operations, significantly impacting safety, efficiency, and economic viability. Proper stope and pillar design ensures the stability of underground excavations, maximizes ore recovery, and minimizes operational risks. Given the complex geological conditions of the Kheratarla Mine, a detailed and methodical approach to designing these geometries is essential.

This research leverages advanced numerical modeling techniques using IMAT software powered by FLAC3D to simulate and evaluate various stope and pillar configurations under realistic in-situ conditions. The primary goal is to identify optimal designs that enhance stability while supporting high production rates. By integrating empirical data with sophisticated modeling, this study aims to provide a robust framework for safe and efficient underground mining operations at Kheratarla Mine.

Through comprehensive analysis and simulation, the study contributes valuable insights into the development of sustainable and economically viable underground mining practices, addressing the specific challenges posed by the unique geological setting of the East Deposit of Kheratarla Mine.

II. LITERATURE REVIEW

Cai et al. (2004) emphasized the importance of accurate design input parameters, such as deformation moduli and strength parameters, in numerical modeling for underground engineering. While in situ tests can determine these parameters, limitations during the preliminary design phase often necessitate using rock mass classification systems like the Q and GSI systems. The GSI system uniquely links to engineering parameters like Mohr-Coulomb and Hoek-Brown strength parameters. However, the study identified challenges in applying the GSI system, including its subjectivity and the need for significant experience. To address this, a quantitative approach was introduced, incorporating block volume and joint condition factors to bridge descriptive geological terms with measurable field parameters, thereby aiding less-experienced engineers in the preliminary design process.

Coulthard (1999) explored the use of numerical modeling in designing excavations and rock support mechanisms in underground mining and tunneling. The study demonstrated the versatility of numerical modeling in tackling various complex issues, including predicting subsidence from longwall coal mining, assessing stress during open stope filling with cemented backfill, analyzing tunnel-tunnel interactions, and evaluating the effects of undermining existing tunnels and shafts. By employing nonlinear stress analyses, Coulthard's work provided critical insights that enhance the safety and efficiency of excavation and support system designs in underground engineering.

Janiszewski et al. (2022) surveyed stope design practices in the mining industry, highlighting a shift from traditional empirical methods to numerical techniques and data-driven approaches. The survey, distributed to experts globally, received 36 responses from 20 countries. While no single stope design method dominated, empirical methods and personal expertise remain prevalent. However, 87% of respondents indicated a readiness to adopt new practices, emphasizing the need for more geotechnical data, automation, and integration into mine planning. Notably, 70% stressed the importance of accessing geotechnical data within three days for effective design. The study underscores the industry's openness to adopting efficient, proven stope design methods, pointing to a data-oriented future in the sector.

Himanshu et al. (2014) used 3D numerical modeling to analyze stoping parameters at the Kayad underground mine of M/S Hindustan Zinc Limited. Their study involved detailed estimation of rock mass properties through laboratory testing at CIMFR and in situ stress measurements from Messy India. Focusing on two lenses at depths under 150 meters, the research simulated extraction proposals to design support systems for drill levels, draw levels, and the brow. Emphasizing safety, the study also addressed backfill properties for void filling, showcasing a thorough, data-driven approach to stope design and mine safety through advanced numerical modeling.

Himanshu et al. (2015) emphasized the importance of stability analysis in designing stoping parameters around areas like wall rocks, stope back, and stope brow. The study highlighted the need for stress, displacement, and safety factor analysis using appropriate rock failure criteria. It stressed the validation of numerical models through practical rock mechanics instrumentation and monitoring. The paper explored various aspects of numerical modeling-based design, supported by case studies from Rampura-Agucha and Kayad mines of M/s Hindustan Zinc Limited, and Bagjata mine of M/s Uranium Corporation of India Limited, demonstrating the application of these designs in real-world scenarios.

Himanshu et al. (2017) explored stope parameter design in mining, focusing on stability analysis of underground workings such as wall rocks, stope back, and brow. They emphasized the importance of considering factors like stresses, displacements, and safety, using appropriate rock failure criteria and analytical tools. The study highlights numerical modelling as crucial in design, underscoring its validation through real-world data and rock mechanics monitoring. Drawing from case studies at Rampura-Agucha, Kayad, and Bagjata mines, the research presents practical insights into numerical modelling-based design, contributing valuable knowledge to mining engineering for informed decision-making and safer operations.

Shahriyar et al. (2019) presents a methodology to assess the impact of stope geometrical parameters on the Probability of Failure (POF) using advanced numerical modelling. The study defines parameter ranges based on surveys from Canadian underground mines, focusing on open stope geometries. A Monte Carlo simulation, combined with FLAC3D, is used to generate diverse stope configurations. The research calculates the POF for different stope geometries, considering failure modes like gravity-driven tensile failure and rock mass brittle failure. Through multi-level factorial design, the study explores the interactions of these parameters on stope stability. Additionally, mathematical optimization techniques are applied to identify the most stable stope conditions and optimal parameter ranges. This research contributes to mining engineering by offering a systematic, data-driven approach to stope design, improving safety and efficiency in underground mining operations through the integration of numerical modelling, simulations, and optimization.

Wang et al. (2022) focus on the stability analysis of surrounding rock in mine stopes using advanced numerical modelling. They employed the 3DMine-Midas-FLAC3D framework to assess rock stability in complex underground mining clusters, specifically in a lead-zinc mine. The study aimed to better understand ground pressure patterns in intricate mining environments. Results showed that the numerical method aligned well with traditional empirical methods, such as the Laubscher and Mathew’s stability diagram methods, offering greater accuracy and reliability. The research highlights the importance of advanced modelling techniques for evaluating stability in complex mining settings, improving safety and operational efficiency.

Zhao et al. (2023) introduced a novel approach for designing stope structure parameters, focusing on rock mass stability in deep mining operations. Their method begins with rock mass quality classification and uses a critical span graph and an improved stability graph to account for joint occurrences and mining-induced stress. This comprehensive framework ensures stope parameters are suited to the specific mining environment. The approach is adaptable to different mining methods and adjusts over time based on mining data. Field engineering cases demonstrate the practical application of this method, enhancing safety and efficiency in deep metal mine design. The study offers a significant contribution to mining engineering, addressing challenges in deep mining.

Erdogan and Yavuz (2017) explored the optimization of stope boundaries in underground mining, focusing on computational techniques and optimization algorithms to improve efficiency. Traditional methods relied heavily on engineers' expertise, but newer techniques offer more economical solutions. The paper reviews various optimization methods, including the Floating Stope Algorithm, which aims to maximize ore tonnage but requires manual adjustments for practical constraints. The Multiple Pass Floating Stope Process (MPFSP) and the Maximum Value Neighborhood Method (MVN) are also examined, though they do not generate optimal stope layouts and have limitations in stope size considerations. Despite these limitations, the Mineable Shape Optimizer is found to be the most profitable option in a gold deposit case study. The paper emphasizes the need for further advancements in stope boundary optimization algorithms and advocates for integrated approaches to improve efficiency, safety, and profitability in underground mining.

III. SIGNIFICANCE OF PROJECT

The significance of this project lies in its focus on addressing the critical issue of stope void stability in underground mining, particularly as the industry increasingly moves toward deeper excavations in search of valuable mineral resources. The project is vital for the following reasons:

- Growing Depth and Stability Concerns: As mining operations progress to greater depths, the risks associated with stope stability intensify. Ensuring the stability of stope voids is crucial to the safety of workers, the protection of underground equipment, and the overall viability of mining operations.
- Open Stoping Method: Open stoping is widely adopted for its cost-effectiveness and speed in excavation. However, it leads to large underground openings that require careful management to maintain stability. The project's focus on this method addresses the challenges associated with maintaining stability in such large openings.
- Role of Geometric Factors: Stope stability is heavily influenced by various geometric factors, including the shape, size, rock type, and inclination of the stope. The project emphasizes the importance of these parameters in designing stable stopes that can withstand the stresses exerted by the surrounding rock mass.
- Empirical and Numerical Approaches: Traditional empirical methods like stability graphs (MTG) and Hoek and Brown failure criteria provide a foundation for preliminary stope design. However, the project integrates advanced numerical modelling techniques, which simulate lithological changes, ground discontinuities, and in-situ stress conditions. These tools enable more accurate predictions and optimization of stope design.

By enhancing stope design through numerical methods, the project aims to improve mining safety, efficiency, and profitability while minimizing environmental impacts and maintaining surface ecology.

IV. METHEDOLOGY

The preliminary study of the area and the problem is followed by an extensive field investigation to enhance the data set which will act as the basis/ constraint for formulating the solution to the problem being faced.

For this study, technical conditions for mining deposits will be assessed. Based on the above factors, a stable stope geometry and pillar dimension will be proposed.

1. **Field work**
    - Data collection and collation: Engineering geological survey, exploration data & in-situ stress data will be collected.
    - Study of ongoing opencast mining operations in the area.
2. **Block Model Preparation in SURPAC:**

Using Exploratory borehole data, solid model of the sub- surface lithology was developed. Also the surface topography was created in the digital model using the survey data provided by the mine. The process involved:

- Importing the survey data as string files and creating a dtm.
- Importing borehole co-ordinates, borehole survey & litho- logs.
- Interpolating data to create a three dimensional model of orebody.

3. Numerical modelling with IMAT:

Preparation of numerical model in IMAT involved the following steps:

- Initial Stope Geometry Decision: Based on practices from other hard rock mines and the rock properties of the wollastonite area, stope dimensions were set at 30-40m length, 15-30m width, and 45m height, with 12m wide rib pillars and 12m thick sill pillars.
- Elastic Modelling: Modelling was conducted using elastic formulations to analyze stope stability under in-situ and induced stress conditions for blocks located about 100m deep, with specific in-situ stress data applied.
- Data Importation:
  - Geometry Import: Surface topography and orebody geometry were imported into IMAT using .dtm and .str files.
  - Block Model Import: A Geological Block Model was imported via CSV, defining an octree grid for FLAC3D numerical analysis.
- Model Construction in FLAC3D:
  - In-Situ Stress Input: Stress conditions were defined based on data provided by the mine.

Table -1 In-Situ Stresses in the region

S. No.	Stress	Value
1	Sigma 1 Fixed Component (MPa)	2.5
2	Sigma 2 Fixed Component (MPa)	1.5
3	Sigma 3 Fixed Component (MPa)	1.8
4	Sigma 1 Depth Component (MPa/m)	0.0220
5	Sigma 2 Depth Component (MPa/m)	0.0140
6	Sigma 3 Depth Component (MPa/m)	0.0180
7	Sigma 1 Azimuth	125.0
8	Datum mRL	750

  - Boundary Conditions: Set as fixed except for the upper boundary, which was free to simulate surface behavior.
  - Mining Sequence: Simulated as a single-stage excavation to assess maximum instability.
  - Grid Refinement: Areas near stopes refined to 2m for detailed analysis.
  - Material Properties Definition: Specific rock mass properties were assigned to differentiate orebody and host rock.

Table-1 Specific Rock Mass Properties

Rock Type	Density MT/m^3	UCS MPa	Bulk Modulus GPa	Poisson's Ratio	Young's Modulus	Cohesion MPa	Dilation Angle	Residual Cohesion	Residual Friction	Tensile Limit MPa	Friction Angle

					GPa			MPa	Angle		
Wollastonite	2.7	35	18	0.25	50	4	2^o	0.5	22^o	1.5	35^o
Skarn	2.7	60	25	0.25	60	8	2^o	3	29^o	6	38^o
Pegmatite	2.7	40	25	0.25	60	6	2^o	3	29^o	4	38^o

Figure 1: A Figure showing the designed stopes within the IMAT model, Vertical Projection, North Orientation

IV. DATA ANALYSIS AND RESULT

In-Situ Stress Conditions: Prior to excavation, in-situ stress analysis was conducted, displaying principal stresses Sigma 1, Sigma 2, and Sigma 3 in equilibrium. These conditions provided a baseline for evaluating stress changes post-excavation.

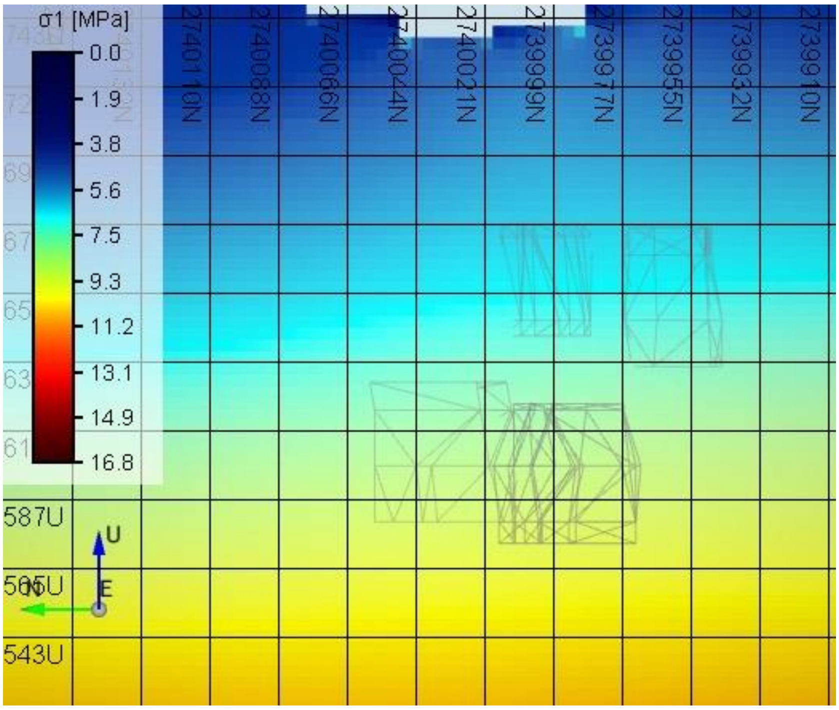

Figure: 2 Transverse Section showing Sigma 1 in the equilibrium condition

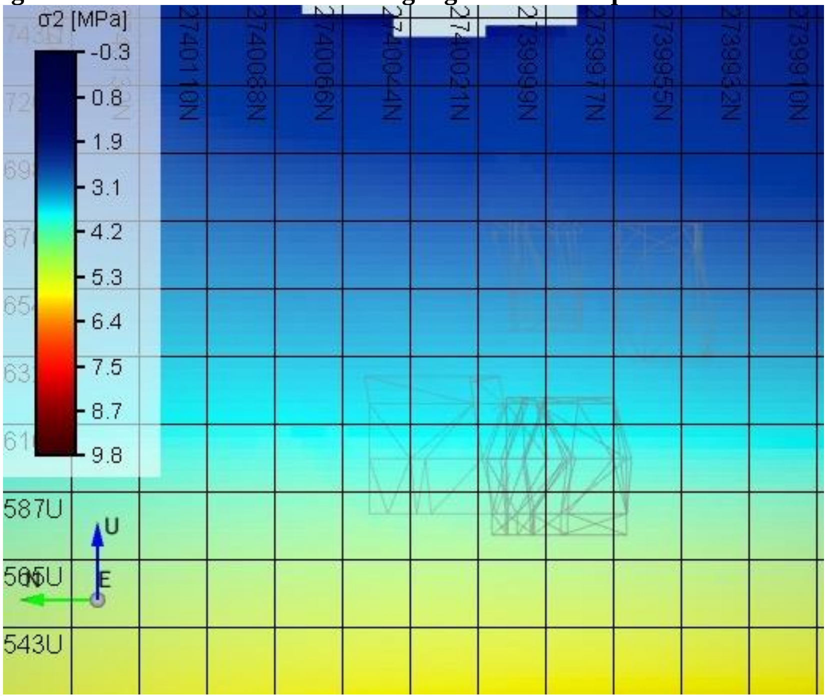

Figure: 3 Transverse Section showing Sigma 2 in the equilibrium condition

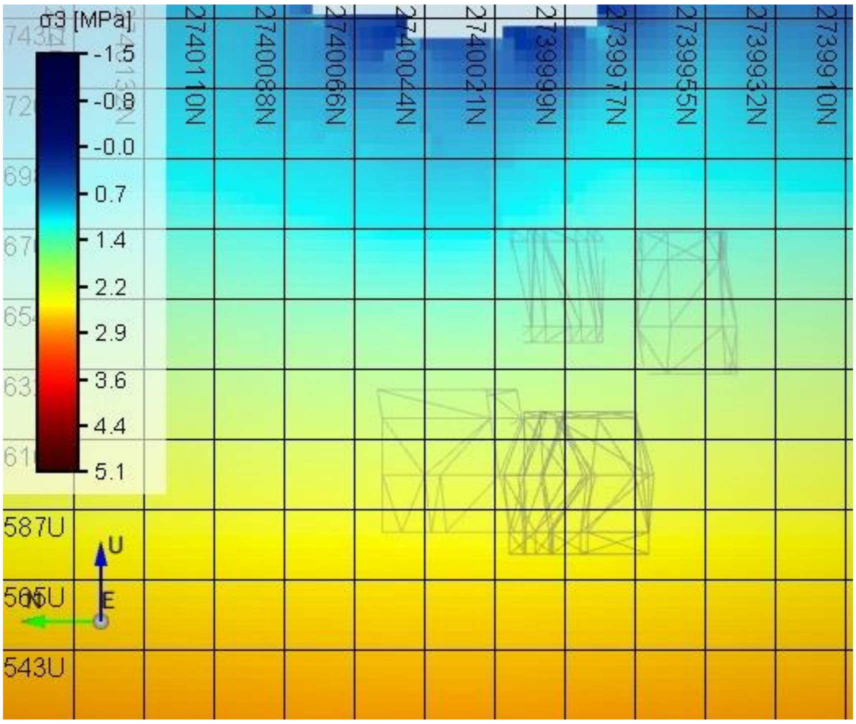

Figure: 4 Transverse Section showing Sigma 3 in the equilibrium condition

Post-Excavation Stress Analysis:

- Case 1: Stope Size 40m x 30m x 45m
    - Sigma 1: Stresses increased from 6-8 MPa to 10-16 MPa at crown and rib pillars, indicating a significant rise in stress concentration.

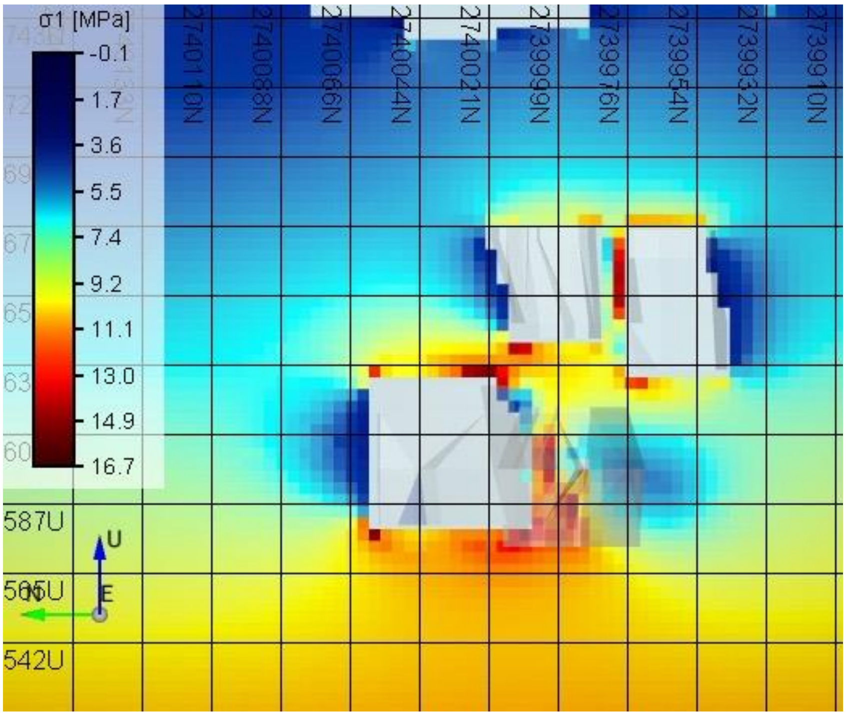

Figure: 5 Transverse Section showing Sigma 1 after mining of stopes sized 40 m x 30m x 45 m

    - Sigma 2: Increased stresses in rib pillars from 3.5-4.2 MPa to 5.2-6.5 MPa, with a decrease in the crown to 1.8-2 MPa, suggesting a destressing effect.

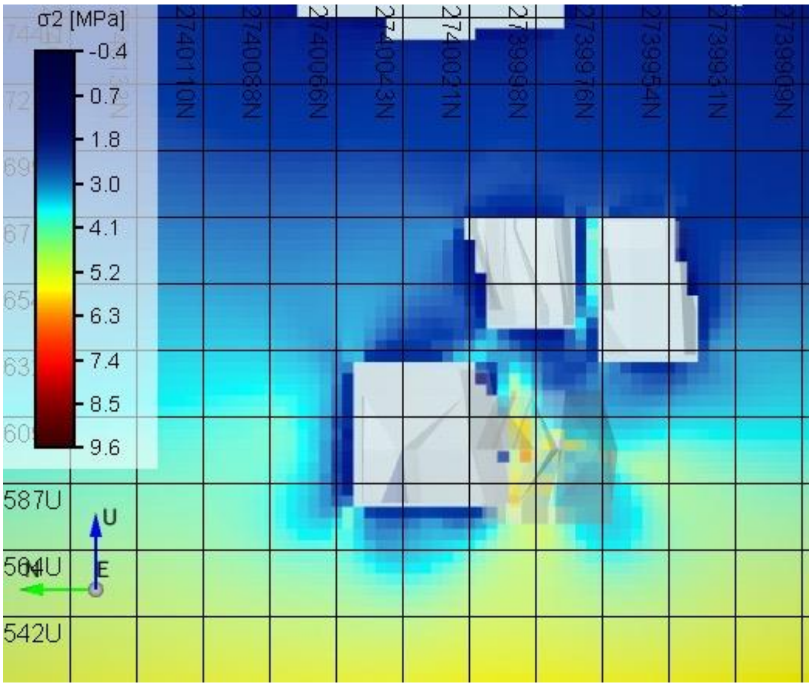

Figure: 6 Transverse Section showing Sigma 2 after mining of stopes sized 40 m x 30m x 45 m

- Sigma 3: Increased from 1.4-2.5 MPa to 2.8-3.6 MPa in rib pillars, with a tensile stress condition in the crown, indicating potential instability.

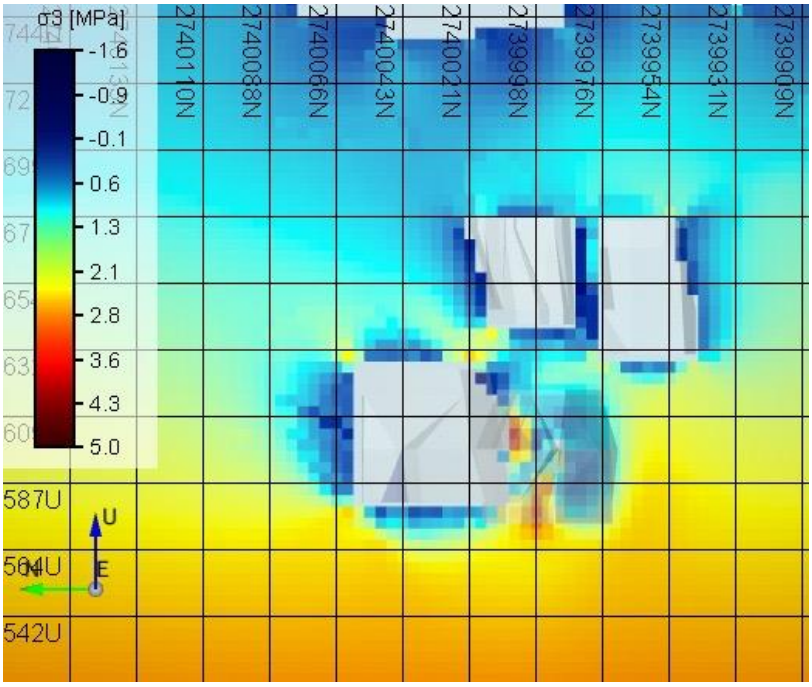

Figure: 6 Transverse Section showing Sigma 3 after mining of stopes sized 40 m x 30 x 45 m

- Case 2: Stope Size 40m x 30m x 36m
    - Sigma 1: Stress increased from 6-8 MPa to 10-12 MPa in the crown and rib pillars, reflecting a lower rise compared to Case 1.

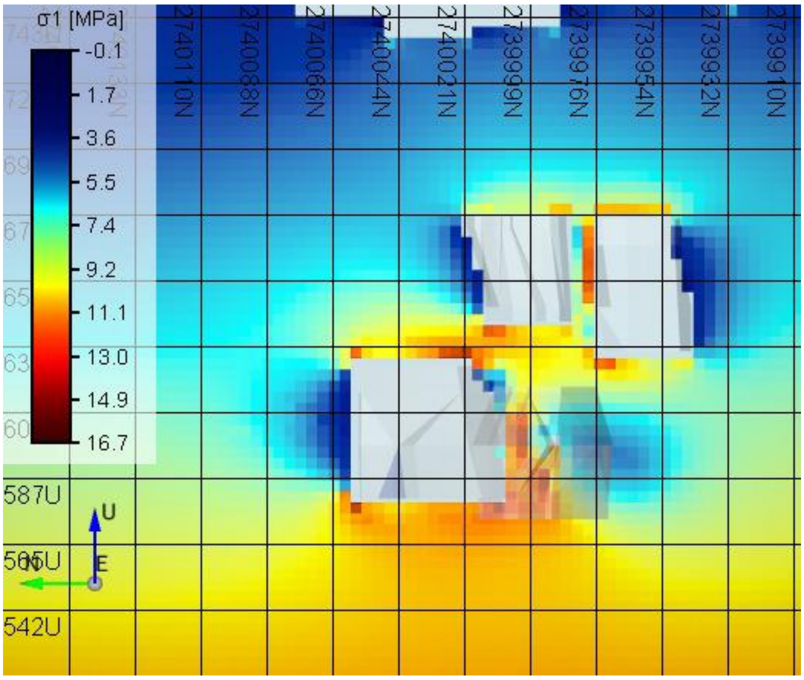

Figure: 7 Transverse Section showing Sigma 1 after mining of stopes sized 40 m x 30mx 36 m

- Sigma 2 and Sigma 3: Exhibited similar patterns to Case 1, with lesser stress increases in the rib pillars and a destressing condition in the crown.

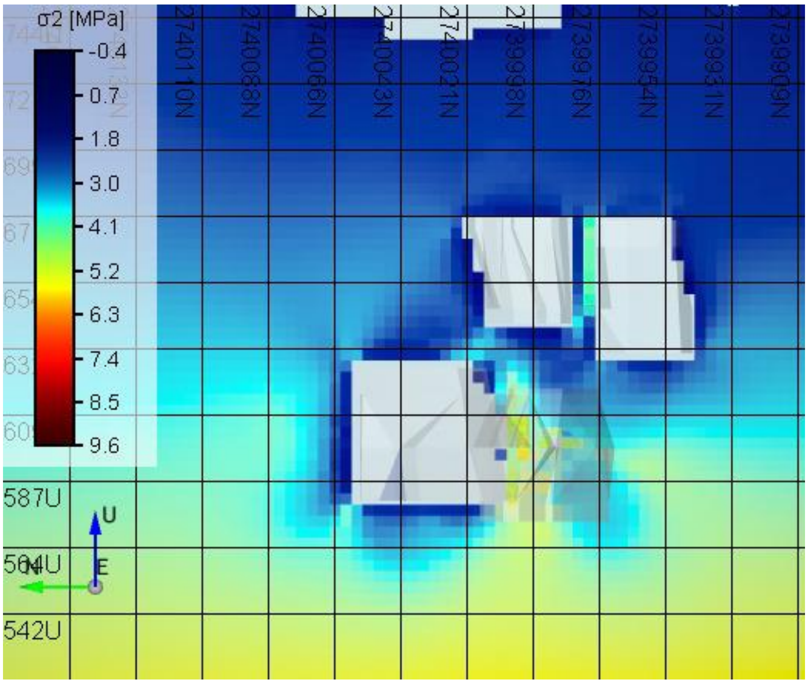

Figure: 8 Transverse Section showing Sigma 2 after mining of stopes sized 40 m x 30mx 36 m

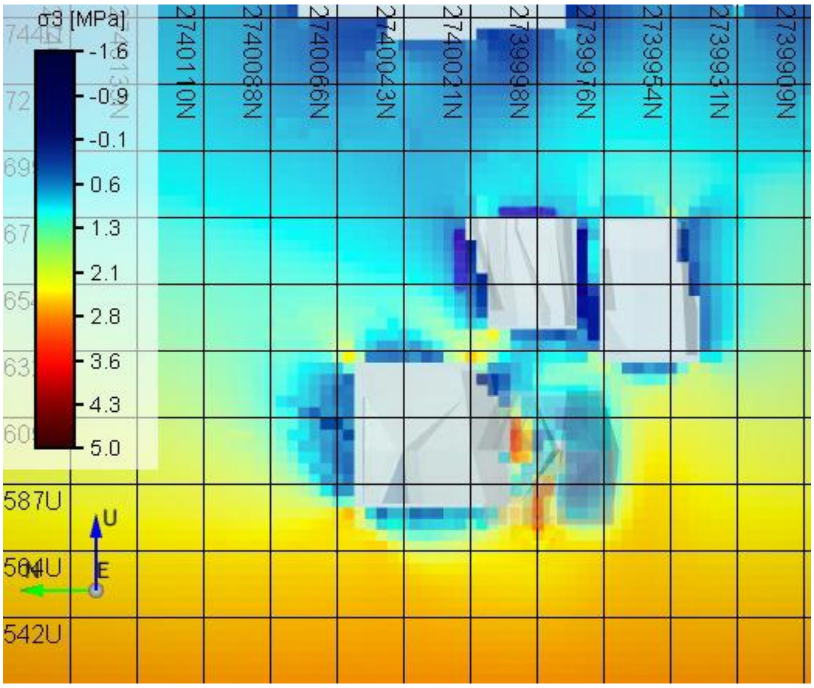

Figure: 9 Transverse Section showing Sigma 3 after mining of stopes sized 40 m x 30mx 36 m

The analysis indicates that the stope geometry in Case 2 provides better stability, with a higher safety factor and lower stress concentrations compared to Case 1. This highlights the importance of optimizing stope dimensions to maintain the structural integrity of underground excavations.

The selection of the stope geometry has been based on stable stope geometry against the increase in stresses in the pillars. However, the destressing conditions in the stope walls also create a potential unconfinement conditions, which may lead to joints opening at the periphery of the exposed walls. This may be triggered by blast vibrations and occurrence of unknown, hidden weaknesses in the wall rocks. The most vulnerable walls are the crown pillar back and the drawn point X- cuts, drill sills and pillar drives.

To avoid such situation all these entries are pre supported (prior to stoping) with interior supports like cable bolting in addition to normal Rock Bolting and SSR, especially for the open stoping method of mining.

Further it is seen that there is destressing and change in orientation of the stress tensors. It indicates that these areas are not suitable for doing any excavations/ Developments as the excavations will experience unconfinement and shear r tensile loading which will open the intact joints and create instability. Hence no permanent development to be done within 15 of the stope boundaries.

However, the ground needs to be instrumented with suitable stress meters and extensometers for monitoring the stability of crown and rib pillars.

VI. CONCLUSION

This study aimed to design optimal stope and pillar geometries for the underground mining of the East deposit at the Kheratarla Wollastonite and Calcite Mine, marking the transition from open-pit to underground operations. The objectives included comprehensive data collection, evaluation of current open-pit practices, creation of a 3D geological model, and numerical modeling to define the best stope and pillar design. These objectives were systematically addressed, leading to the following outcomes.

- Extensive data collection, including topographical surveys, in-situ stress data, and lithological details from boreholes.
- The creation of a 3D geological model using SURPAC, which provided a detailed view of the orebody's geometry and mineralization, aiding in identifying feasible underground mining zones and defining parameters for numerical analysis.
- Evaluation of current open-pit operations, revealing challenges like a high stripping ratio, limited dumping space, and boundary constraints, driving the need for underground mining. Surface geological features helped refine rock mass properties for modeling.
- Assessment of mining methods, with Sub-Level Open Stoping (SLOS) chosen due to its suitability for the steeply dipping orebody and competent host rock.

- Numerical modeling using IMAT and FLAC3D simulated stope and pillar configurations, assessing stress, deformation, and safety. This led to the identification of stable stope geometries and pillar dimensions, with recommendations for rib and crown pillar placement to enhance stability.

The study successfully achieved its goals, offering a robust framework for safe and economically viable underground mining. These findings contribute to sustainable mine planning, particularly in optimizing stope and pillar designs for challenging geological conditions. The study's scope was limited to the first two blocks of the orebody, but similar designs can be applied to subsequent blocks, with adjustments based on operational feedback.

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