Thesis Project

Investigation into the appropriateness of room-and-pillar mining system with pillar recovery at the Zhomart Mine

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Originality Statement

I, Adil Gabdullin, hereby declare that this thesis titled, " Investigation into the appropriateness of room-and-pillar mining system with pillar recovery at the Zhomart Mine" is a result of my own original research. It has not been submitted elsewhere for any degree or qualification, and it is composed of materials for which I have fully recognized and credited any sources. Where the intellectual contributions of others have been incorporated, they are appropriately acknowledged and cited.

Signature: Adil Gabdullin

Date: 07.04.2024

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Abstract

This thesis investigates the appropriateness of the room-and-pillar mining system, focusing on pillar recovery at Zhomart Mine, a complex orebody in Kazakhstan's Karaganda region. Given the mine's unique geological characteristics, this study evaluates whether traditional room-and-pillar mining remains suitable amid concerns over subsidence and mine stability. Utilizing the University of British Columbia (UBC) Mining Method Selection Wizard and Rocscience's RS3 for numerical modeling, this research assesses alternative mining methods, particularly Cut & Fill and Sublevel Stoping, against the current room-and-pillar approach.

The findings indicate that the room-and-pillar method, while traditionally favored for its simplicity and cost-effectiveness, ranks lower in suitability due to the mine's geotechnical challenges. Simulations predict significant subsidence and compromise structural integrity following pillar recovery, supporting a transition to more adaptive mining strategies. The thesis advocates for Cut & Fill and Sublevel Stoping, which provide greater control over ground subsidence and enhance operational safety and environmental sustainability.

This comprehensive study not only underscores the need for a systematic reassessment of mining strategies in light of evolving geological insights but also contributes to the broader discourse on sustainable mining practices. The thesis concludes with recommendations for Kazakhmys to undertake an economic evaluation, considering the long-term benefits of adopting more suitable mining methods that align with the mine's operational and environmental goals.

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1. Introduction

1.1 Background

Located in Kazakhstan's mineral-rich region, the Zhomart Mine is an important part of the nation's mining sector. As mining engineers, one understands that in order to guarantee effective extraction while preserving surface infrastructure, mining method selection techniques must be optimized. The current room and pillar mining system is the main topic of this work, appropriateness of this method and the consequences of pillar recovery receiving particular attention. The objective of this paper is to suggest a better mining strategy by comprehending the properties of the ore body and host rock.

1.2 Problem statement

One problem that Zhomart Mine finds itself confronted with is related to the choice of mining systems. The present room and pillar approach will now call for a critical evaluation in respect of Zhomart Mine's unique geological characteristics since this system conventionally worked best for more uniform and less complex orebodies. The irregular shape of the orebody creates the need for selective mining, as well as the presence of critical surface structures requires a mining approach that minimizes the risk of subsidence. This evaluation is particularly urgent given the implications of pillar recovery processes on the integrity of surface structures and the overall landscape. To address these challenges, this project will utilize the UBC Mining Selection Wizard to objectively evaluate and demonstrate that systems such as the cut and fill mining is more suitable for Zhomart Mine's conditions compared to the traditional room and pillar method. This decision support tool will consider the mine's specific constraints, including orebody geometry, geomechanical parameters and the necessity for selective mining. In order to offer further justification for re-evaluation of the appropriateness of the room and pillar mining system at Zhomart Mine, the project will employ numerical modeling tools such as RS3 from Rocscience, to model the potential occurrence of subsidence during the pillar recovery process. These simulations will provide crucial insights into the spatial aspects of ground movement and subsidence occurrence. By integrating the analytical capabilities of the UBC Mining Selection Wizard with the predictive power of RS3 simulations, this project aims to foster a safer, more efficient, and environmentally responsible mining operation at Zhomart Mine.

1.3 Objectives:

1. Review the host rock and ore body characteristics to determine the appropriate mining system.
2. Simulate the current mining system with pillar recovery to capture the effect of the pillar recovery on the surface.
3. Suggest an appropriate mining system for the orebody considering the characteristics of the host rock and host rock, as well as the protection of surface structures.

1.4 Hypothesis:

The Room and Pillar mining system is not the optimal choice for the Zhomart Mine given its specific geological and operational parameters.

Rationale:

1. Geological Challenges:

The Zhomart Mine is characterized by weak ore and host rock conditions, layered geology with the presence of weak aleurolite which challenge the structural integrity and stability typically required for effective Room and Pillar mining especially in the narrow vein parts of the deposit. These conditions likely lead to increased subsidence and structural issues that are less effectively managed by the Room and Pillar method compared to alternative techniques such as Cut & Fill.

2. Operational Stability:

Room and Pillar mining, while advantageous in stable geological settings, may not provide the necessary ground support in mines like Zhomart, where the geological structure is less accommodating. The hypothesis suggests that alternative methods, which involve active management of ground stability such as backfilling in Cut & Fill mining, could significantly mitigate these issues.

4. Safety and Environmental Sustainability:

The hypothesis also considers the safety of mining operations and their environmental impact. Room and Pillar mining may pose higher risks of catastrophic failures and environmental degradation in settings like Zhomart Mine due to inadequate control over subsidence. A method that incorporates immediate structural support could not only enhance safety but also minimize environmental impacts.

1.5 Justification of the research project

- The primary motivation for this research is to enhance mine safety and stability. The current Room and Pillar method has been identified as potentially inadequate given the mine’s geological complexity. By investigating alternative mining methods, particularly

Cut & Fill, the research aims to propose solutions that can significantly reduce risks of subsidence and structural failures, thereby safeguarding the lives of mine workers and protecting valuable equipment.

- Mining operations, particularly those employing less suitable methods, can have severe environmental impacts, including landscape alteration, habitat destruction, and pollution. By exploring mining methods that better align with the environmental management goals of sustainable development, this research supports the pursuit of eco-friendly mining practices. The goal is to reduce the mine's ecological footprint and ensure compliance with environmental regulations, which is increasingly important in the global push towards greener mining technologies.

1.6 Scope of work

The project considers addressing special conditions in the Zhomart Mine within an approach that combines geotechnical analysis with numerical modeling and joins it with implementation of strategies for mining system improvements. The Project will be developed based on three core aspects that contribute to the overall objective of improving safety, efficiency, and sustainability of the mining operations at the Zhomart Mine. Key areas under scope are outlined below.

Data Collection and Review: Collection of extensive geological data on the ore body and host rock, its mineral composition, structural features, and mechanical properties.

UBC Mining Method selection – empirical assessment method

The data collected will serve as a base for input into the UBC Mining Method Selection tool developed at the University of British Columbia to identify the appropriateness of the room and pillar mining system compared to other techniques.

Pillar recovery effect – numerical modeling assessment

Current Mining Configurations: Existing room and pillar mining configurations will be simulated through the use of advanced numerical modeling tools. In this study, Rocscience's RS3 software will be used to build a baseline model of current practices to compare and analyze.

Pillar Recovery Impact Analysis: Comprehensive forward simulations for major changes that would be induced by mining in the stress distribution, regarding surface stability. This will include a probe into the associated changes in loading conditions to the pillars and potential subsidence scenarios due to the removal of pillars.

2. Literature review

2.1 Current Room-and-Pillar mining system, experience at Zhomart Mine

2.1.1 Site Characterization

The Zhomart Mine in the Jaman-Aibat copper sandstone deposit of the Karaganda region is unique, representing one of the most complex geological and structural settings pertinent to its ore-bearing rock mass. The room and pillar development system—a system for developing solid minerals (ore, coal, etc.) by rooms separated from each other by pillars supporting the roof—is used for the development of flat and inclined deposits with dip angles up to 20 degrees of small and medium thickness under stable and moderately stable ore and enclosing rocks (Hamrin, 1980). The conditions for using this development system are high strength of ores and enclosing rocks. The technical and economic indicators of the room and pillar development system with the use of self-propelled equipment are quite high. Along with this, it has significant disadvantages - the constant presence of people in the open cleaning space, loss of ore in the pillars, and an increase in the volume of voids supported by an increasing number of inter-chamber pillars (ICP) (Nieto, 2010).

At the deposits located in the Ulytau area with the room and pillar system at great depths, to reduce the pressure from the overlying rock mass on the inner-chamber pillars, the ore deposits are divided into panels using belt barrier pillars. Which, in turn, take the main load on themselves, thereby relieving the inter-chamber pillars for the safest and maximum extraction of chamber reserves. In such cases, chamber reserves are worked out by several rooms with the leaving of solid or columnar support pillars. Pillars are divided by their purpose into inter-chamber, barrier, separating, protective, and others. They can be temporary and permanent. For permanent pillars, parameters are adopted that ensure the maintenance of the worked-out space for a long time, temporary for the period of working out chamber reserves. Currently, it has been confirmed that it is impossible to support the overlying rocks with pillars over a long period of time (Bitimbaev, 1997). Cases of destruction of inter-chamber pillars and collapse of roof rocks with emergence of subsidence on the earth's surface are known in the Zhezkazgan, Mirgalimsai, Vishnevogorsk, and other mines (Zhiyenbayev, 2024). Over time, as well as under the influence of mining operations, brittle failures accumulate in the inter-chamber pillars (ICP), culminating in their destruction and sudden collapses of the overlying strata.

2.1.2 Pillar recovery process at Zhomart Mine

According to geotechnical reports from the operating company "Kazakhmys", the gradual deterioration of the geomechanical situation at the Zhezkazgan deposit is characterized by an increase in the number of destroyed pillars, and the areas and volumes of collapse zones. Since the mid-1990s, collapses of the overlying strata over large areas at the Zhezkazgan deposit have occurred in the form of technogenic earthquakes and were accompanied by air shocks in the mines. Therefore, in 1996, a concept for further effective and safe development of the Zhezkazgan deposit under the existing mining and geomechanical conditions was developed, the essence of it was to simultaneously with the development of the remaining balance reserves of the room and pillar system in previously developed panels, to conduct redevelopment of the ore pillars with the extinguishing of the accumulated worked-out spaces by collapse. Moreover, the concept is prescribed to extinguish voids in weakened areas with partially destroyed ICP by controlled self-collapse of the overlying strata, and in areas with critical surface structures - by hydraulic backfilling with enrichment tails. That is, a fundamental decision was made to transition from long-term maintenance of open worked-out spaces to their extinguishment. As originally anticipated by the concept, the main method of void extinguishment was supposed to be redevelopment. However, a number of objective reasons have emerged that complicate its planning and conduct. These include:

- The built-up structures on the earth's surface with engineering communications (most often), which burdens redevelopment with the costs of time and resources to move protected objects beyond the ground subsidence area.
- The weak strength characteristics of the rock mass, overlapping geology with various rock interlayer thicknesses, often with weakened sections in the suite of deposits.

Figure 1. Surface structures at Zhomart Mine taken from Google Earth Pro

However, the main problem with redevelopment turned out to be the chain reaction of ICP destruction, initiated by the redistribution of loads from the extracted to the remaining pillars. The concentration of support pressure on the ICPs located at the edge of the collapse zone leads to their overload and destruction following a domino effect (Zhiyenbayev, 2024). A characteristic example from the experience of the South Zhezkazgan mine is shown in the figure below:

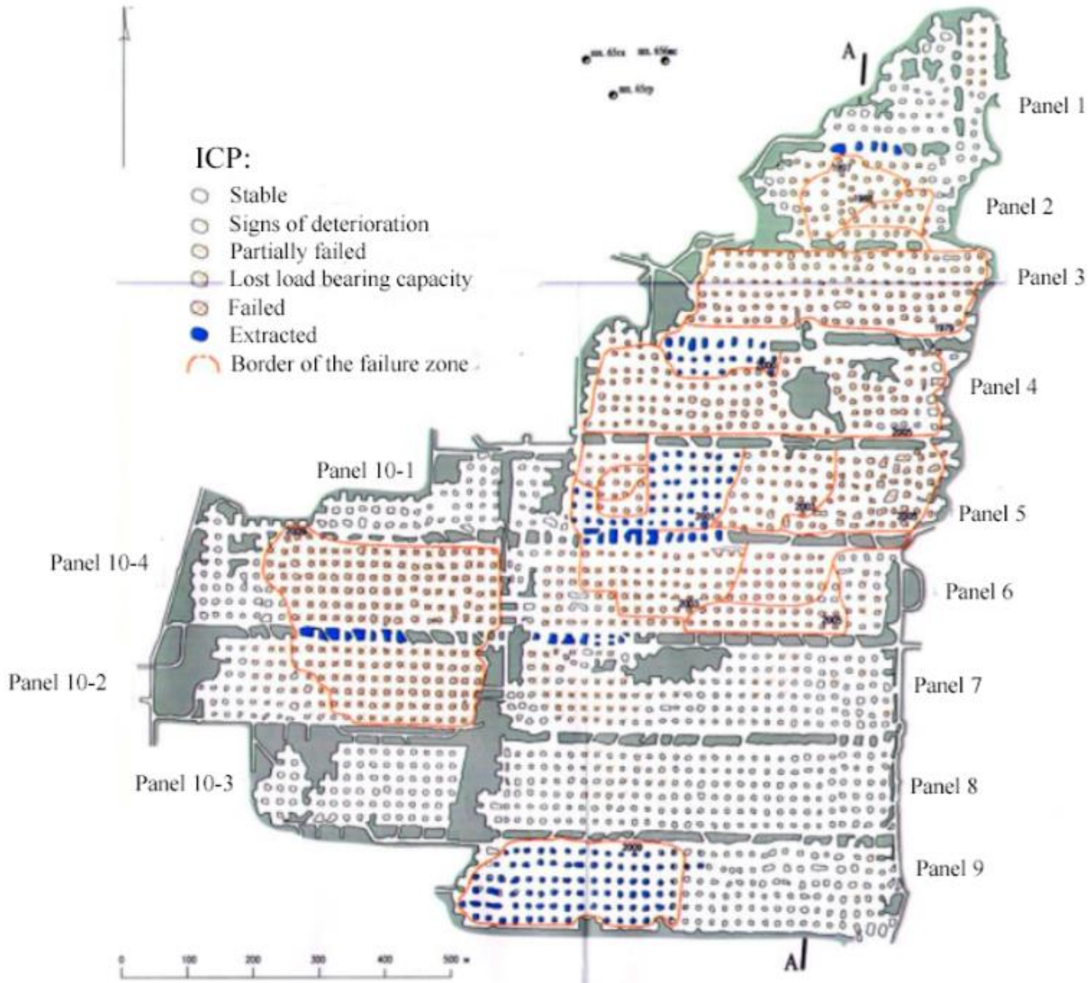


Figure 2. State of mining operations, redevelopment, and collapses of the overlying strata at the Jaman-Aibat deposit (Zharaspaev, 2023).

After the extraction of 22 pillars in panel 4, a chain reaction of ICP destruction began, and its collapse occurred. In panel 5, the chain reaction of ICP destruction began after the development of 39 pillars. The redevelopment was stopped. The example from practice shows that a significant obstacle to the redevelopment of extensive deposits from the open worked-out space is the insufficient stability of the ICP. In extensive worked-out spaces with a large span of undermining of the overlying strata, the redevelopment of pillars is much more difficult and dangerous than in individual extraction units (panels, blocks) with small spans.

According to Figure 3, to confirm this fact, it is sufficient to analyze the extraction indicators of ICP in panels. A total of 1514 pillars were processed, of which only 164 pillars (11%) were successfully extracted. In the collapse zones, 705 pillars (47%) were crushed by rock pressure. This means that at this deposit, the volume of voids extinguished by uncontrolled collapse of the overlying strata after the chain reaction of ICP destruction exceeds the volume extinguished by controlled collapse during redevelopment by 4.3 times (Zhiyenbayev, 2024). Due to the impossibility of roof extraction and the danger of a chain reaction of ICP destruction, panels with an extraction capacity of more than 12 meters are also inaccessible for redevelopment from open working space.

The insufficiency of currently used methods of controlling rock pressure to stabilize the geomechanical situation at the Zhezkazgan deposit is vividly illustrated by the dynamics of accumulation of ICPs destroyed by rock pressure as shown in the graph below. This means that the front for redevelopment from open working space, in recent years considered the main method of extinguishing accumulated voids, is narrowing at a fairly rapid pace.

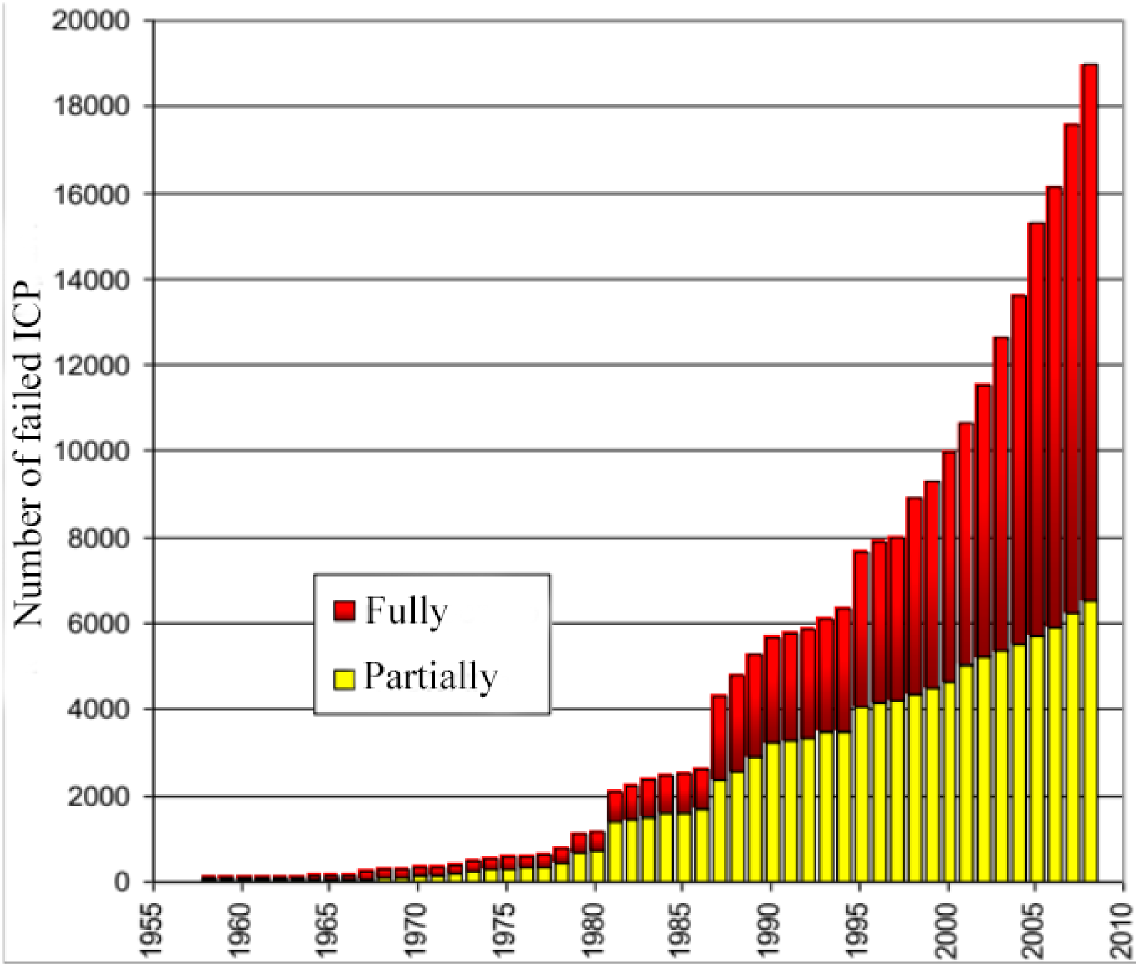


Figure 3. Increase in the number of destroyed ICPs at the Zhezkazgan deposit (Zhiyenbayev, 2024)

Based on geological, geotechnical, Hydrogeological, and technical parameters Jaman Aibat Deposit is considered an analogue of Zhezkazgan deposit. Furthermore, the initial design parameters for the room and pillar system for Zhomart Mine were inferred from the Zhezkazgan deposit. Although, after the collapse of 4 rows of pillars in the first 2 panels, it was discovered that the design parameters that were based on geological and geomechanical properties of Zhezkazgan deposit were not suitable for Zhomart mine. The strength parameters of the rock mass at Zhaman-Aibat deposit is almost half of those at Zhezkazgan deposit accompanied by much more layered geology with the presence of weak aleurolite (Zharaspaev, 2017).

2.1.3 Ground Failure Mechanisms

The causes of ground instability mentioned above usually manifest in various types of ground failure mechanisms in underground mining operations. Figure 4 depicts the type of failures experienced in underground excavations due to the influence of in-situ stress and rock mass structure. When excavations are driven in a low stress mining environment, failure is mainly due to continuity and distribution of natural fractures in a brittle rock mass. Low stresses also allow the unraveling of blocks from the excavation surfaces if the rock mass is highly fractured as shown in the Figure below:

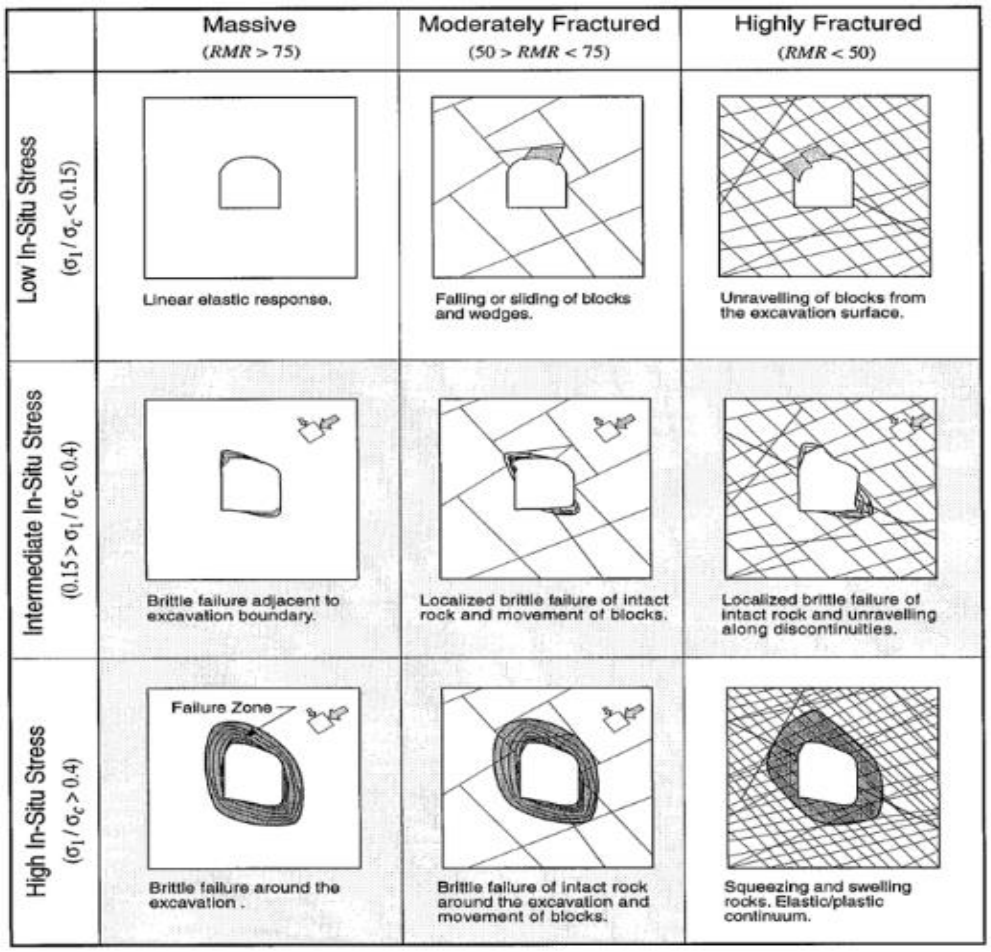
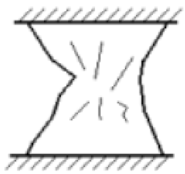
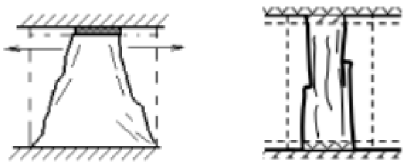
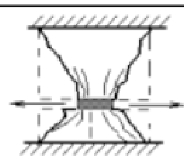
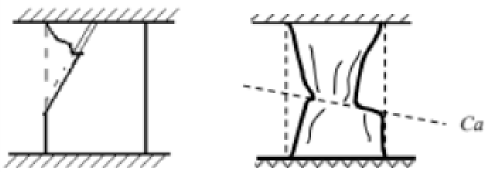
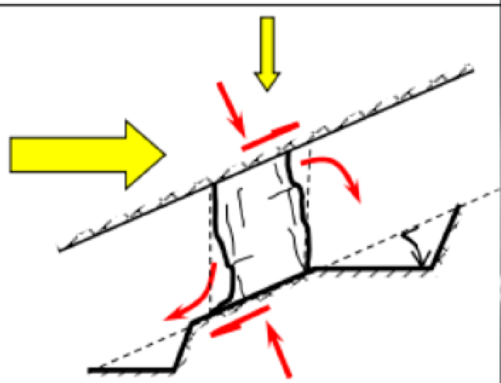


Figure 4. Ground failures in different levels of stress and rock structures (Martin et al., 1999)

However, in high stress environments as in the case of the Jaman-Aibat deposit, new stress-induced fractures are created and usually they are parallel to the excavation boundary (Martin et al., 1999). Failure manifests as squeezing and swelling of rocks in high stress. Stress induced failure in brittle rock masses are associated with slabbing and spalling and the failure zone exhibits a notched-shape regardless of the excavation shape. The far field stress coupled with excavation geometry and the rock mass strength also influences the depth of failure significantly. According to Castro and McCreath (1997), in intermediate stress environments rectangular shaped excavations with a flat roof are more stable than those with arched roofs.

Table 1. Typical forms of ICP failure at Zhomart Mine (Zhiyenbayev, 2024)

Failure Modes	Failure Mechanism
	The formation of spall cracks due to compressive loads that exceed the bearing capacity when fully bonded with the enclosing rocks (normal contact conditions).
	The formation of detachment cracks due to the presence of weak interlayers at one or two contacts (weak contact conditions) and the development of tensile stresses.
	The formation of detachment cracks due to the presence of weak interbeds within the ore body under normal contact conditions.
	Along steeply dipping and gently dipping tectonic disturbances and large cracks with vein minerals or clay of friction.
	Along cross cracks and interlayer cracks, and glide planes on inclined deposits, ICPs, formed vertically, are destroyed by normal and shearing forces. The shape of the destroyed ICPs becomes inclined.

The development of destruction over time is an important characteristic that is taken into account when assessing the stability of the worked-out space. As stated by “Kazakhmys” reports, mining experience at the Zhezkazgan deposit has established that the beginning of dangerous geomechanical processes, posing a threat to the safety of those working in the mine and the preservation of objects on the earth's surface, is the destruction of ICPs and the collapse of inter-chamber ceilings. Therefore, the first means of monitoring the Zhezkazgan deposit massif are systematic visual surveys of the worked-out space to identify and record signs and facts of the destruction of pillars, and roof collapses of chambers and ceilings. The frequency of visual surveys can vary from once a year (in areas where stability does not raise questions) to once a day (in responsible areas with intensive development of the geomechanical situation).

During visual inspections, the appearance of new and the development of existing cracks from the lateral surfaces of ICPs, roofs of chambers, and ceilings are identified. Visual inspections are conducted at Zhezkazgan deposit in such a way that repeated inspections can trace changes in the geomechanical situation over time. For example, registered cracks can be marked with chalk, measuring the width of their opening, marking delaminations from pillars and roofs with the date of their registration.

Figure 5. Formation of cracks on the lateral surfaces of pillars and in the roofs of chambers at Zhezkazgan deposit

Long-term observations have established that the process of destruction of columnar ICPs goes through several stages, which are well distinguished visually. The stages of pillar destruction are shown in Figure 6. The frequency of inspections of the worked-out space is chosen such that the process of pillar destruction can be traced.

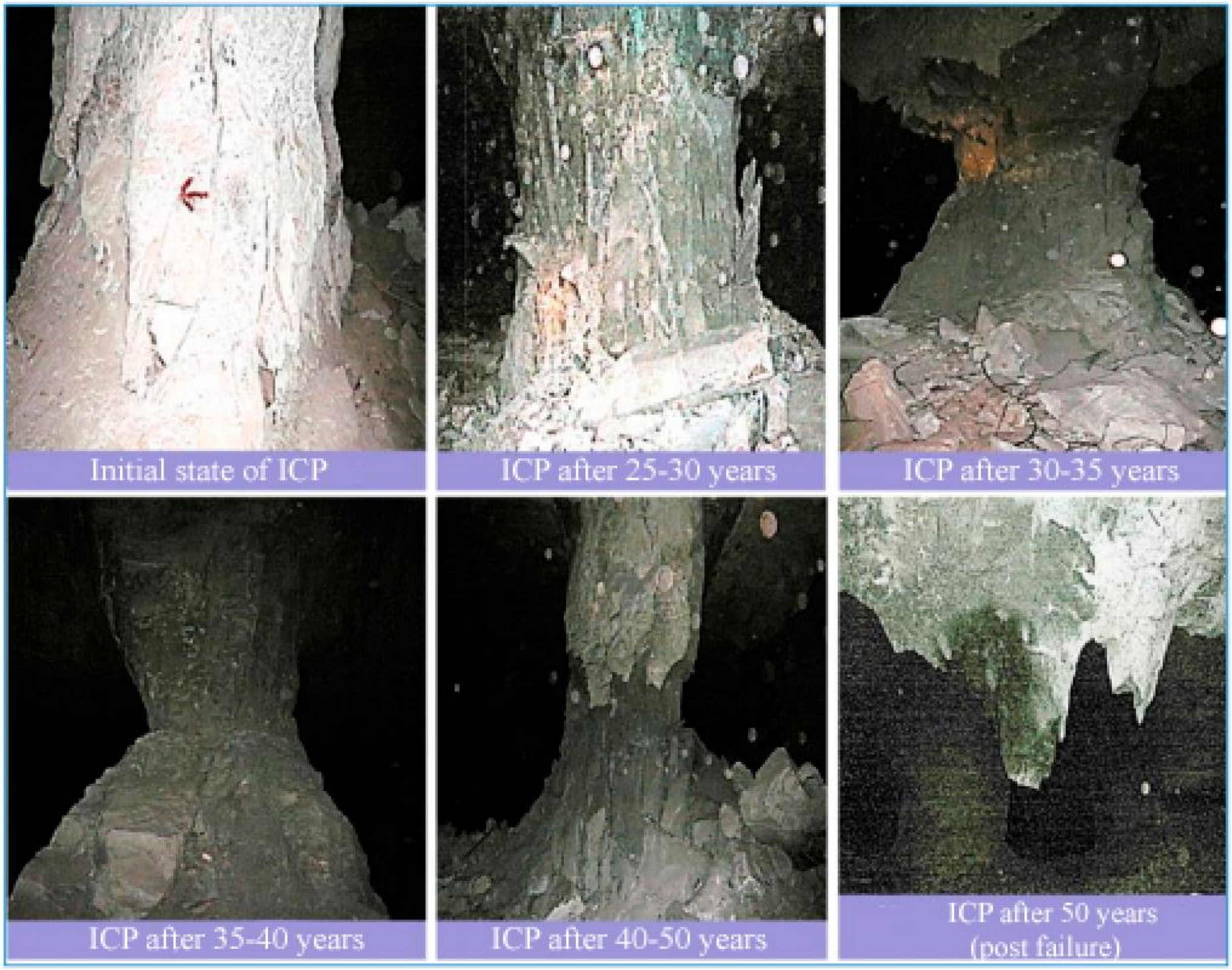


Figure 6. Stages of pillar failure captured from Zhezkazgan deposit

When it comes to the roof of the chambers, when cross-cutting chambers and first inter-chamber pillars are formed, the roof, secured by anchors, delaminates from the overlying rocks and hangs on the anchors bolts. Numerous discontinuous cracks appear, necessitating their forced collapse. In areas of the roof not reinforced with shotcrete, discontinuous cracks up to 1.5 to 2.0 meters in length with an opening width of up to 0.5 cm are visible. According to Zhiyenbayev (2024), in most chambers, in the face zone after ore extraction, within the first hours after exposure, the destruction of the lower layer of roof rocks occurs, exposing the anchors up to 0.5 meters. The roof of the chambers is packed with thin layers of alternating rock, compressed by tectonic stresses, then these patterns of roof collapses (delaminations) correspond to the loss of stability from longitudinal compression by horizontal stresses.

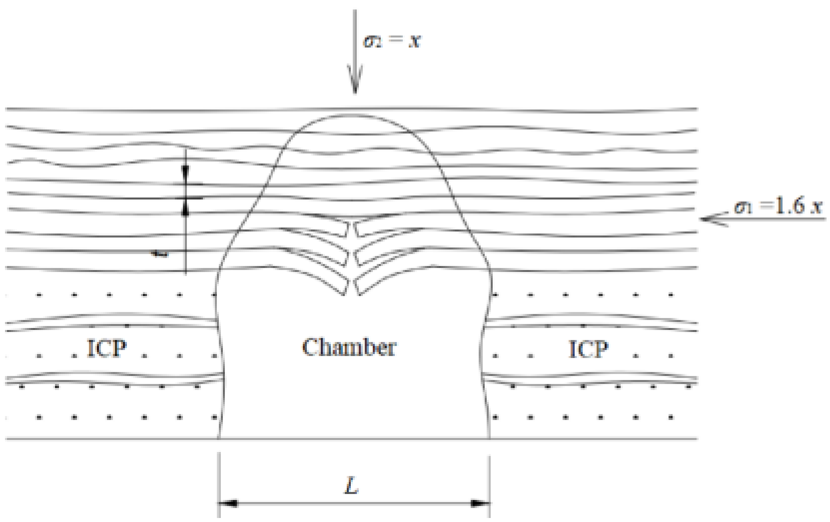


Figure 7. Shape of the roof collapses in chambers at the Zhomart mine

Figure 8. Types of roof failures in chambers at the Zhezkazgan deposit

2.1.4 Subsidence occurrence

The redevelopment of gently dipping ore deposits with the extraction of ore from previously left pillars entails a change in the method of controlling rock pressure: rigid support of the overlying mass is replaced by its collapse. The transition of the mass into new support conditions leads to a sharp intensification of geomechanical processes, primarily the displacement of rock masses.

Large volumes of mass collapse and shift. After the movement of the collapsed rocks into the worked-out space, a void forms under the upper contour of the collapse zone. This in turn, leads to the void rising upwards causing surface subsidence (Nieto, 2010). The equivalent span of the worked-out space, not supported by ore pillars, must exceed the critical limit. If this condition is not met, the collapse process of the overlying strata will conclude with the formation of a natural equilibrium arch. The overlying rocks will hang, forming a support pressure zone on the pillars and the mass surrounding the collapse zone.

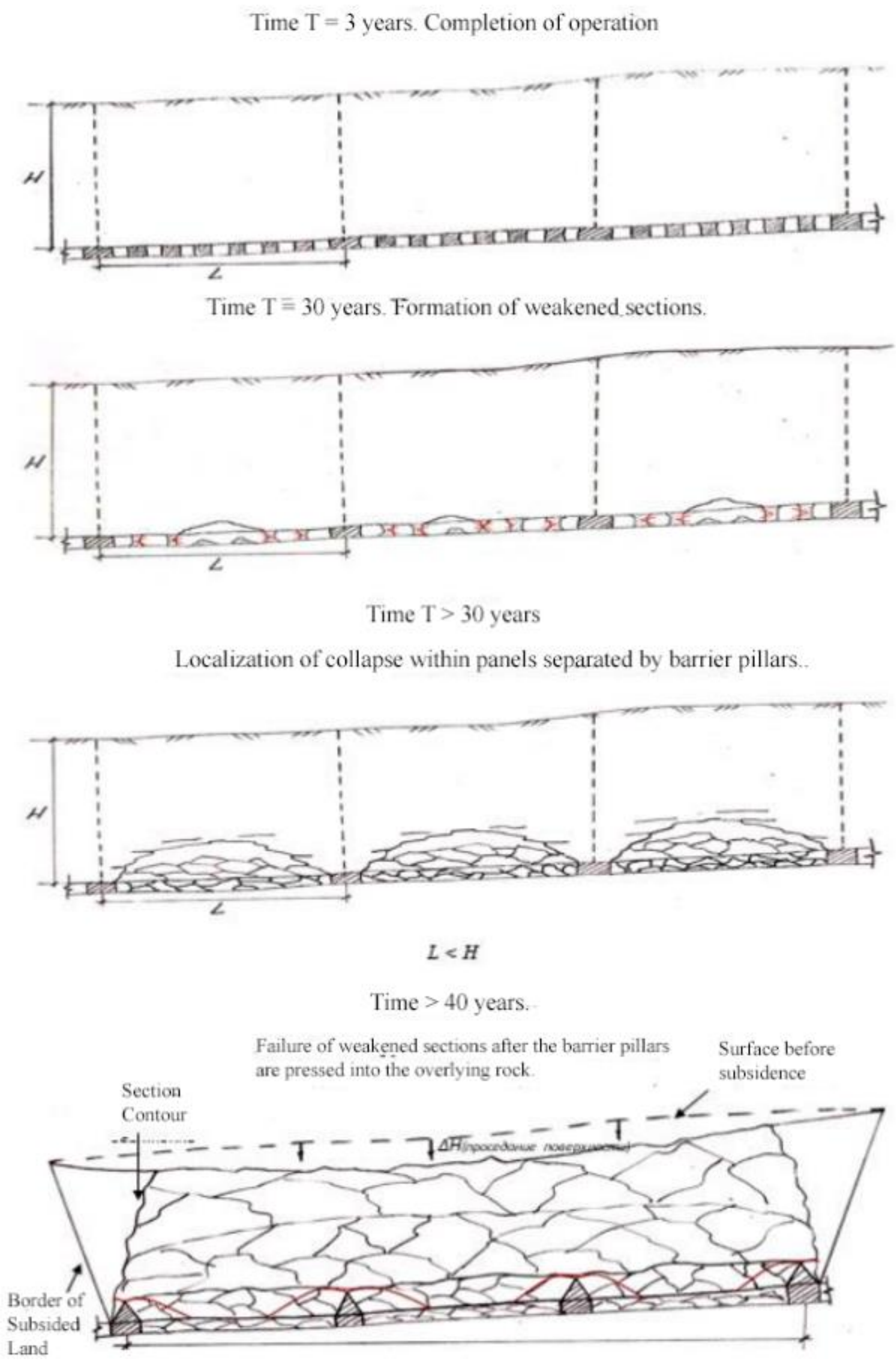


Figure 9. Dynamics of the development of areal collapses over time at Zhezkazgan deposit

In 2020-2021, within the framework of the "Program of Work to Stabilize the Geomechanical Situation at the Mines of the Production Association 'Zhezkazgan Svet Met', work was resumed to study the displacement of the earth's surface using methods of radar space monitoring at the Zhezkazgan deposit and the "Zhomart" mine (Kazakhmys Development LLP, 2021).

In the course of the work to determine subsidence by the method of radar interferometry based on space radar imaging from COSMO-SkyMed and Sentinel-1b spacecraft, refining data on settlements at the Zhezkazgan deposit, Zhylandy deposit, and Zhomart mine were obtained. As a result of the analysis of the obtained settlements, a number of local zones were identified where uniform progressive settlements over time were observed.

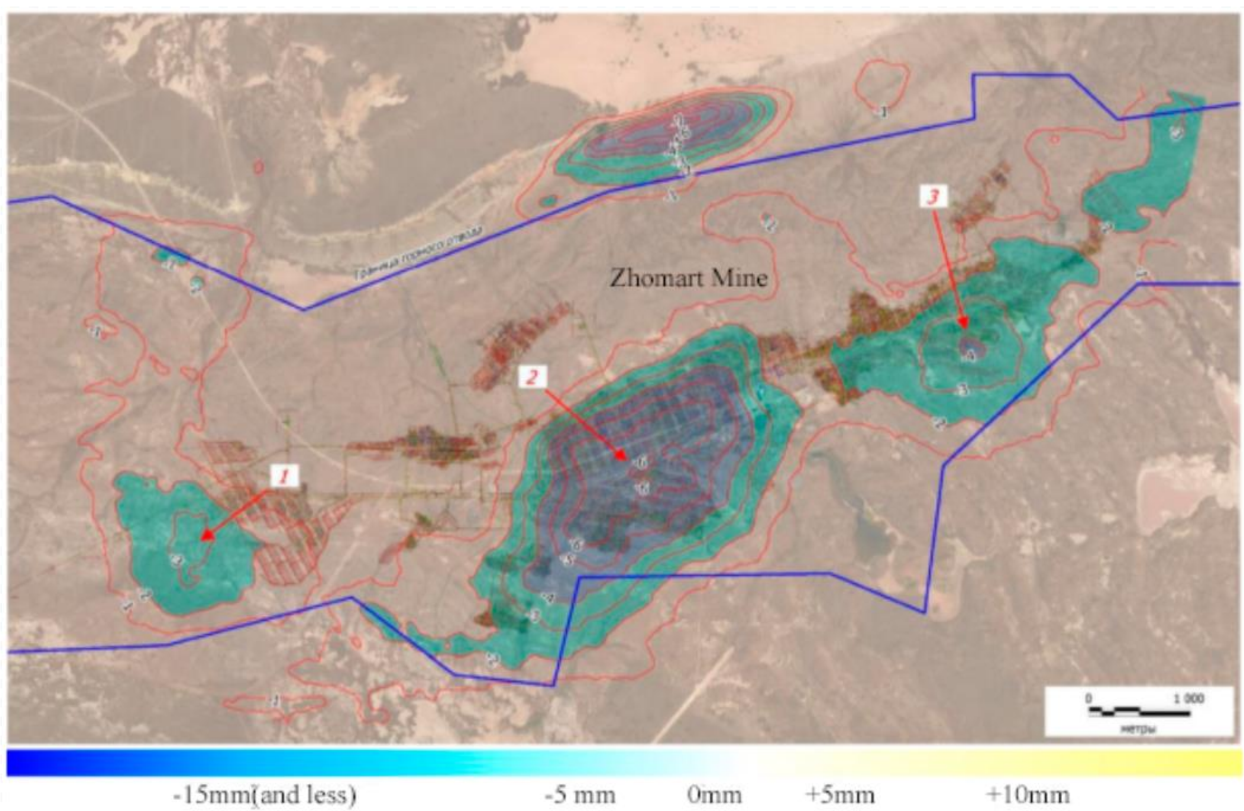


Figure 10. Subsidence map for 228 days (29.03.20-19.10.20) of the "Zhomart" mine according to Sentinel-1b data

Zones with settlements of more than 1 mm are highlighted in blue. Contour lines are drawn at 1 mm intervals. According to the results of space radar interferometry, the maximum subsidence at site No2 for the year 2021 was 6.7 mm, and the maximum subsidence along profile line No1 for 2021 was 7.4 mm (Kazakhmys Development LLP, 2021).

2.2 Design of Inclined Orebodies

Designing such mining operations on an inclined ore body is particularly problematic. The problem is mostly seen in room and pillar mines where both the orientation and the slope of the ore body greatly affect stress and failure mechanisms that occur within the pillars. It will explain the failure mechanisms occurring in inclined pillars while stating the design criteria of the combined compression and shear test system on the basis of the studies and analyses.

The mining of inclined orebodies under shear loading introduces complex failure modes that differ significantly from those experienced in horizontal or mildly dipping seams. Suorineni et al. (2014) indicated that the failure modes of inclined orebodies are subjected to a combination of axial compressive stress and shear stresses, primarily governed by the loading conditions of shear. The main identified failure mechanisms are sliding along the dip direction, shear dislocation, and buckling, each affecting the failure caused by the inclination angle, pillar geometry, and the rock mass properties.

Thus, inclined pillars are more prone to shear-induced failures due to directional concentration of stresses, which enhance the shear stress component along the inclined plane. Jessu, Spearing, & Sharifzadeh (2018) conducted laboratory and numerical studies on the strength performance of inclined pillars and found that the inclination increases the susceptibility of the shear failure of the pillar, hence calling for an urge toward understanding the mechanism to perfection for guiding the design of mining structures.

Designing mining operations for inclined orebodies requires a meticulous assessment of the load-bearing capacity of pillars, accounting for the combined effects of compression and shear. The complexity of stress conditions necessitates the development and application of a combined compression and shear test system that can accurately simulate the in-situ stress environment of inclined pillars. Such a system is essential for determining the critical stress thresholds that lead to failure, enabling the optimization of pillar dimensions and mining layouts to mitigate the risk of collapse.

Suorineni et al. (2011) present case histories where the influence of shear loading on mining operations is described, with these reinforcing the importance of integrating geological and geotechnical data into the design process. The combined compression and shear test system is to be capable of duplicating the specific conditions of the Zhomart mine orebody as closely as possible, both in inclination angles and the characteristics of the rock mass, to allow for reliable data acquisition for the optimization of the design.

2.2.1 Numerical Analysis and Failure Mechanisms

It, therefore, gives impetus that numerical analysis is paramount to explore the failure modes and mechanisms of mine pillars under shear loading. Ma et al. (2016) used numerical simulation to give an insight into the failure behavior of mine pillars by shedding light on the influence of geometric and material properties on the slope angle of inclined orebodies. The following work will be presented below, which allows one to appreciate the numerical model of the distribution of stresses and the patterns of failures. It also allows adopting appropriate reinforcement to improve the stability of the pillar. The models developed in the same line as in the above studies are by Jessu et al. (2018) and Ma et al. (2016) studies, presenting an opportunity to investigate the effects of various mining parameters on inclined pillar performance under different design scenarios. This allows one to identify the parameters by which the design would be most suitable to allow for the least amount of risk of failure while still achieving the most recovery of the ore.

2.3 UBC Mining Method Selection Tool

The UBC Method represents a significant advancement in mining engineering. The tool is structured in such a way that it acts as a decision support tool in the selection process of the appropriate mining method for a given ore body. Developed at the University of British Columbia, the tool captures a decision support developed system to optimize the method selection in mining based on a comprehensive system of criteria, including the technical, economic, environmental, and safety aspects (Miller-Tait, 1995). The significance of the UBC Mining Method Selection Wizard is the fact that it helps in carrying out the right, informed, objective, and systematic selection, thereby providing the optimal solution for the mining operations in efficiency, safety, and sustainability.

2.3.1 Framework and Operational Mechanism

The framework used by the UBC Mining Method Selection Wizard in its operations is a multi-criteria decision-making operational mechanism (MCDM). Although the selection process involves the comparison of different sets of criteria, they are all targeted towards increasing the success of the project. The wizard receives input on technical details, geological and geotechnical data, economic factors, and environmental and safety considerations and then uses a scoring system to assess compatibility of all methods of mining with the project requirements

(Miller-Tait, 1995). This would result in a more refined comparison of possible mining strategies once each method under consideration is carefully analyzed and rated with regards to their suitability to the particular conditions and constraints in that orebody. The result is an ordered list of mining methods that gives the decision-maker a quantified basis to make a choice according to the driving overall goals of efficiency, safety, and environmental stewardship (Darling, 2011).

2.3.2 Significance and Impact

The importance of UBC Mining Method Selection Wizard is not just confined to being a decision support tool. It leads to the development of a holistic methodology for mining method selection, which encourages consideration of economic viability, environmental sustainability, operational safety, and technical feasibility. In this sense, the wizard has a lot to do in moving the environmentally friendly, sustainable mining practices forward to keep up with the growing level of responsibility in the industry for extracting resources in a responsible manner (Mijalkovski, 2021a). It aids in the identification of methods of mining that will not only promise economic gain but ensure there is minimization of environmental impact and safety to personnel involved in mining hence aiding in attaining the broader goal of sustainable development within the mining sector (Alpay & Yavuz, 2007).

2.3.3 Recent Enhancements and Applications

Perhaps the most interesting aspect in recent scholarly works is increasing the capability of the UBC Mining Method Selection Wizard through enhanced methodologies of decision-making and adaptation of this tool to the different phases in the mining industry. For instance, Ali and Kim (2021) proposed a Wizard enhancement using the TOPSIS technique—a decision-making approach which improves the efficiency of the tool in considering complex and conflicting criteria, thus the robustness in the selection process of the mining method. Mijalkovski et al. (2022) stressed in a similar manner the flexibility and applicability of the UBC methodology to reach a decision on the choice of an underground mining method. Their research highlights how this tool can be adapted to complex geological settings such as that of the Zhomart Mine.

2.4 Numerical Modeling

Computational modeling acts as an essential tool within mine engineering. Models are systems that enable the analysis of a system's properties and behavior, with the potential to forecast future results under various circumstances (Hammah and Curran, 2009). RS3, from Rocscience, is a modern geotechnical software providing powerful and detailed 3D finite element analysis in modeling complex geological scenarios and stress variations from mine activities (Munemo, 2021). According to Stacey (2018), the essence of numerical modeling lies in converting physical systems into mathematical formulations, fundamentally grounded in solid mechanics principles. This approach allows for an in-depth examination of material stress and strain, crucial for assessing deformation, potential failures within rock formations, and subsidence occurrence.

2.4.1 Limitations of Empirical Approaches

The limitations of empirical methodologies in adequately capturing the complexities of rock layer interactions are underscored by Nguyen and Niedbalski (2016). These methods fall short in considering critical factors such as geological formations, properties of rock masses, discontinuities, and groundwater presence. This gap highlights the relative effectiveness of numerical methodologies in forecasting the effects of subsurface activities on slope stability.

2.4.2 Configuration and Simulation Procedures

The process of model configuration demands meticulous attention to establish precise boundary and initial conditions, reflecting the real-world extent of rock masses. Another important aspect of model configuration is the presence of contour and wireframe models. It outlines the three-dimensional shape of objects being modeled. It emphasizes the significance of interactive elements and their interconnections within the model's framework. Such models can depict various mining structures, including ore bodies, tunnels, the rooms and pillars typical in underground mining environments (Miladinović, 2011). For visualizing and entering data into these models, an understanding of the objectives behind creating a wireframe model is essential. This understanding guides the determination of input parameters, such as the dimensions of the ore deposit and the extent of tunnels, facilitating analysis from an isometric perspective.

Evolution of Modeling Techniques

Numerous approaches, including the Finite Element Method (FEM), Boundary Element Method (BEM), and Finite Difference Method (FDM), have been introduced by the advancement of numerical modeling techniques. More recent approaches, such as the Discrete Element Method (DEM) and Discrete Fracture Networks (DFN), have improved our comprehension of the behaviors of rock masses (Faraj & Hussein, 2023). FEM is used extensively to simulate the elastic and inelastic behaviors of rock masses, especially in the RS2 and RS3 modeling frameworks.

2.5 Finite Elements Method

FEM is highlighted as a versatile and powerful computational tool used to solve complex problems in engineering and physics. It involves discretizing a complex system into smaller, simpler parts known as finite elements (Radhakrishnan & Reese, 1970). Simple equations that approximate these finite elements are then assembled into a larger system of equations, modeling the whole problem. FEM then uses variational approaches from the calculus of variations to approximate a solution by minimizing an associated error function. Compared to other numerical techniques, this method is distinct as it can handle complicated shapes and configurations, materials with different isotropic or anisotropic layers that have linear, nonlinear, or viscous properties, a variety of boundary conditions, and the order in which construction is completed for projects (Radhakrishnan & Reese, 1970). Conventional theories of rock mechanics typically depict rock as an elastic, homogeneous, and isotropic substance, which restricts their use to geometrical problems with regular shapes. But a more nuanced approach is required due to the complexity of rock masses in real life, which are typified by networks of joints and fissures. These flaws affect how rocks behave under load by introducing non-homogeneity and anisotropy. When faced with such complexities, the shortcomings of traditional theories become apparent. Zienkiewicz (1965) pointed out that the finite element method effectively handles the complexities of anisotropy and nonuniformity in stress analysis, making it a strong substitute for conventional methods. In this manner, the FEM methodology allows for detailed modeling of stress-strain behavior in earth materials, giving insight into their deformation and stability and potential failure mechanisms in mine structures.

2.5.1 FEM Software: RS3

RS3 by Rocscience is a 3D Finite Element Method Analysis Software for geotechnical applications. In fact, RS3, therefore, enables complex geological scenarios with full geometrical configurations, including the complexity met in room and pillar mining operations. These facilities enable the input of all detailed geometrical configurations, material properties, and boundary conditions that engineers need for the simulation of physical behavior of rock masses and mining structures under assorted operational scenarios.

2.5.2 Continuous Models

A continuum model sees the material in question as continuous, even when such material may be, at the microscopic level, heterogeneous or discrete (Zienkiewcz, 1967). In the geotechnical and mining context, these models are paramount in view of simulating the mechanical behavior of soil or rock mass. Details of the granular structure are not modeled explicitly but averaged or smoothed out. This approach would, therefore, enable an engineer to predict the response of underground structures to the effects of mining activity, external loading, or other environmental factors within the framework of continuum behavior. For instance, the "strain-softening" behavior might be consistent with experiments showing a dilating response of the material (Radhakrishnan & Reese, 1970). The discontinuum model includes the Discrete Element Method (DEM), uses the distinct element concept to account for the material as an assembly of many individual discrete components, thus considering the fabric. Discontinuum models are quite good in problems where geometric change is very high. For instance, they are of great application with regard to block caving, rockfalls, or to the simulation of fractured rock mass in which individual block behavior or joint behavior has a critical influence on stability and deformation (Faraj & Hussein, 2023). The main FEM and its implementation in the software RS3 is exceptionally good where the rock mass can be closely approximated with a continuum and is capable of giving useful information on failure mechanisms, stress distribution, and deformation over a large area.

3. Methodology

3.1 Zhomart Copper Mine

Geological Setting and Tectonic Complexity

According to the geological characteristics provided by the operating company "Kazakhmys", the Jaman-Aibat deposit is located in the Zhezkazgan-Sarysu depression 130 km southeast of Zhezkazgan, and that the geological and structural characteristics define the mineralization and geotechnical conditions and is categorized into 4 groups due to their occurrence in specific blocks, such as the Central, Eastern, Western, and Northern. The mineralisation occurs in lenses in the terrigenous gray-terrestrial-sedimentary rock series and contains ore bodies of the Taskuduk suite and the whole Zhezkazgan suite. The mineralization extends for 14 km along a west-east axis, to a length of around 5 km along north-south axis. The depth of the orebody is 360-730 meters, plunging from east to west and north. The orebody is considered tabular with a slight plunge of approximately 10 degrees. On the deposit, the ore bodies show mainly a gentle dip with variable thickness that ranges between 0.5 to18 meters and hosts copper content ranging from 0.4% to 2.14%, whereas the average grade is at 1.69%. Such features underscore geological complexities of the deposit that tend to be categorized second and third groups on the basis of complexity of the geological structures of its Central/Eastern and Western/Northern sections respectively.

3.1.2 Rock Mass Properties

Composition and Strength of Rock

In the case of the Jaman-Aibat deposit, the mineralogical composition is characterized primarily by chalcocite, bornite, and chalcopyrite, with complex ores also containing galena and sphalerite. The second factor concerns engineering-geological properties: especially the strength of a rock mass, which ensures very stable bases for the technology of mining. According to the Protodyakonov scale, one can rate in the interval between 6 and 8, which indicates from average strong up to strong intensities that influence drilling, blasting, and some specific methods of the excavation technique. It describes diversified stratigraphy with major implications on mining strategy and pillar design, especially in the narrow part of the deposit that is mined—in between interlayers of dark-gray and green aleurolite, argillite, and ore-bearing sandstone.

On the fissuring and fracturing, the description of the geology of the area shows a lot of extent in massif rocks of the deposit. Descriptions mention cross-interbedded and cross-cutting cracks in the rock massif, with higher calcite crack density. These are common rock mass characteristics of a highly fractured rock mass that may affect the stability of underground opening. Accordingly, such detailed geomechanical studies to guide mining designs certainly become indispensable. Its fissured nature along with strength variability renders it prone to failure, especially in room and pillar method, where only part of the pillars can be mined out leaving: the rest of the structures have to hold. Geotechnical Considerations for Mine Stability and Support Requirements Many factors influence safe and efficient mining at Zhomart Mine; as such, the importance of the status of the roof and walls' stability alongside other geotechnical parameters can never be overstated. Recorded as the level III (third) stability group of roof rock is moderate, and therefore it has to be cautiously treated while designing the support systems so that under no circumstances they shall collapse over the workers. The variability in rock mass properties across various sections of the mine further generates enormous complexities, indicating adaptive and robust strategies for support so as to accommodate the geotechnical heterogeneity of the deposit. The strength properties of the Ore-Hosting Rocks values provided below are taken from Zhezkazgan deposit which as mentioned earlier is much stronger than in case of Zhomart mine and Zhaman-Aibat deposit (Zharaspaev, 2023).

- Gray sandstones: Uniaxial compressive strength (σсж) values range from 48 to 281 MPa(165); tensile strength (σр) – from 2.3 to 12.8(7.5) MPa.
- Brown fine-grained sandstones: σсж = 27–163 MPa, σр = 1.3–11.6 MPa.
- Raymund conglomerates: σсж = 84–141 MPa, σр = 6–10.1 MPa.
- Aleurolites and argillites: σсж = 10–88 MPa, σр = 0.5–7.5 MPa.
- Average principal stress in Annenkov Region was □ = 19.5-25 MPa

The mechanical properties of ore and ore bearing rock were provided by the “Kazakhmys” reports.

Table 2. Mechanical properties of ore and ore bearing rock of Zhomart Mine (Zhiyenbayev, 2024)

Material name	Unit weight (MN/m3)	Poisson’s ratio	Young’s Modulus (MPa)	Failure Criterion	Peak Friction Angle (degrees)	Peak Cohesion (MPa)
Rock	0.027	0.2	4700	Mohr-Coulomb	35	8.7

Current Room and Pillar Design Parameters:

The design parameters were obtained from a geomechanical plan of Zhomart Mine provided by “Kazakhmys” company.

- Distance between barrier pillars – 80 m.
- Panel span in light – 130 m.
- Width of the barrier pillar – 20 m.
- Planned pillar dimensions - 10x10x10 m.
- Diameter of columnar inter-chamber pillars (ICP) and chamber width – 9 m.

3.2 UBC Mining Method Selection Tool

University of British Columbia (UBC) Mining Method Selection Tool, a framework developed based on The Nicholas Method (Nicholas, 1981) enhanced the way mining systems are selected, with particular regard to selecting mining methods for deep-ore deposits (Miller-Tait, 1995). Incorporating a quantitative approach, the tool uses a specific score system and a pre-defined collection of criteria with respect to deposit geometry and geotechnical parameters for the assessment of various mining methods. This approach allows for an objective comparison and ranking of the possible mining systems on the basis of empirical data and analysis.

The criteria include deposit geometry and geomechanical parameters. The main distinguishable feature of the UBC method from the Nicholas approach, is the replacement of Rock Quality Designation (RQD) as an input for ground conditions with Rock Mass Rating (RMR) for ground conditions, and the inclusion of the Orebody depth in geometric parameters (Miller-Tait, 1995).

The scores given for each mining system are 1 to 5 for each of the set of criteria, and in an event that a certain condition readily rules the application of a method, then the method even receives a penalizing score of - 49 (Darling, 2011). This framework is designed to subtly assess each mining method's level of suitability, considering the characteristics of the ore body and the surrounding rock mass.

3.2.1 Input Parameters:

The deposit's geometry is dissected into five key factors: general shape, thickness, orebody orientation, depth below surface, and size. For instance, in the context of the Zhomart mine, where orebody shape is irregular, this particular geometry factor plays a critical role in method selection.

Table 3. Definition of Deposit Geometry Input Parameters for UBC method (Miller, 1995)

Orebody Shape	Equidimensional	All dimensions are on the same order of magnitude
	Platy/Tabular	Two dimensions are many times the thickness, which does not usually exceed 35 m
	Irregular	Dimensions vary over short distances
Ore Thickness	Very narrow	< 3m
	Narrow	3 - 10 m
	Intermediate	10 - 30 m
	Thick	30 - 100 m

	Very Thick	> 100 m
Orebody Plunge	Flat	< 20°
	Intermediate	20 - 55°
	Steep	>55°
Orebody Depth	Shallow	0 - 100 m
	Intermediate	100 - 600 m
	Deep	> 600 m
Grade Distribution	Low	The grade at any point in the deposit does not vary significantly from the mean grade for that deposit
	Moderate	Grade values have zonal characteristics, and the grades change gradually from one to another
	High	Grade values change radically over short distances and do not exhibit any discernible pattern in their changes

3.2.2 Geotechnical Parameters

Geotechnical parameters consist of the Rock Mass Rating (RMR) and Rock Substance Strength (RSS) of the ore, hanging wall (HW) and footwall (FW). The RMR is classified using Bieniawski's 1973 Rock Mass Rating system. The system assesses the rock mass by six major factors: Uniaxial Compressive Strength (UCS) of the rock mass, Rock Quality Designation (RQD), joint spacing, condition of joints, and ground water conditions.

Table 4. Bieniawski 1973 (CSIR) rock mass rating

Classification Parameters	Range of values
Strength of intact rock material	0 - 15
Rock Quality Designation (RQD)	3 - 20
Spacing of Joints	5 - 30
Condition of Joints	0 - 25
Ground Water Conditions	0 - 10

Meanwhile, the Rock Substance Strength (RSS) is estimated from the uniaxial compressive strength (σc, MPa) of the rock mass. It is defined by the ratio of UCS to Principal Stress, it varies at different depths which calls for a differentiated analysis for deeper and shallower areas of the deposit.

These parameters are essential for the evaluation of physical and mechanical properties of the rock mass which are directly connected to the safety, efficiency, and feasibility of each mining method. Due to the lack of geotechnical data provided by the company, for the Zhomart Mine case study, available geological information will be used to approximate the RMR values.

Table 5. Geotechnical Parameters (Miller, 1995)

Rock Mass Rating (RMR)	Very Weak	0 - 20
	Weak	20 - 40
	Moderate	40 - 60
	Strong	60 - 80
	Very Strong	80 - 100
Rock Substance Strength (RSS)	Very Weak	< 5
	Weak	5 - 10
	Moderate	10 - 15
	Strong	> 15

Table 6. Ranking of Geometry/Grade distribution and Rock mechanics for different mining methods

mining method	general shape			ore thickness					ore plunge			grade distribution			depth		
	M	T/P	I	VN	N	I	T	VT	F	I	S	U	G	E	SH	I	D
open pit mining	4	2	3	1	2	3	4	4	3	3	1	3	3	2	4	0	-49
block caving	4	2	0	-49	-49	0	3	4	3	2	4	3	2	2	2	3	3
sublevel stoping	3	4	1	-10	1	3	4	3	2	1	4	4	4	3	3	4	2
sublevel caving	3	4	1	-49	-49	0	4	4	1	1	4	3	2	2	3	2	2
longwall mining	-49	4	-49	4	3	0	-49	-49	4	0	-49	4	1	0	2	2	3
room and pillar	0	4	2	4	3	1	-49	-49	4	0	-49	4	2	0	3	3	2
shrinkage stoping	0	4	2	4	4	0	-49	-49	-49	0	4	3	2	2	3	3	2
cut & fill stoping	1	4	4	3	4	4	1	0	1	3	4	2	3	4	2	3	4
top slicing	1	2	0	1	1	0	2	1	4	2	0	2	1	1	2	1	1
square set stoping	0	1	4	4	3	2	0	0	2	3	2	0	1	3	1	1	2

M = massive, T/P = tabular or platy, I = irregular
VN = very narrow, N = narrow, I = intermediate, T = thick, VT = very thick
F = flat, I = intermediate, S = steep
U = uniform, G = gradational, E = erratic
S = shallow, I = intermediate, D = deep

Rock mechanics characteristics

Rock mass ratings

mining method	ore zone					hanging wall					footwall				
	VW	W	M	S	VS	VW	W	M	S	VS	VW	W	M	S	VS
open pit mining	3	3	3	3	3	2	3	4	4	4	2	3	4	4	4
block caving	4	3	2	0	-49	3	3	3	2	2	3	3	3	2	2
sublevel stoping	1	3	4	4	4	-49	0	3	4	4	0	0	2	3	3
sublevel caving	3	4	3	1	0	4	4	3	2	2	1	2	3	3	3
longwall mining	6	6	4	2	2	6	5	4	3	3	-	-	-	-	-
room and pillar	-49	0	3	5	6	-49	0	3	5	6	-	-	-	-	-
shrinkage stoping	0	1	3	3	3	0	0	2	4	4	0	0	2	3	3
cut and fill	0	1	2	3	3	3	5	4	3	3	3	3	2	2	2
top slicing	3	2	1	1	0	0	0	2	3	3	0	0	1	2	2
square set	4	4	1	0	0	4	4	1	0	0	3	1	0	0	0

RMR ratings: VW = 0-20, W = 20-40, M = 40-60, S = 60-80, VS = 80-100

Rock substance strength

mining method	ore zone				hanging wall				footwall			
	VW	W	M	S	VW	W	M	S	VW	W	M	S
open pit mining	4	3	3	3	3	3	4	4	3	3	4	4
block caving	4	2	1	0	4	3	2	0	4	3	2	1
sublevel stoping	0	2	4	4	0	1	4	5	0	1	3	3
sublevel caving	2	3	3	2	4	3	2	1	1	2	2	2
longwall mining	6	5	2	1	6	5	2	2	-	-	-	-
room and pillar	0	0	3	6	0	0	2	6	-	-	-	-
shrinkage stoping	0	1	3	4	0	1	3	4	0	2	3	3
cut and fill	0	1	3	3	3	5	4	2	1	3	2	2
top slicing	3	2	1	0	3	2	2	2	2	2	1	1
square set	4	3	1	0	4	2	1	0	3	2	0	0

RSS ratings VW = very weak, W = weak, M = medium, S = strong.

The decision process for which methods of excavation are chosen is based on a unique scoring system through which each method attains a number of specific points. The data are then gathered, and an overall score is placed into an allocated table that serves as a base for the selection of extraction methods. In its essence, it is an objective methodology that does not favor or skew toward any individual mining system that will extract the ore body. The purpose of this method is to identify all possible methods of extraction that meet the criteria of the ore body as posted in Table 6 that are considered the most optimal. It establishes a hierarchical order of the mining methods based on their efficiency which is determined by its total score, higher the score underlines higher efficiency. From this list, those that score negatively and hence are unsuitable for the particular ore body concerned can be immediately dismissed. Furthermore, in case the total score is equal to zero, the option is not outright rejected but is not advised due to its limited applicability. The favorable methods are considered those that score above 23 and show little variance among themselves. The cost of excavation varies across different methods, ranging from low to high (Balt and Goosen, 2020). Thus, economic consideration must be employed to identify the most appropriate extraction method for specific conditions (Mijalkovski, 2021a).

3.3 RS3 Numerical Modeling

To analyze the current mining system's impact on surface infrastructure, RS3 numerical modeling was utilized. This software allows us to simulate ground behavior, subsidence, and stress distribution. The figure below illustrates the geomechanical plan of the Zhomart mine provided by "Kazakhmys".

Figure 11. Geomechanical plan of the Zhomart Mine

3.3.1 Model Setup:

Due to the limited computational power available, as well as, time constraints a certain section was selected for simulation. The part of panel 48 that has been partially extracted was chosen for simulation.

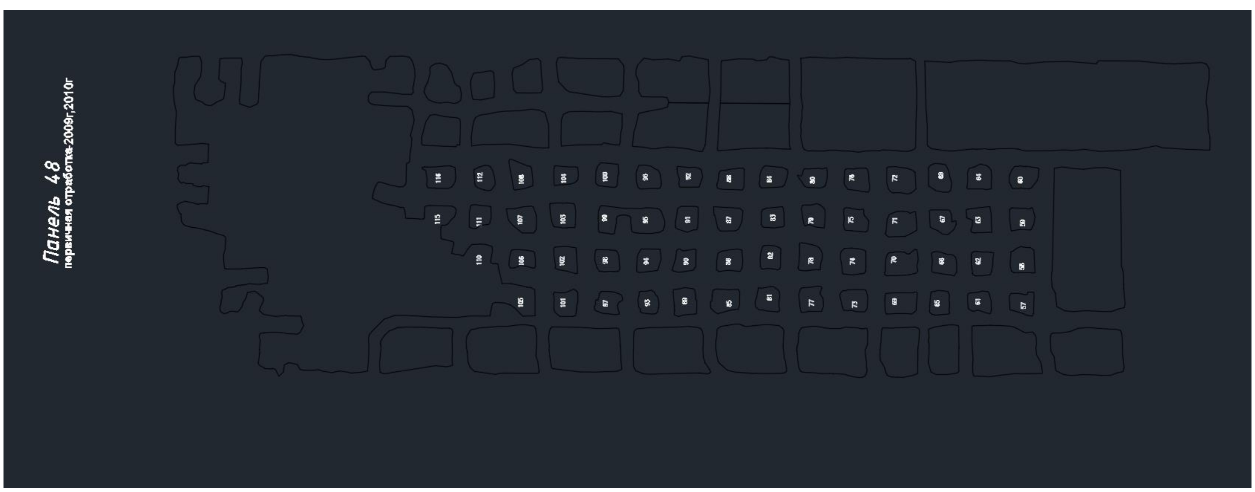


Figure 12. Selected section of the Panel 48 for numerical modeling

Panel 48 is located around 600 meters below surface containing 59 inter-chamber pillars numbered from 57 to 116. The pillar dimensions are 10x10x10 meters. The span is 9 meters, and the width of the barrier pillars is around 20 meters with varying lengths.

3.3.2 Input Geometry:

The 3D contours of the room and pillar section were to be imported to RS3 software. However, only a 2D plan schematic was provided for utilization, thus, using AutoCAD software the 3D wireframes were built based on the given information as can be seen from figure 13.

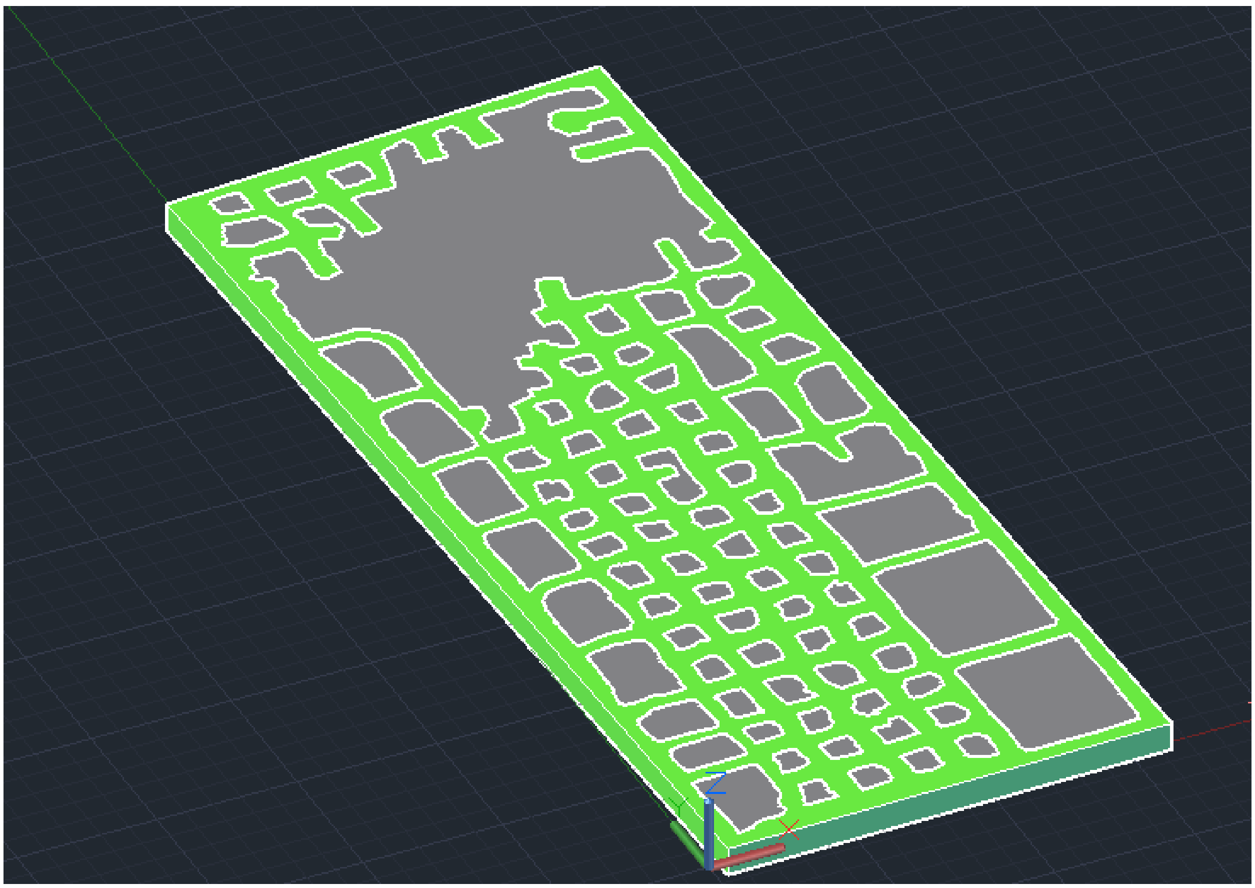


Figure 13. Room and Pillar geometry built in AutoCAD software

3.3.3 Material Properties:

After geometry was imported it was necessary to define the materials. Material 1 would be defined as copper sandstone ore and be assigned to the pillars, roof and floor of the excavation. The imported file consisted of rooms and pillars, however in order to define the roof and floor of the excavation an external box was created that would be defined as the ore along with the pillars. Rooms geometry was assigned to be hollow or extracted. Below are the material properties defined in the software.

Table 7. Input Parameters for RS3 Simulation

Input Parameters		Units
Inital Loading	Field Stress & Body Force	
Unit Weight	0.027	kN/m^3
Strength Parameters		
Failure Criterion	Mohr-Coulomb	
Material Type	Plastic	
Peak Cohesion	8.7	MPa
Peak Friction Angle	35	degrees
Peak Tensile Strength	8	MPa
Residual Cohesion	5	MPa

Residual Friction Angle	35	degrees
Residual Tensile Strength	0	MPa
Stiffness Parameters		
Poisson’s Ratio	0.22	
Young’s Modulus	4700	MPa
Field Stress		
Ground Surface Elevation	600	m
Unit Weight of Overburden	0.027	MN/m^3
K1	1.6	

The model was automatically restrained for underground excavation by RS3 software, after which it was discretized and meshed accordingly using a 4-nodded triangle, uniform mesh.

In order to simulate the pillar recovery process, rows of pillars are to be extracted one by one to imitate the retreat upon recovering the pillars. The process consists of the following stages shown in figure 14-16.

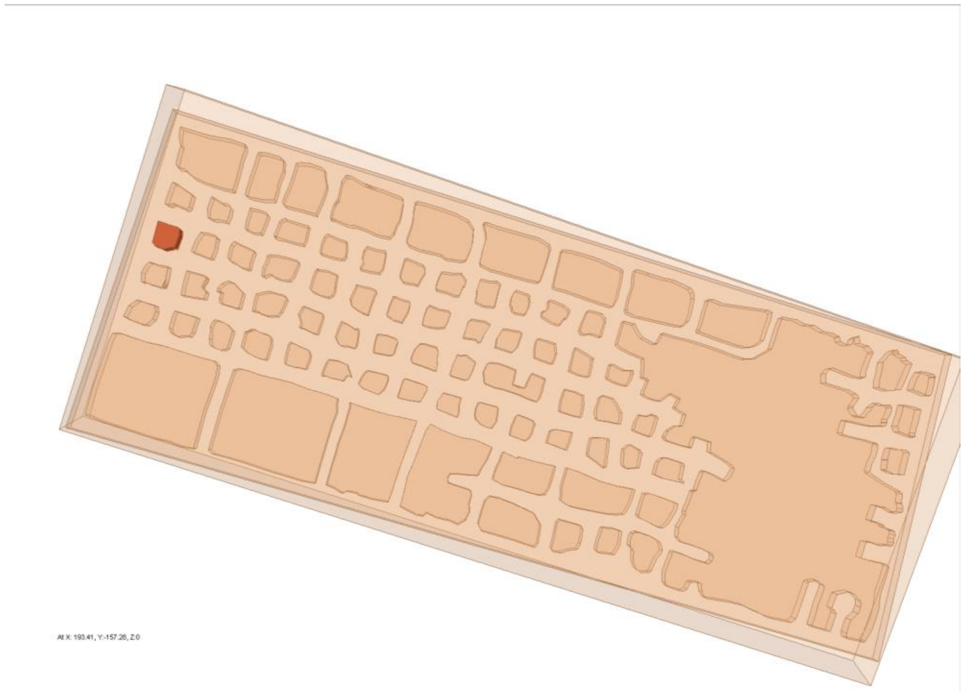


Figure 14. Stage 1 - Removal of a singular pillar

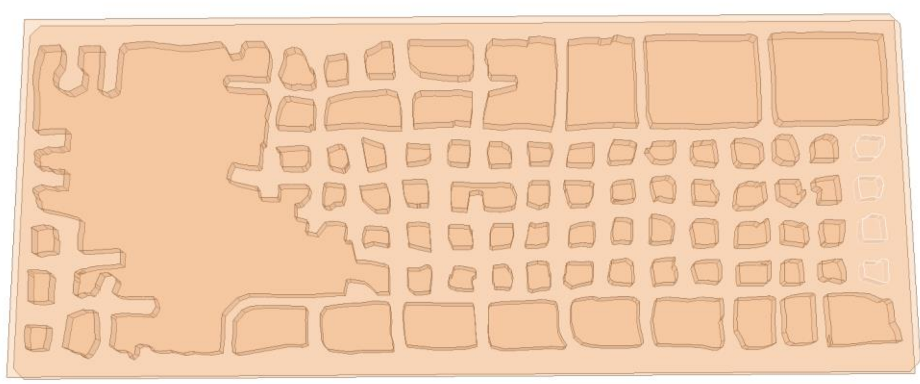


Figure 15. Stage 2 - Removal of the first row of pillars

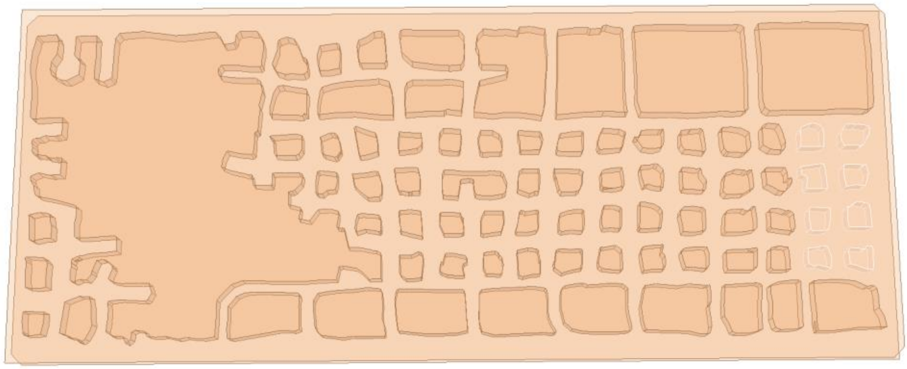


Figure 16. Stage 3 - Removal of the second row of pillars

4. Results & Discussion

4.1 Application of UBC to Zhomart Mine:

Using the Excel implementation of UBC developed by Jeff Breadner (1999), the table below shows the final input parameters for Zhomart mine.

Table 8. UBC Input Parameters

Parameters for the deposit geometry and grade distribution	
Orebody Shape	Tabular
Orebody Thickness	Intermediate
Orebody Plunge	Intermediate
Orebody Depth	Deep

Grade Distribution	Gradational
Rock mechanical characteristics	
Rock Mass Rating (RMR)	
RMR Ore	Weak
RMR Hanging Wall	Moderate
RMR Footwall	Moderate
Rock Substance Strength (RSS)	
RSS Ore	Weak
RSS Hanging Wall	Moderate
RSS FootWall	Moderate

Table 9. Final Results obtained by UBC Selection Tool

Final Results		
Rating	**Mining System**	**Points**
1	Cut & Fill	33
2	Sublevel Stoping	31
3	Longwall	28

4	Sublevel Caving	26
5	Block Caving	25
6	Square Set	19
7	Top Slicing	18
8	Room and Pillar	16
9	Open Pit	-17
10	Shrinkage Stoping	-29

As a result, the highest scoring systems are Cut & Fill mining with 33 points and Sublevel Stoping with 31 points. The Room and Pillar method appears to be eighth in the list among ten different methods which are constituted by relatively weak host rock and ore parameters in conjunction with other orebody parameters. The low ranking of the Room and Pillar method underscores the challenges associated with weak ore and rock conditions, aligning with the RS3 simulation results which highlighted significant subsidence and compromised structural integrity following pillar recovery. The high rankings for Cut & Fill and Sublevel Stoping suggest their better suitability in managing the identified challenges, offering more stable solutions for the Zhomart mine's conditions.

4.2 Subsidence Analysis through RS3 Simulation

The simulation began with a baseline model representing the initial conditions of the panel, including the distribution and integrity of pillars. The room and pillar mine was then subjected to a systematic removal of pillars from the south side, moving northward, to mimic the recovery process and the resulting stress distribution as well as displacement were documented through sequential screenshots at various stages: after the removal of the first pillar, removal of each of the first row of pillars, followed by further retreating recovery of pillars row by row as indicated in Figures 14-16.

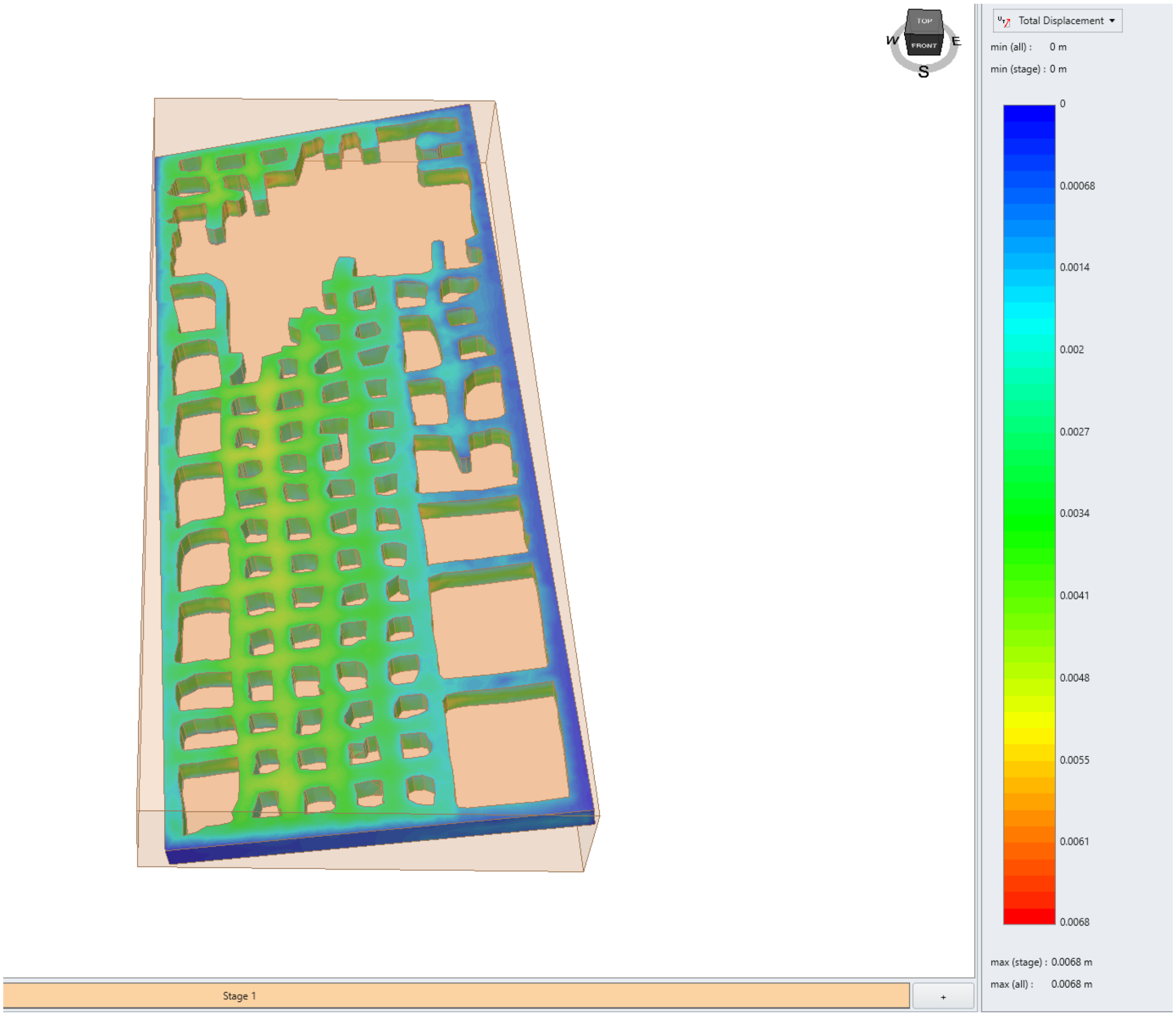


Figure 17. Model of the initial stage with indicated total displacement

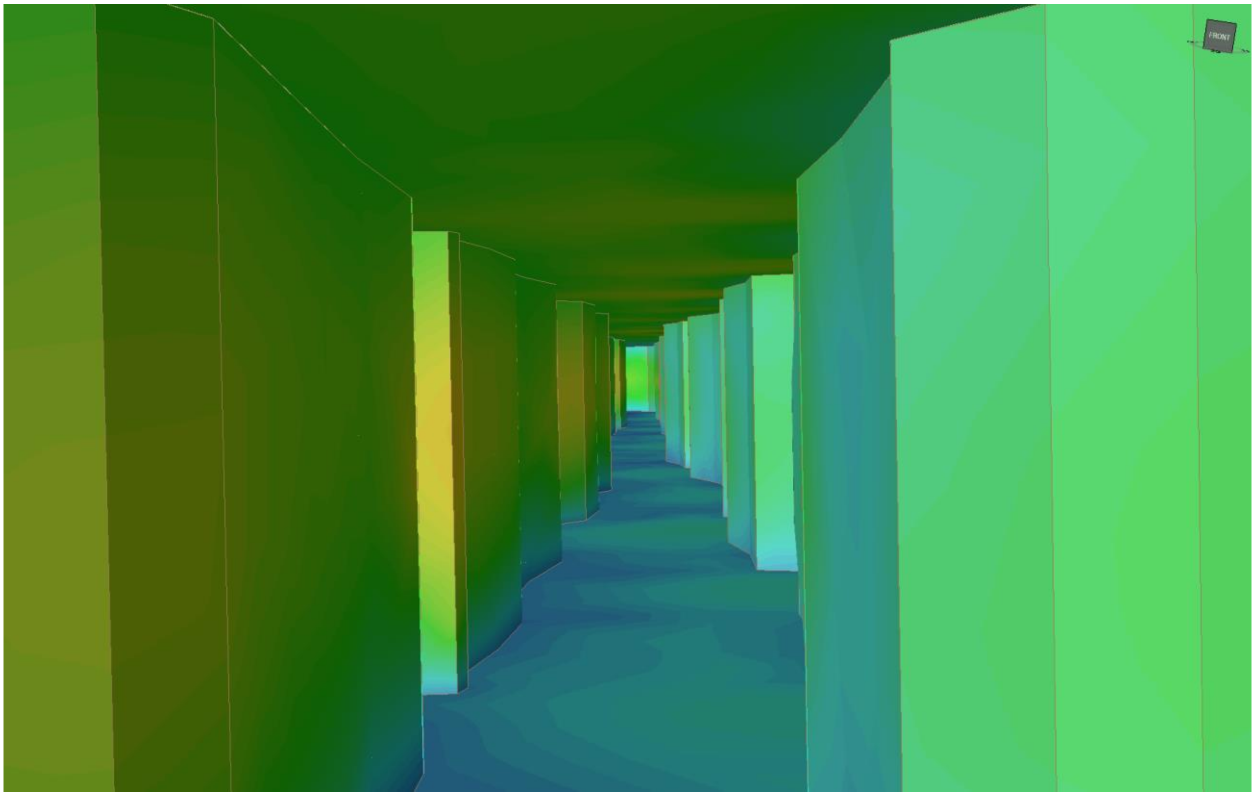


Figure 18. Inside view of the initial stage

The results of modeled displacement in the initial stage where all the inter-chamber pillars are intact showing an average displacement of 4-5 millimeters, with higher values recorded at the middle of chambers in the roof, especially in the central part of the panel.

Figure 19 indicates the modeled principal stress sigma 1 distribution. It can be noticed that the main stress concentration is mainly on the pillars with principal stress sigma 1 of around 25 MPa and the roof of the chambers are experiencing stress of around 15 MPa.

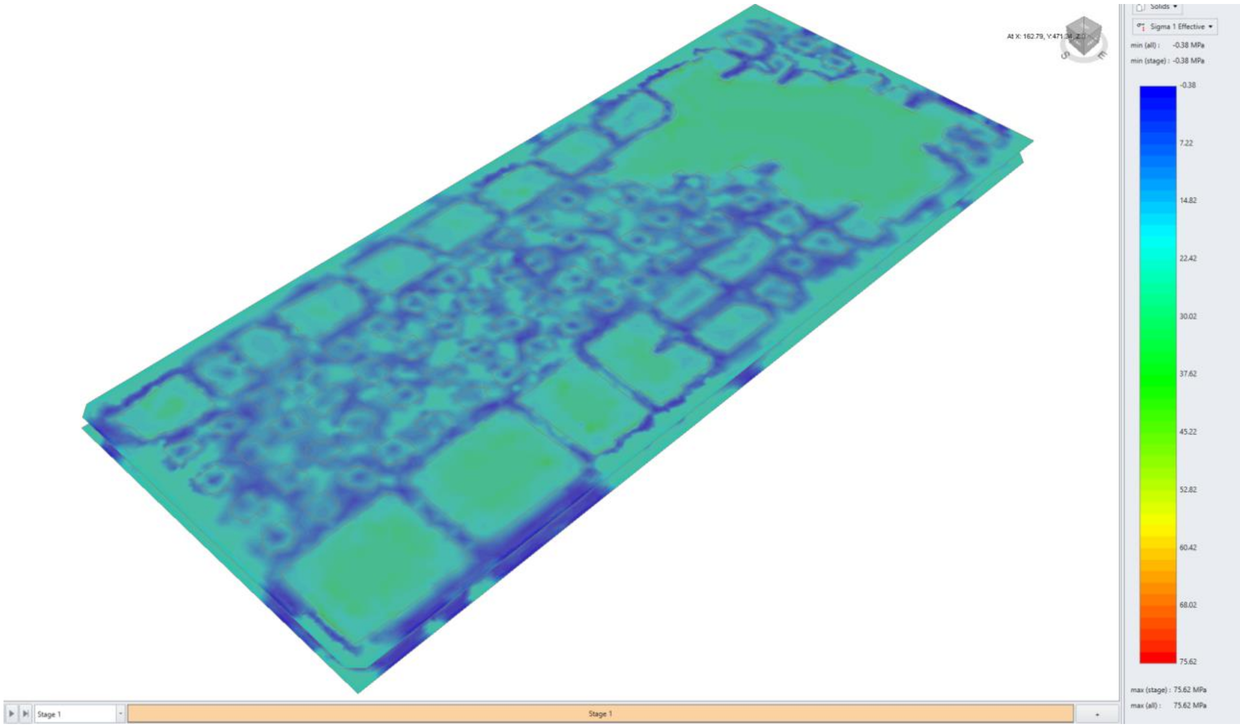


Figure 19. Sigma 1 effective stress distribution at the initial stage

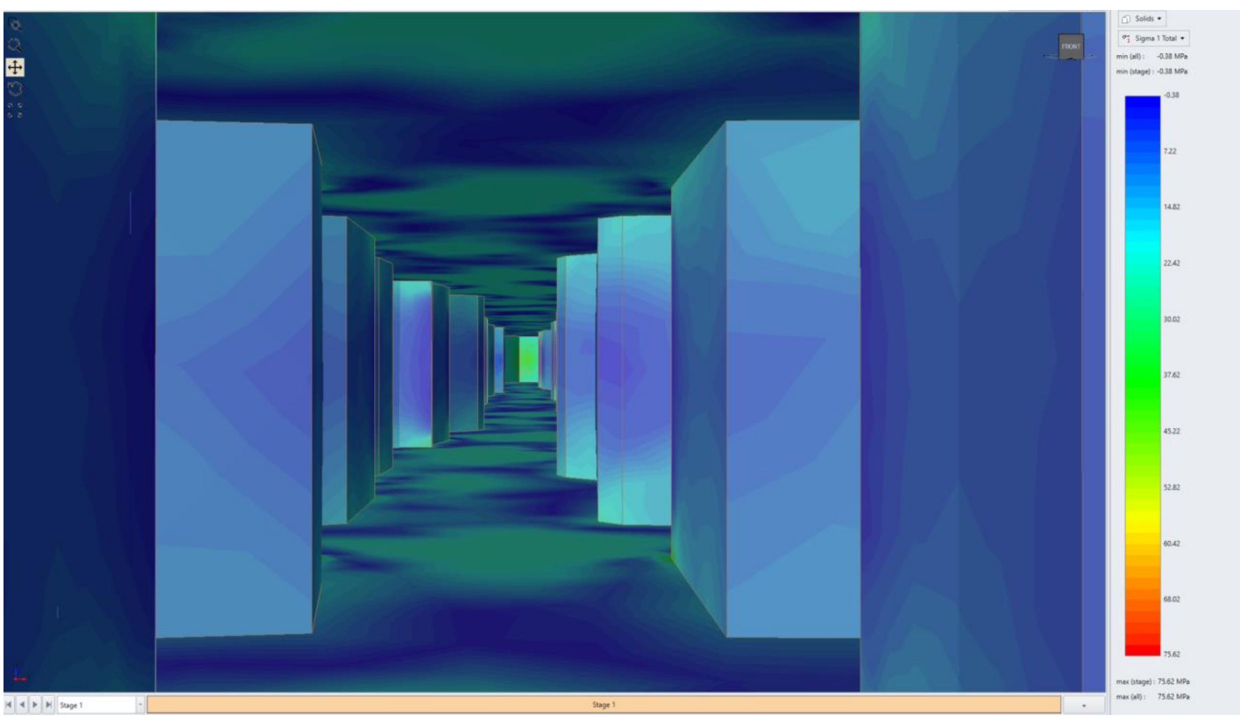


Figure 20. Sigma 1 effective stress distribution at the initial stage inside view

Figure 21 illustrates the vertical stress distribution from within the chambers. Notably there is a stress concentration in the middle of pillar sides of around 15 MPa which indicates that the pillars remain stable at the core with its outer shell breaking away giving it a more circular shape as illustrated in figure 6.

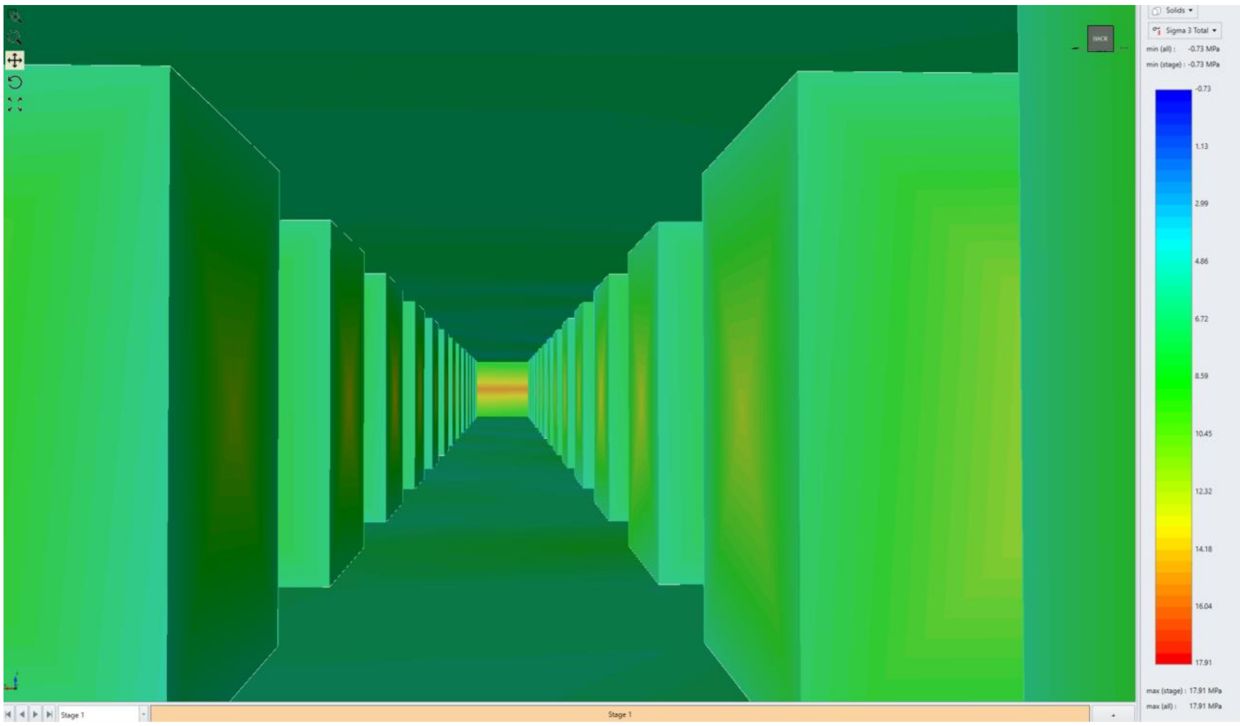


Figure 21. Sigma 3 distribution at the initial stage inside view

4.2.1 Single pillar recovery

In order to investigate the consequences of pillar recovery a singular pillar was recovered from the panel which as can be seen from figure 22 resulted in a significant increase of displacement in the roof area to 1.6 cm. Whilst under normal circumstances such displacement value would imply constant monitoring of the area for cracks propagation due to the high risk of failure, in this case the pillars are expected to fail after the completion of the recovery process.

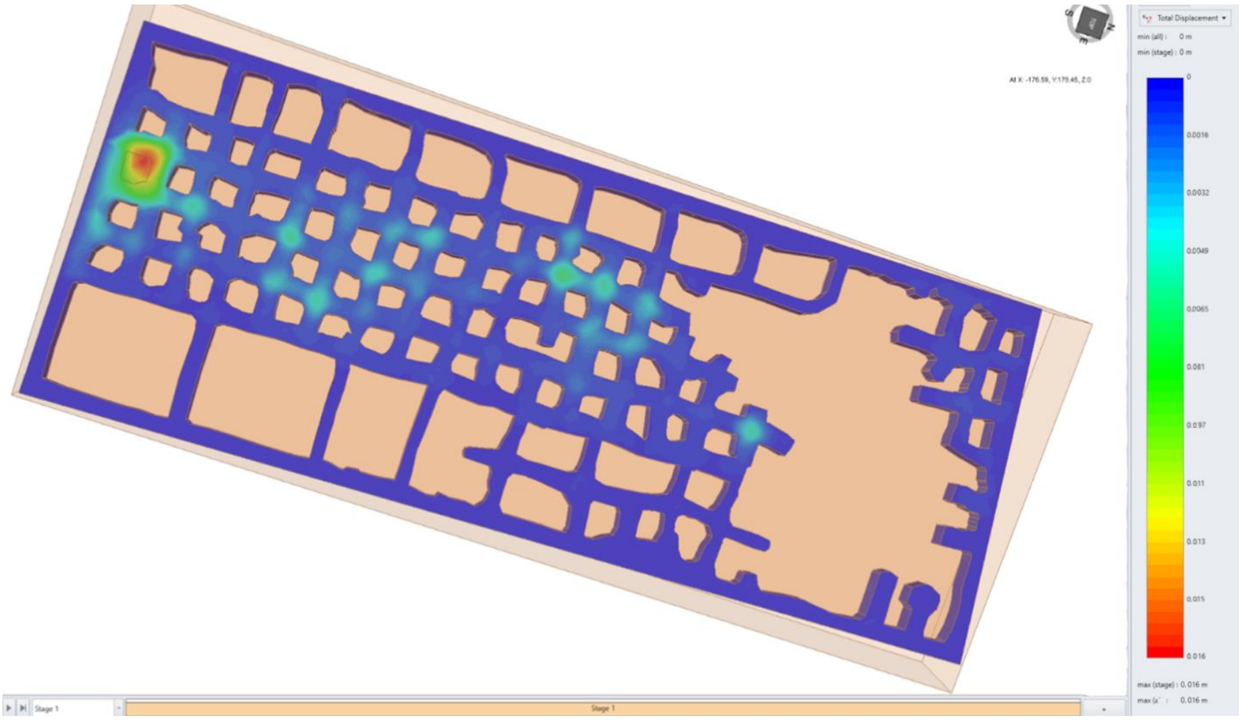


Figure 22. Single pillar recovery effect on total displacement

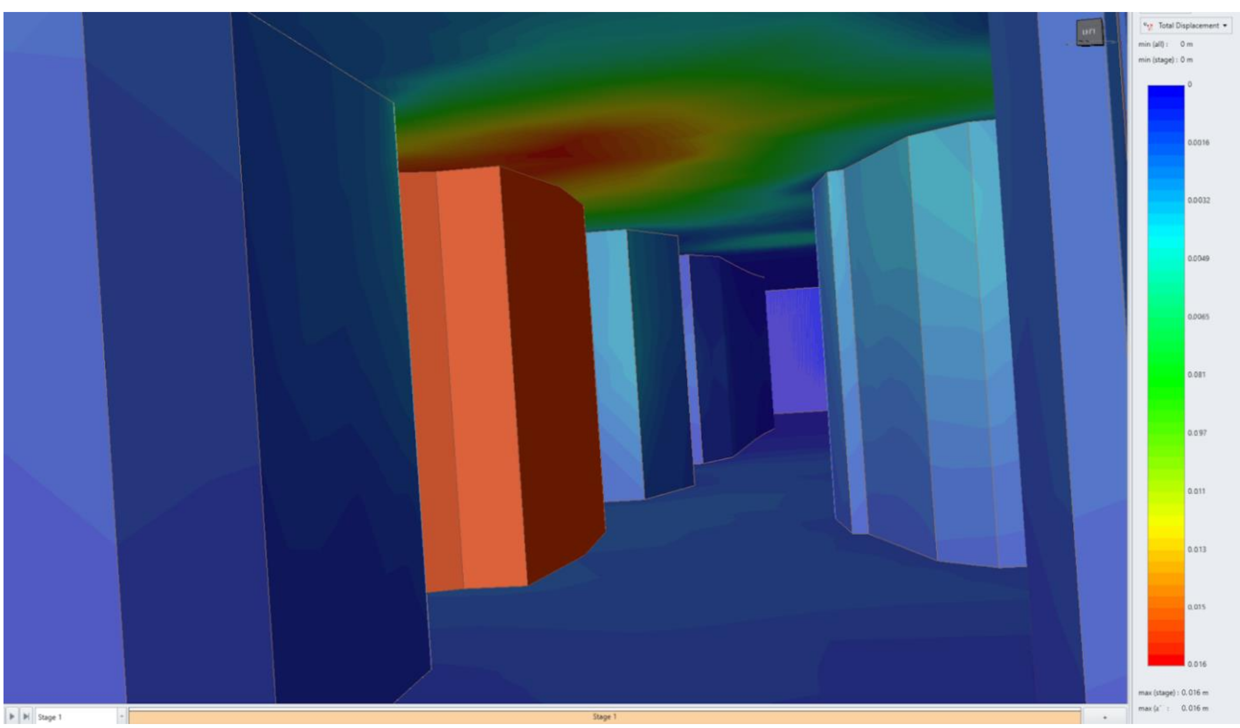


Figure 23. Single pillar recovery effect on total displacement isometric view

4.2.2 First row recovery

Upon removal of the first four rows of pillars, sigma 1 value increased to around 40 MPa on the barrier pillars due to the redistribution of stress. Along with the stress, the total displacement concentration accumulated on the roof area above recovered pillars at a value of 6.8 cm indicating the beginning of deformation.

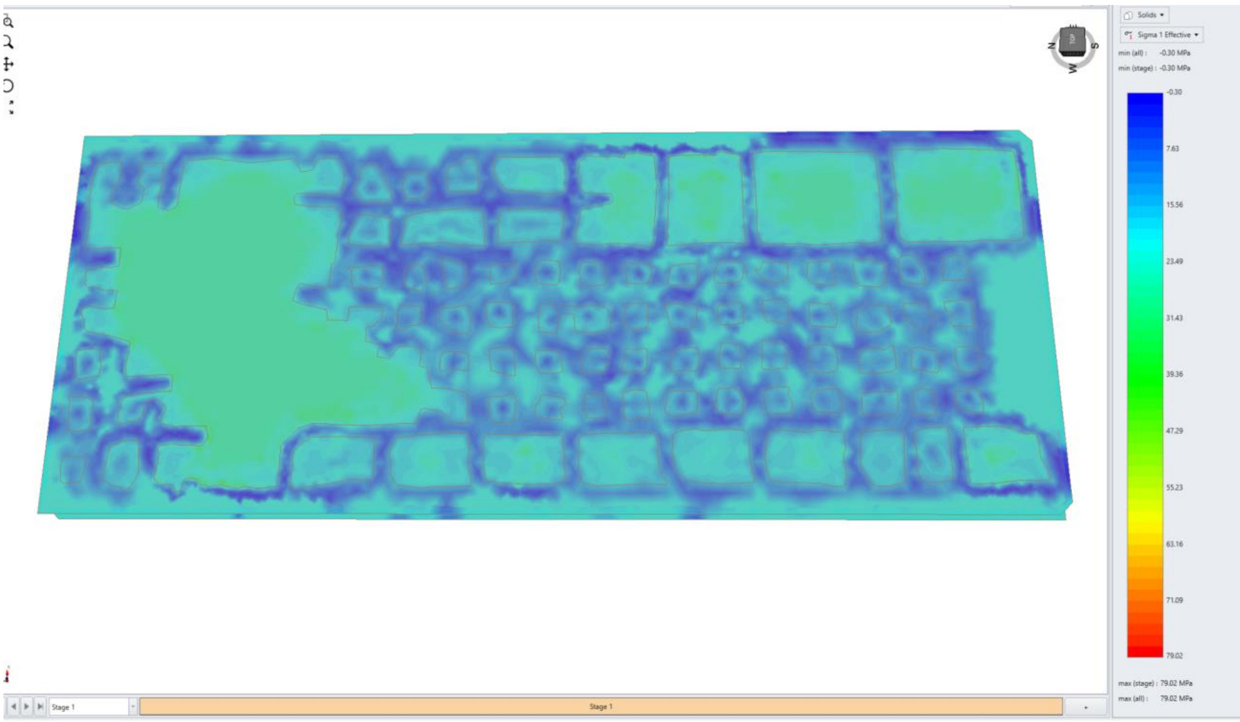


Figure 24. Sigma 1 distribution for first row recovery stage

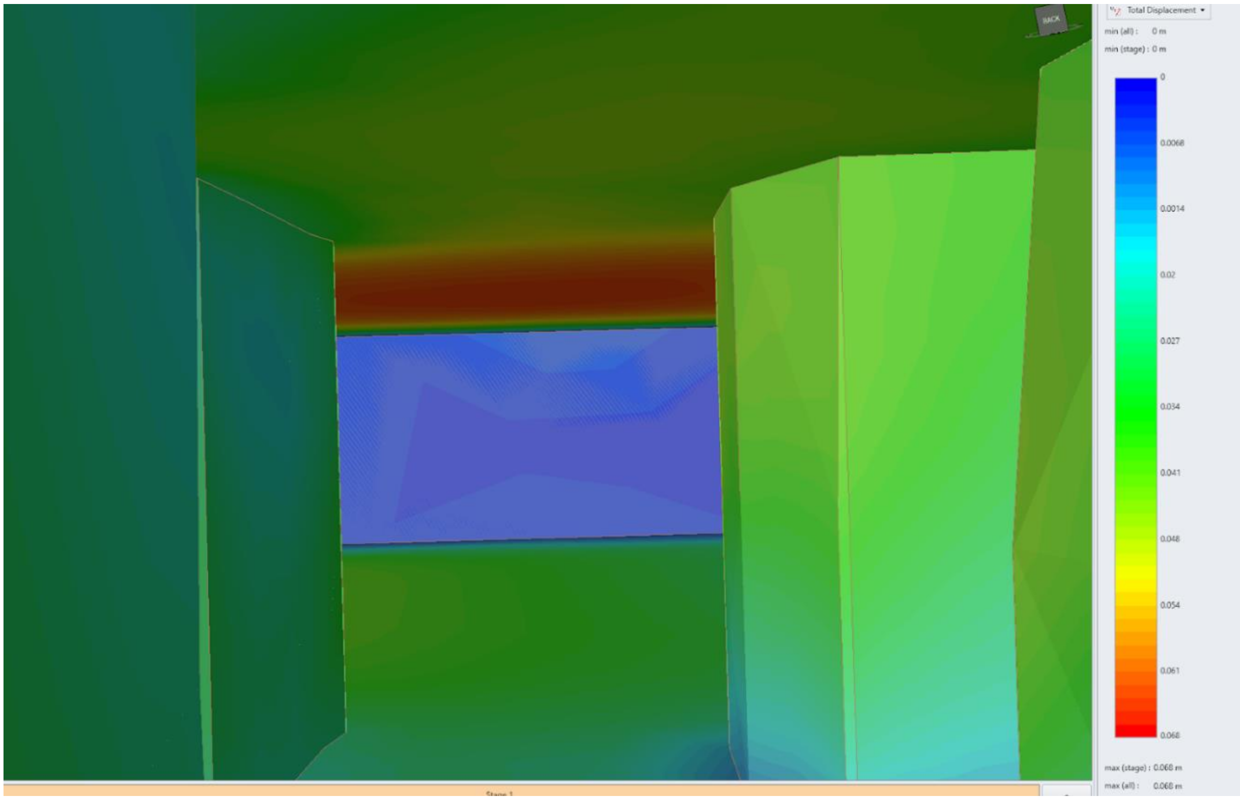


Figure 25. First row recovery stage inside view

4.2.3 Second row recovery

As a result of stress redistribution, the rest of the ICP pillars as well as the barrier pillars are experiencing much higher sigma 1 values of around 60-70 MPa which imply potential for extensive roof failure.

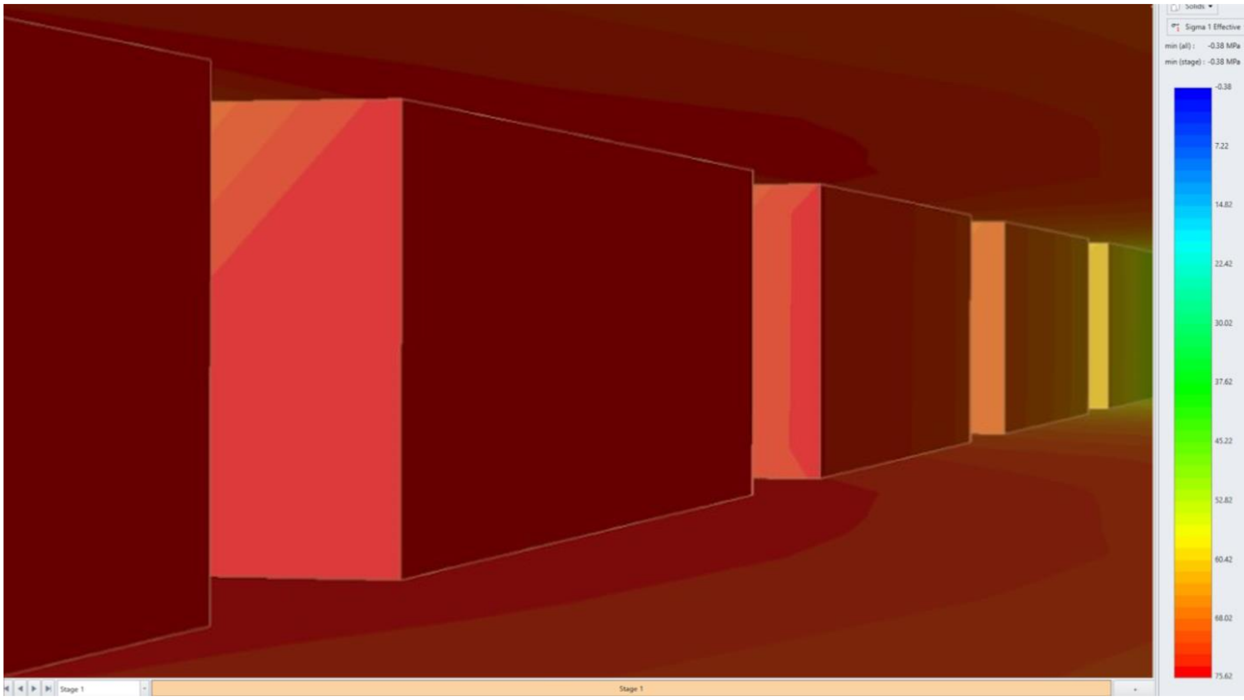


Figure 26. Stress redistribution upon second row recovery inside view

4.2.4 Yielded Elements Analysis

The structural integrity of the mine was further analyzed through the observation of yielded elements at its initial stage and when the two rows of pillars are removed. As can be seen from Figure 27, initially, the model displayed minimal yielded elements, indicating a stable structure under the existing conditions.

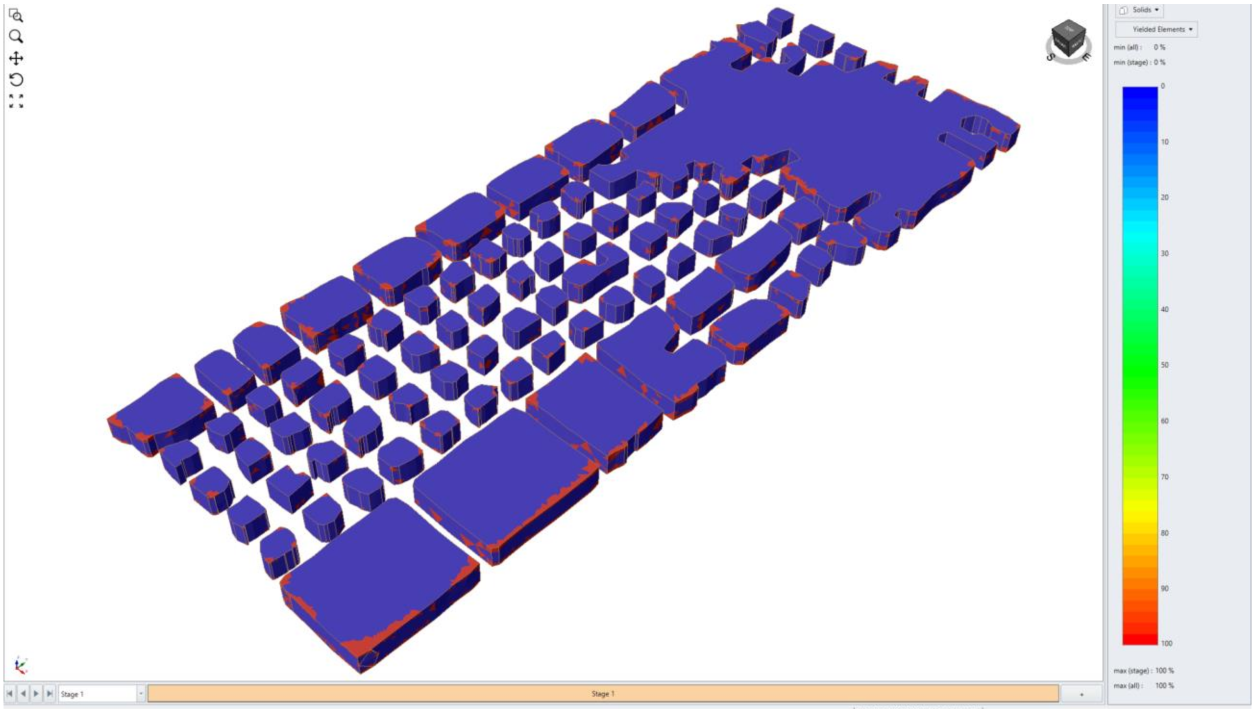


Figure 27. Yielded elements at the initial stage

However, as the simulation progressed and two rows of the pillars were removed, figure 28 shows a marked increase in the number of yielded elements across the panel, signifying a considerable compromise in structural integrity. It demonstrates that upon early stages of recovery a chain reaction will cause roof failures across the panel disrupting operations, mine stability and generating significant subsidence potentially damaging key surface infrastructure and the environment.

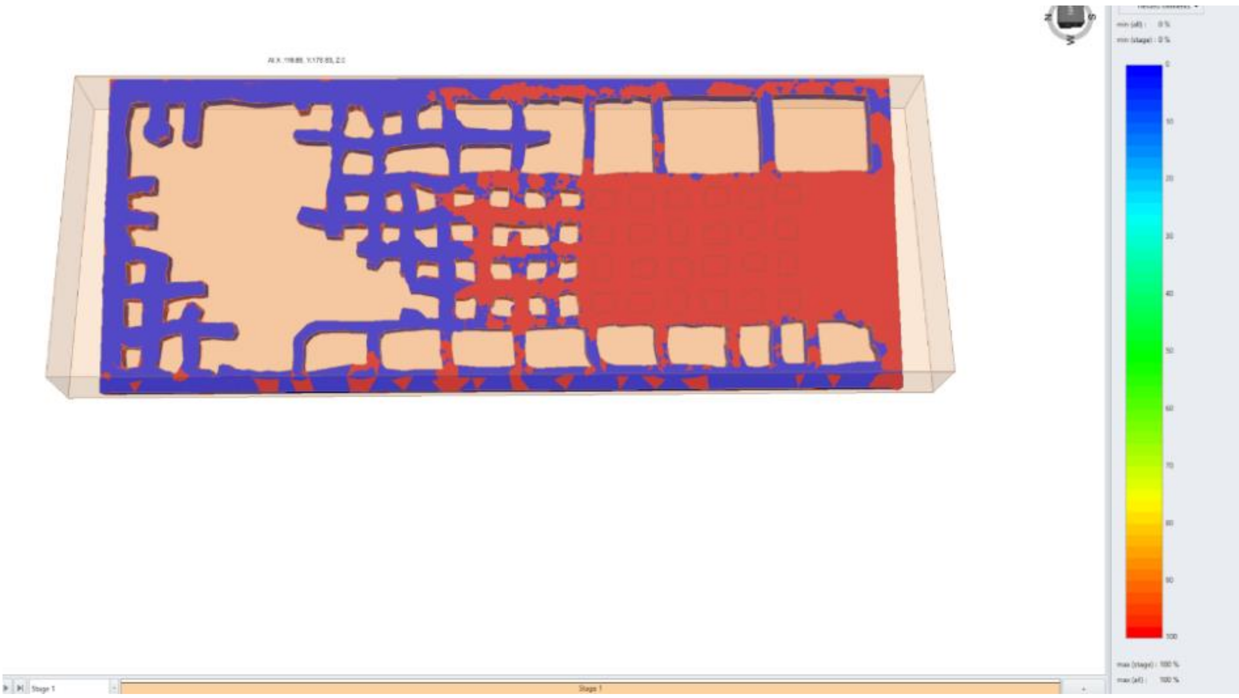


Figure 28. Yielded elements after removal of two rows of pillars

4.2.5 Discussion of results

As a result, the recovery process of the current room and pillar mining system at Zhomart mine appears to have a significant impact on ground subsidence and mine stability. In order for safe operations the design parameters should be optimized by increasing the size of the pillars or installing substantial roof support. However, the weak host rock and ore mass parameters, substantial depth, high ore grade as well as the presence of key surface structures on the surface calls for a transition to a different mining system, cut and fill emerges as a compelling alternative (Nieto, 2009).

Cut & Fill Mining is particularly advantageous for the Zhomart Mine due to its capability to control ground subsidence effectively—a crucial factor in mines with weak rock conditions. This method involves backfilling the void left after ore extraction with waste rock or tailings, which supports the roof and prevents collapse. This is essential in environments like Zhomart, where the ore and host rock exhibit lower strength, increasing the risk of collapse. Additionally, Cut & Fill allows for selective extraction, which maximizes ore recovery and minimizes waste, aligning with the need for efficient resource utilization at Zhomart. Its precision and flexibility in orebody following are unmatched, particularly beneficial in the irregular orebody structures typical at Zhomart.

Sublevel Stoping, on the other hand, offers an efficient solution for the deep ore bodies. This method allows mining in a stress-relieved environment, which is critical given the deep orebody depth at the mine that contributes to high stress conditions. Sublevel Stoping facilitates a more systematic extraction of ore through the creation of sublevels from which horizontal drifts extend into the ore. This method reduces the ore's exposure to potential collapse by limiting the size of the open stope, thereby enhancing stability. It also supports a continuous operation flow, improving productivity and safety by reducing the exposure of workers to unstable zones.

Both methods offer significant improvements over Room and Pillar in terms of safety, efficiency, and environmental impact. Cut & Fill's ability to immediately fill the voids reduces the environmental footprint by limiting surface subsidence, which is a critical consideration given the proximity of key surface infrastructure at Zhomart. Sublevel Stoping, with its methodical approach to high-grade, steeply inclined deposits, minimizes ore dilution and enhances resource extraction efficiency, making it particularly suitable for the geometric conditions at Zhomart.

Although the cut and fill mining method is more expensive in terms of operational costs, due to the backfilling techniques, it is still more compatible with the characteristics of the Zhomart Mine.

5. Conclusion & Recommendation

The comprehensive assessment of mining methods at Zhomart Mine reveals significant limitations with the current Room and Pillar method, particularly concerning mine stability and subsidence management. The application of the UBC tool and RS3 simulations unequivocally demonstrate that alternative methods, notably Cut & Fill and Sublevel Stoping, are better suited to the geological and operational specifics of the Zhomart Mine. These methods not only align with the mine's need for enhanced safety and efficiency but also offer strategic benefits in terms of resource recovery and environmental impact management.

5.1 Recommendations:

Transition to Cut & Fill and Sublevel Stoping:

Kazakhmys is strongly advised to consider a phased transition towards Cut & Fill and Sublevel Stoping systems. Cut & Fill, in particular, should be prioritized for areas where ore body configuration and rock stability are critical concerns. This method's ability to backfill excavated areas promptly helps maintain ground stability and significantly reduces the risk of subsidence that can impact surface infrastructure and surrounding ecosystems.

Economic Evaluation:

While it is acknowledged that Cut & Fill entails higher operational expenses due to backfilling techniques, an economic evaluation should be conducted to comprehensively assess its long-term financial impacts compared to the potential costs associated with subsidence damage and operational disruptions under the current system. The evaluation should include a cost-benefit analysis comparing the initial increased costs of implementing Cut & Fill against the potential savings from reduced environmental remediation, lower risk management costs, and the possible extension of mine life due to improved recovery rates and safer operational conditions.

In summary, while the adoption of Cut & Fill involves higher upfront costs, the method is justifiable operationally for the Zhomart Mine. It promises to enhance the structural integrity of mined areas, minimize ecological disruption, and provide a safer working environment, thereby aligning with the strategic objectives of Kazakhmys for sustainable and responsible mining operations.

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