Pitwall stability enhancement through structural analysis – a practical case study

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ABSTRACT

Ensuring the stability of pitwalls in open pit mining is a critical aspect of the safety of personnel, equipment, and the surrounding environment. Complex geological and geotechnical conditions encountered in practical open pit mining often present challenges in accurately assessing slope stability. This study employs both DIPS and Swedge software to enhance pitwall stability analysis. DIPS examines discontinuity orientations and distributions, providing essential geological insights, while Swedge simulates potential wedge failure modes, determines their sizes, and calculates factors of safety crucial for pitwall stability assessments. While both DIPS and Swedge have found individual or combined applications in numerous studies, a comprehensive and systematic evaluation of their performance across a spectrum of pitwall conditions, particularly in extreme weather environments, remains a major research subject. By combining the strengths of DIPS and Swedge, the study - not only refine our understanding of pitwall stability mechanisms but also developed a robust methodology applicable across diverse geological and climatic conditions. The results of this research contribute significantly to the body of knowledge in rock mechanics and open pit mining practices, offering practical guidance for enhancing pitwall stability in various operational contexts.

1 INTRODUCTION

Open pit mining stands as a pivotal process in the extraction of valuable resources from the Earth's crust. However, this endeavour comes with its challenges, particularly in ensuring the stability of pitwalls. Pitwalls are critical for the safety of personnel, the protection of equipment, and the prevention of environmental disasters (Zvarivadza, 2015; Moloi and Zvarivadza, 2016; Mametja and Zvarivadza, 2017; Segaetsho and Zvarivadza, 2019; Williams et al, 2021; Yang et al, 2023). This paper presents a study that delves into the complexities of pitwall stability, utilizing advanced software tools and methodologies to enhance our understanding and management of this critical aspect of open pit mining. As the mining process advances, the rock mass comprising the slope loses its equilibrium, succumbing to the forces of gravity and external pressures. This can result in slope disintegration, caving, and sliding, posing significant threats to safety and operational continuity. The complex geological and geotechnical conditions encountered in practical open pit mining further exacerbate these challenges. A comprehensive and accurate assessment of slope stability becomes crucial to mitigate these risks effectively.

Pitwall stability is not merely an engineering concern; it is the fulcrum of the entire open pit mining operation. The safety of personnel working in and around the pit, the integrity of expensive mining equipment, and the prevention of environmental disasters all hinge on the stability of pitwalls. A failure in pitwall stability can have cascading effects, leading to disruptions in operations, potential injuries or fatalities, and ecological damage. Consequently, continual monitoring and sophisticated analyses are imperative to uphold pitwall stability throughout the lifecycle of an open pit mining project. Tackling the dynamic challenges of pitwall stability, recent technological advancement has played a pivotal role. Radar-based technologies have revolutionized the monitoring practices associated with pitwalls. These systems provide real-time data on the structural integrity of pitwalls, offering unprecedented insights into potential instabilities. By continuously monitoring changes in the pitwall structure, radar-based technologies empower mining operators to detect early signs of instability, allowing for timely interventions and mitigations.

Pitwall stability is influenced by an array of factors, both geological and environmental. Geological structures, rock stresses, groundwater conditions, the strength of discontinuities, and the intact rock strength all play significant roles in determining the stability of pitwalls. The interplay of these factors creates a dynamic and complex scenario that necessitates a nuanced approach to stability analysis. The slope design criteria flowchart, as outlined by Stacey in 1968, underscores the multifaceted considerations involved in stability analysis. From structural analysis to rock strength, groundwater considerations, and the in-situ stress state of the rock mass, each aspect contributes to the overall understanding of pitwall stability.

In addressing the challenges of pitwall stability, this study shines spotlight on the role of structural analyses. Understanding the structural complexities of the pitwall is fundamental to devising effective strategies for stability enhancement. The integration of two advanced software tools, DIPS and Swedge, adds a layer of sophistication to these structural analyses. DIPS, by examining discontinuity orientations and distributions, provides valuable geological insights. This geological understanding is crucial for tailoring stability solutions that are not only effective but also specific to the unique geological conditions of the pitwall.

The study leverages the complementary strengths of DIPS and Swedge to enhance the analytical process. With its geological focus, DIPS lays the groundwork by dissecting the discontinuity patterns within the rock mass. Swedge, however, takes this geological understanding and applies it to simulate potential wedge failure modes. This simulation is a crucial step in determining the sizes of potential failures and calculating the factors of safety, which are paramount in any stability assessment.

Despite the individual applications of DIPS and Swedge in various studies, - a significant gap exists in systematically evaluating their combined performance across diverse pitwall conditions. The study recognizes this void and endeavours to fill it by offering a refined understanding of pitwall stability mechanisms. This goes beyond theoretical exploration; it aims to develop a robust methodology applicable across a spectrum of geological and climatic conditions. The research seeks not only to enhance our theoretical understanding of pitwall stability but also to provide practical insights that can be implemented in real-world mining scenarios.

2 BACKGROUND OF CASE STUDY MINE

This case study is based on the Kaunis iron ore mine located in Northern Sweden. The mine has a strong focus on every aspect of sustainability – Social, safety, environmental and economic aspects. The mine has several open pits, this study focusses on Tapuli open pit. At Tapuli, possible failures are classified as structurally controlled (SRK Consulting, 2022) (Sjöberg, 2020). Therefore, most of the failures are controlled by major structures like faults, joints and foliation. In this sense, structural analysis amongst other issues like pore pressure rock mass properties and compressive strength (UCS) are key to understanding the failure dynamics and expectations.

2.1 Geotechnical Domains and Models

The geotechnical domain model of the Tapuli open pit is shown in Figure 1. There are three major lithological units. The Quartz Phyllite on the footwall, Skarn – the ore-bearing zone – and carbonates, mostly dolomitic marble, on the hanging wall, with additional Phyllite on the southern extreme of the model shown. The open pit has been subdivided into four geotechnical domains based on the expected failure modes, as shown in Figure 2, and almost coincides with the geological lithologies. Figure 3 shows the fault model with most of the major faults striking in the NW-SE direction. However, it is important to note that there exists a critical fault zone not included in the fault model but lies along the entire contact between the Quartz Phyllite and Skarn.

The Tapuli open pit RQD overview is presented in Figure 4.

The RQD model on the other hand shows that most of the domains have medium to high RQD except for the earlier mentioned fault zone between the QP and Skarn: Most of this contact is in the NE-N-NE domain, SE-E and SW.

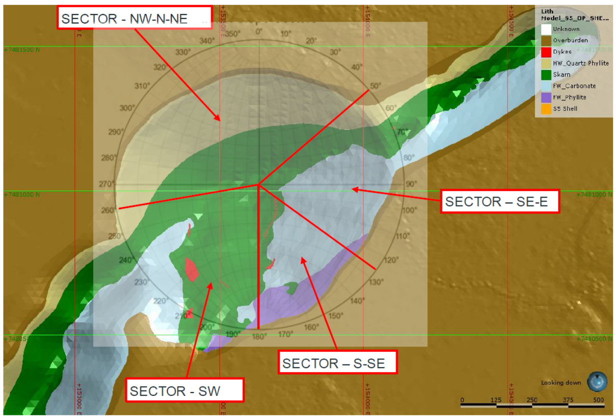

Figure 1 The four geotechnical domains - design sectors at Kaunis Iron (Kaunis Iron geotechnical database, 2023).

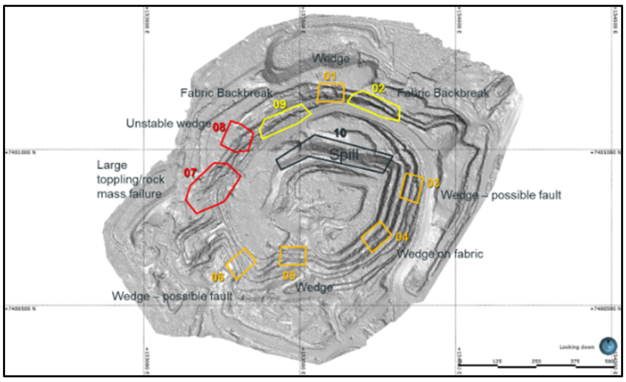

Figure 2 Possible Failure modes in relation to geotechnical domains (Kaunis Iron geotechnical database, 2023).

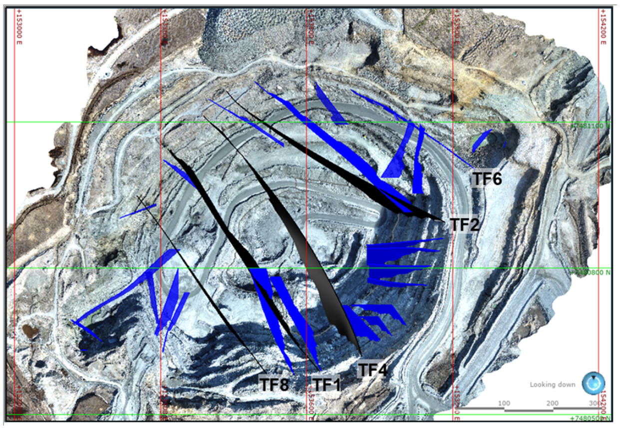

Figure 3 Tapuli Fault Model (Kaunis Iron geotechnical database, 2023).

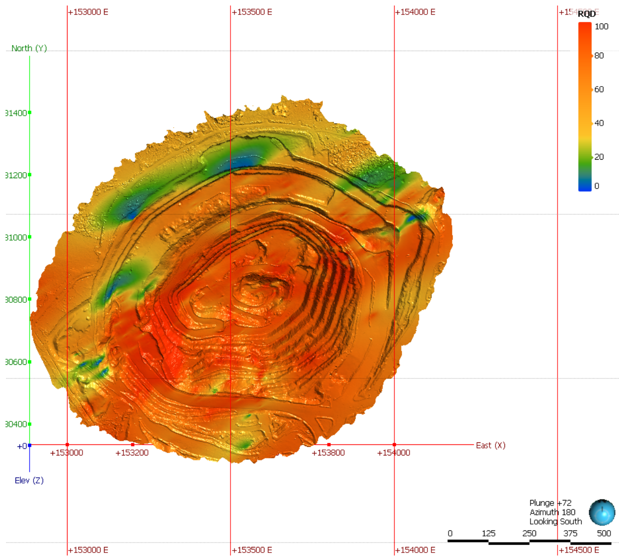

Figure 4 Tapuli RQD evaluated on a pit design.

3 TAPULI OPEN PIT STRUCTURAL MAPPING

Structural mapping in open pit mining is crucial for representing the stratigraphic, geological, and tectonic structures found at the mine. The aim is to optimize the exploitation planning and increase the efficiency and productivity of the mine (Patra et al, 2023). Additionally, the continual sampling of the rock mass through structural mapping of bench and highwall faces can provide an abundance of high-quality discontinuity data (Elmouttie et al, 2016). This can provide an opportunity to enhance pitwall stability performance once the data is used in the pitwall design. Some common structural mapping techniques used in mining operations are - described in the following text.

3.1 Face Mapping

This is considered - one of the most important processes of representing the stratigraphic, geological, and tectonic structures found at an open pit mine (Patra et al, 2023). It usually involves physical mapping of the structures.

3.2 Ground Movement Study

In underground mines, this approach aims to obtain the progressive development of roof failure and mining-induced strata movement for the combined surface and underground mining conditions. It also identifies the vertical and horizontal zones of the disturbed overburden and assesses the slope behaviours influenced by the underground mining activity. This is mostly used in a combined underground and surface mining situation. (Wang et al, 2020)

3.3 Photogrammetry

This innovative technology is used for geological face mapping. Many researchers have recently published articles, which present numerous cases of Unmanned Aerial Vehicles photogrammetry (UAV-photogrammetry) applications, such as the identification of faults, fractures, bedding surfaces (Patra et al, 2023). For open pit mines, photogrammetry has been widely used for structural mapping, with studies demonstrating its effectiveness in overcoming limitations of traditional face mapping methods (Pátíková 2004, Mathis 2011, Medinac 2020). It has been particularly useful in characterizing major structural zones and fabric structural orientation, and in planning geotechnical drillholes for potential pit expansion (Mathis, 2011). The integration of unmanned aerial vehicle (UAV) technology has further enhanced the spatial and temporal resolution of the collected data, allowing for faster and on-demand data collection (Medinac 2020). However, the use of photogrammetry in inaccessible areas of mines, such as unsupported underground sites, remains a challenge (Russell, 2018).

3.3.1 Application of Photogrammetry at Kaunis Iron

Considering the distinct weather patterns prevalent in the geographic region of the mine, characterized by an extensive six-month period of darkness coupled with sub-zero temperatures, traditional physical mapping methods are rendered impractical and unsafe. This challenge is notably exacerbated by the complete obscuration of pitwalls during the winter season, visually depicted in Figure 5.

Figure 5 Snow covering the pitwalls at Tapuli open pit in winter.

Consequently, a strategic shift towards mapping procedures integrates Unmanned Aerial Vehicle (UAV) technology in conjunction with laser scanning methodologies to facilitate safer and more effective mapping endeavours. The resultant output of these combined approaches yields point cloud data, subsequently utilized for structural mapping through commercial packages like Maptek's Point Studio software. The mapping workflow is shown in Figure 6.

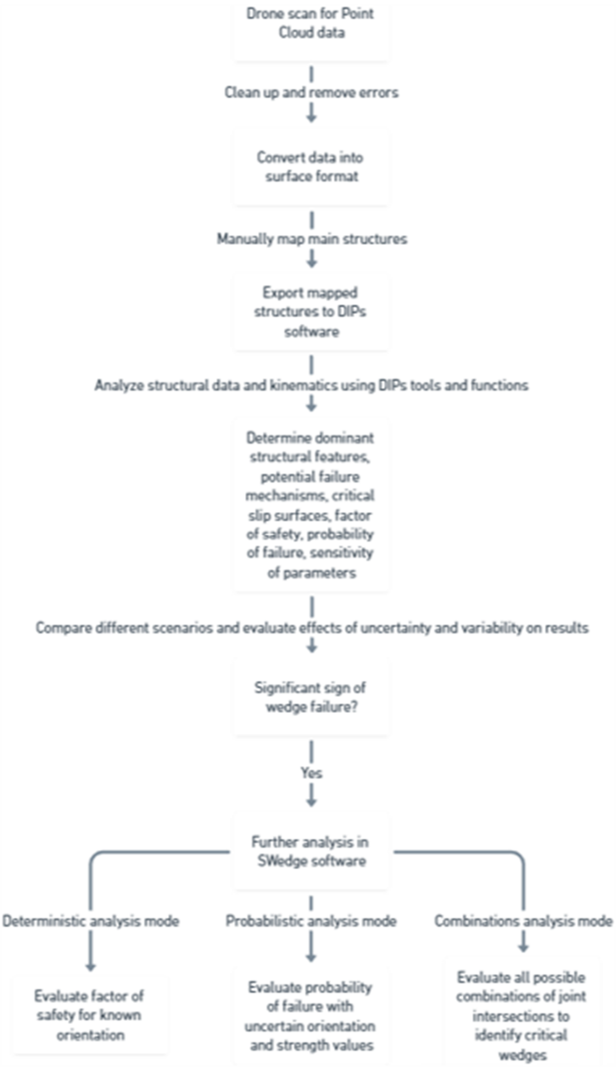

Figure 6 Workflow of how the point cloud data is used for mapping.

Further practical observations reveal an additional limitation of photogrammetry not mentioned earlier: the inability to comprehend the infill characteristics between identified critical joints within a mapped area. To address this gap, borehole logging data sourced from Optical Televiewer (OTV) and Acoustic Televiewer (ATV) methodologies can be employed. This supplementary data is instrumental in assessing the properties of infill material within the specified area, recognizing that slope instability can arise not solely from structural formations but also from the nature of joint infill properties - such as swelling clay and slickensides joints - which may pose heightened risks. This is primarily because, for structural controlled failures, the shear strength of the joints is an important factor which can be directly altered by presence of water and the type of infill. While fault and rock mass models serve as guiding frameworks, their application differs significantly in the operational implementation of rock mechanics, bench by bench.

This approach serves as a crucial verification tool, validating the data registered within the models against practical on-site applications for better slope management. Figure 7 presents an example of planned blast point cloud data of one of the mining faces. Mapping using commercial software Point studio Geotechnical tool is illustrated in Figure 8.

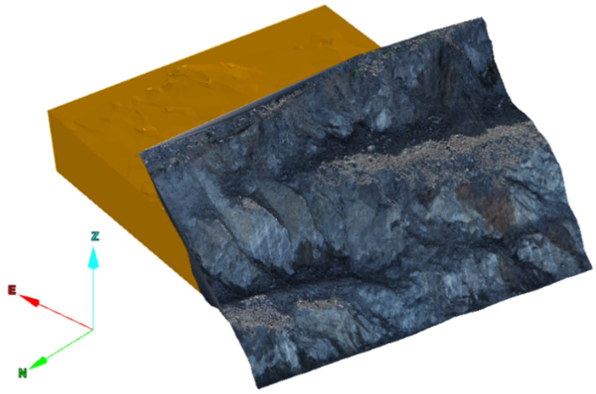

Figure 7 The planned blast point cloud data of the face.

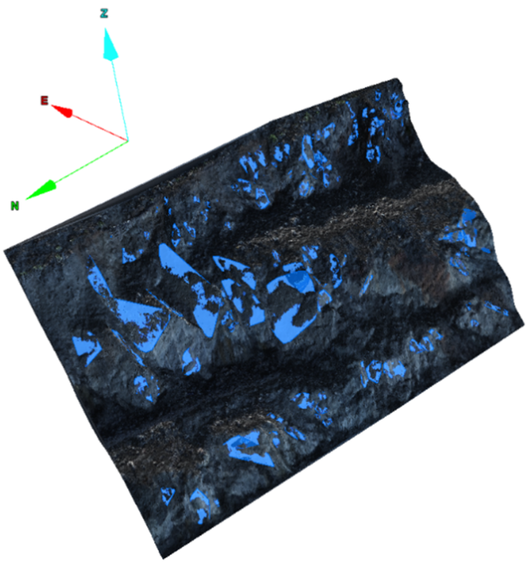

Figure 8 Mapping using commercial software Point studio Geotechnical tool.

3.4 *Further details on the research study approach*

The methodology for using structural analysis for pitwall stability is shown in Figure 6. Figure 9 compliments with an additional fabric-based approach.

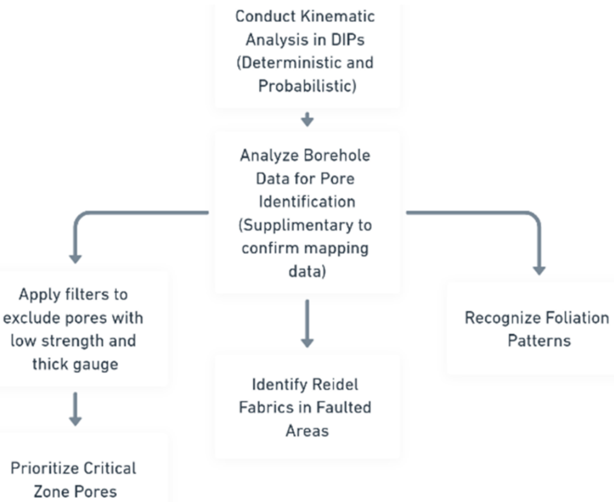

Figure 9 Fabric based structural analysis approach.

4 CHALLENGES IN ASSESSING SLOPE STABILITY AT TAPULI OPEN PIT

Slope stability assessment in open pit mines, especially in extreme weather and cold freezing environments, presents several unique challenges. These challenges are further amplified if the mine is controlled by structural failure. Some of the key challenges encountered are discussed in the following text.

4.1 *Geotechnical consideration*

The stability of open pit slopes is related to the safety and development of a mine (Du et al, 2022). It is principally controlled by the properties of geological discontinuities of the slope, such as bedding planes, faults, cleavage, and joints (Du et al, 2022) (Nizametdinov et al, 2022) (Bridges, 2013). Therefore, a comprehensive investigation of these geological discontinuities' geometry and shear strength is crucial (Du et al, 2022).

4.2 *Freeze - Thaw cycles*

In cold regions, the freeze-thaw action significantly affects the mechanical properties of the rock mass (Shin, 2020). This natural process poses a significant effect on the stability of an open pit slope (Hong et al, 2021). Therefore, the cycle of the freeze-thaw action is imperative to be considered in the stability analysis. (De Bryun, 2019) asserts that the freeze-thaw cycle usually causes the deterioration of the mechanical properties of the rock mass, thus leading to instability. Of all the four seasons in Sweden, spring poses much of a challenge and most of the minor failures are recorded around this time of the year when the snow and ice are melting from the pitwalls. Many faults crossing the open pit are not cemented and as such act a water pathway, allowing a great influx of meltwater during spring and early summer Therefore, monitoring the pitwalls during this period is critical.

While not per-se part of the pitwall, additional care is also taking in spring to monitor large ice blocks and the risk they pose falling down. Many of the faults in the SW sector (Figures 2 and 3) and water pathways, leading to big ice walls forming on the pitwalls in this area in winter.

4.3 *Structural Failure Control*

The failure of open pit pitwalls is mainly controlled by the shear strength of discontinuities within the rock masses. Determining of the shear strength parameters of rock mass discontinuity significantly impacts the slope stability calculations (Azarfar et al, 2019). Geological factors such as the regional geology, faulting, and emplacement of the ore can define the different lithological and structural domains in the pit. (Carvalho, 2018). Hydrogeology and understanding of the groundwater flow regime impact overall stability can also contribute significantly to failure control. Enhanced structural mapping of the different domains and rock type controls both bench design and overall stability, which includes both joint sets as well as major structural features such as dykes and faults. Identifying alteration zones that may affect rock strength is also important, especially different alterations within the same rock type which must be grouped separately. (Carvalho, 2018). Alteration plays a major role in Tapuli, with major clay weathering of feldspar-rich sections along water-conducting faults in the Quartz Phyllite domain.

5 STUDY RESULTS

5.1 Results with DIPs for a Blast SP5 132 21 taken as an example for the deterministic approach.

5.1.1 Results from DIPs

After mapping in Point Studio software, mapping data was obtained for SP5 132 21 blast. The joint sets picked after mapping are shown in Table 1. Figure 10 presents the distribution of Dip for every-showing foliation of 50º. It is important to quickly note from the stereograph (Figure 12) that there is a populous joint set dominating at a shallow angle.

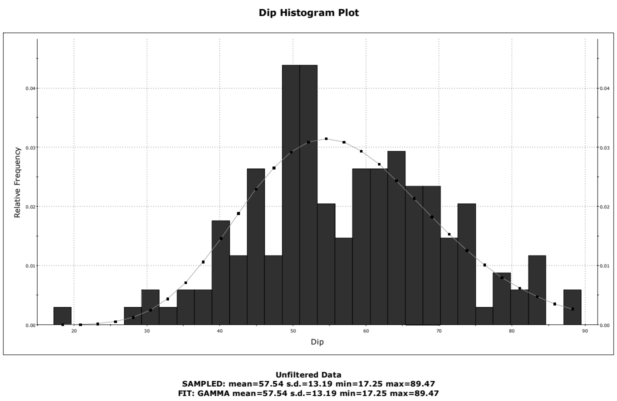

Figure 10 Distribution of Dip for every-showing foliation of 50º.

Table 1 Joint sets obtained from mapping

Joint Set	Dip	Range	Dip.Dir	Range
J1	53º	±10º	223º	±10º
J2	56º	±10º	264º	±10º
J3	59º	±10º	303º	±10º
J4	75º	±10º	286º	±10º
J5	47º	±10º	325º	±10º
TF3 Fault	70º	±10º	180º	±10º

The rock mass lithological properties for the case study mine are presented in Table 2. Some of the findings from DIPs analysis are given in Figures 11 to 16.

Table 2 Lithological Geotechnical Properties

Lithology	Density (t/m3)	IRS (R-rating)
Phyllite	3.4	R6
Skarn	3.0	R5
QP	2.8	R6
Marble	2.8	R5

The first step is to look for the obvious failure types using kinematic analysis in DIP.

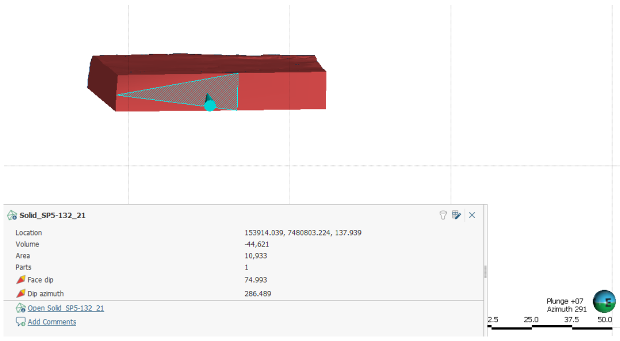

Figure 11 Slope Orientation characteristics -Dip and Dip Direction.

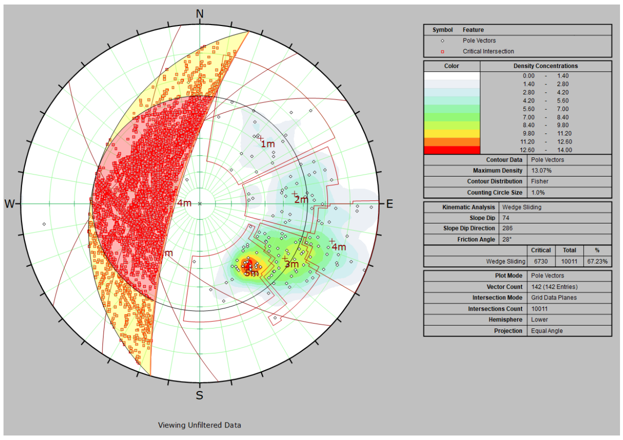

Figure 12 Class 1 Unfiltered data based on actual mapping from Photogrammetry and shows 67.23%.

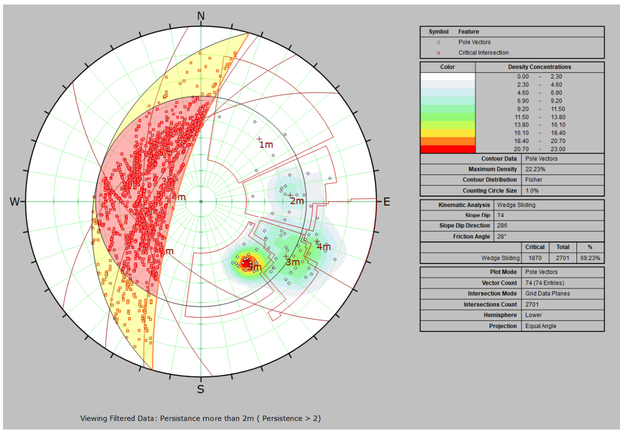

Figure 13 **Class 2 Filtered with persistence of more than 2m and shows 69.23%.**

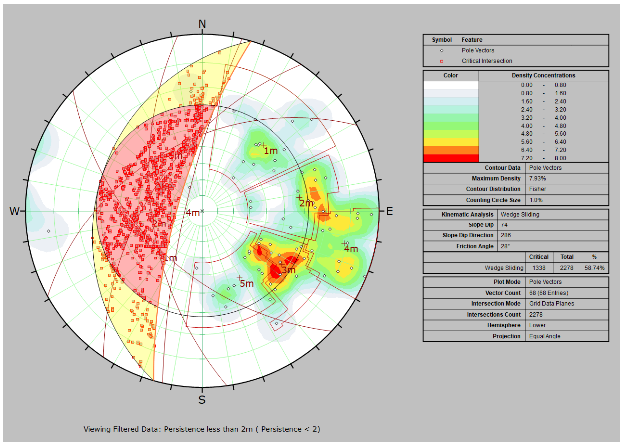

Figure 14 **Class 3 Filtered with joint persistence of less than 2m and shows 58.78%.**

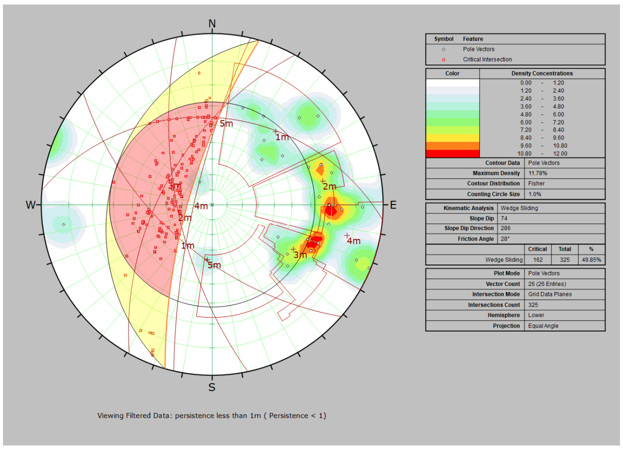

Figure 15 **Filtered with joint persistence of less than 1m and shows 48.85%.**

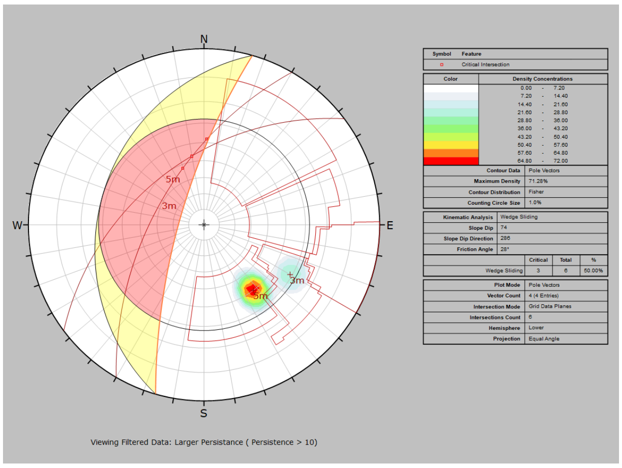

Figure 16 **Filtered with joint persistence larger than 10m and shows 50%.**

5.1.2 Discussion

The analysis of wedge type of failure concerning pitwall stability using DIPs Rocscience software provides valuable insights into potential failure scenarios. The data is categorized into five classes, as shown in Figures 12-16, each representing a different level of filtering and joint characteristics:

Class 1: Unfiltered Data - This class includes all the raw data before any cleaning or filtering. It contains noise from blasting and conflicting mapping of the previous bench face. The critical wedge sliding possibility for this class is **67.23%**.

Class 2: Joints > 2m - This class represents data that has been filtered to remove noise from blasting, small joints, and microfractures. It only includes joints with a persistence of more than 2 meters. The critical wedge sliding possibility for this class is **69.23%**.

Class 3: Joints < 2m - This class includes data with noise from blasting, small joints, and micro fractures, but excludes joints with a persistence of more than 2 meters. The critical wedge sliding possibility for this class is **58.78%**.

Class 4: Joints > 1m - This class includes data with noise from blasting and micro fractures but excludes joints with a persistence of less than 1 meter. The critical wedge sliding possibility for this class is **48.85%**.

Class 5: Joints > 10m - This class represents potential faults and only includes joints larger than 10 meters. The critical wedge sliding possibility for this class is **50%**.

Each class represents a different stage of data refinement, from unfiltered initial data with various disturbances to progressively filtered data sets. This analysis helps in understanding the impact of different factors like blasting noise, joint sizes, and potential faults on pitwall stability. It facilitates informed decision-making for enhanced stability and safety measures within the pitwall. The Histogram of dip direction and its relative frequency for the wall on sp5 132 21 is shown in Figure 17.

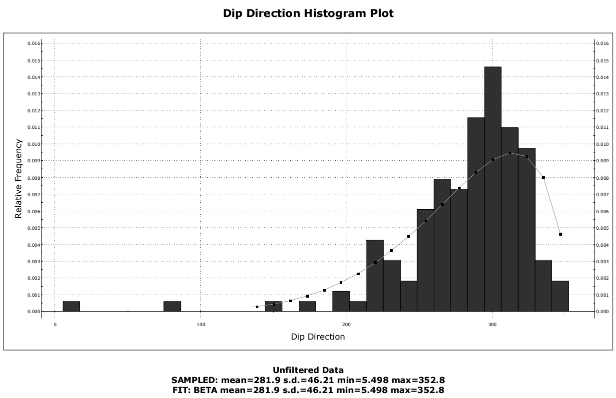

Figure 17 Histogram of dip direction and its relative frequency for the wall on sp5 132 21.

From Figure 17, the joint set with dip direction around 300° is the most frequent, this signifies J3 and J4 (foliation joints). Figure 18 shows the histogram of dip direction and its quantity for the wall on sp5 132 21.

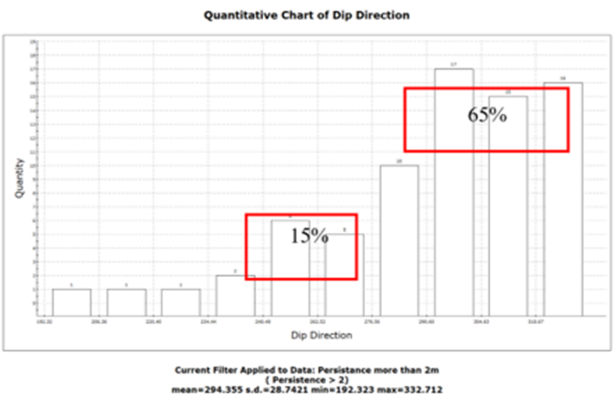

Figure 18 Histogram of dip direction and its Quantity for the wall on sp5 132 21.

Based on the dip direction analysis in this area 65%, of the mapped joints are between 290º and 320º dip direction and the other majority of 15% on between 250º and 270º the schematic diagram below helps to visualize the joint sets as they relate to the slope. Figure 19 presents the visual representation of slope to joint set outlook.

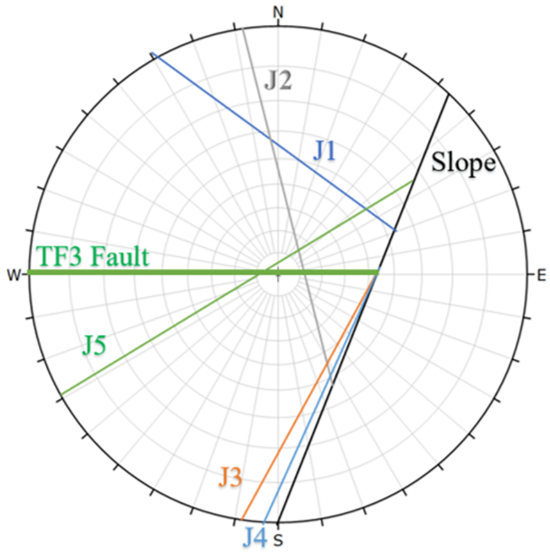

Figure 19 Visual representation of slope to joint set outlook.

It is important to note that joint sets J3 and J4 are remarkably close to the dip direction of the slope and in terms of data filtering, these joints may be related to a common mistake in mapping referred to earlier as conflicting mapping of previous face "blankslag". Considering that, J3 is the most frequent as indicated by Figure 12, it is a good idea to not view them exactly as dominant but because of the previous face. TF3 from the fault model in relation to the blast solid sp5 132 21 is shown in Figure 20.

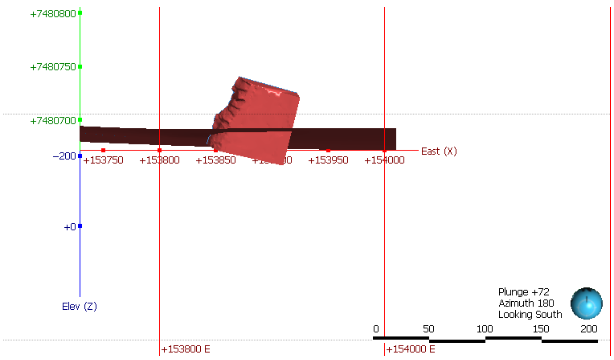

Figure 20 TF3 from the fault model in relation to the blast solid sp5 132 21.

5.2 Results from Swedge

SWedge was utilised to perform through stability analysis of the mine pitwall. Figures 21 to 35 highlight some of the key observations from this analysis.

5.2.1 Combination of TF3 vs J3 in SWedge

In the Swedge analysis, when TF3 and J3 are designated as the first and second joints governing wedge failure, the findings reveal that the Safety Factor (SF) is notably 1.1624, among other outcomes, as shown in Figure 21. This wedge forms a blankslag which can be a potential contributor to backbreak.

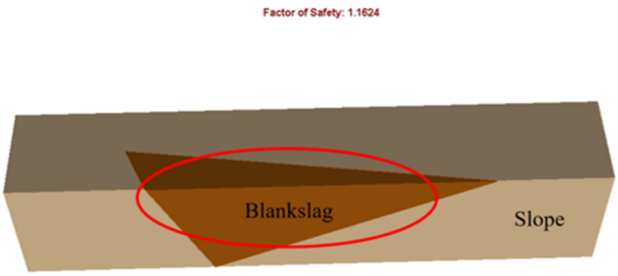

Figure 21 TF3 vs J3 combination shows 1.16 SF.

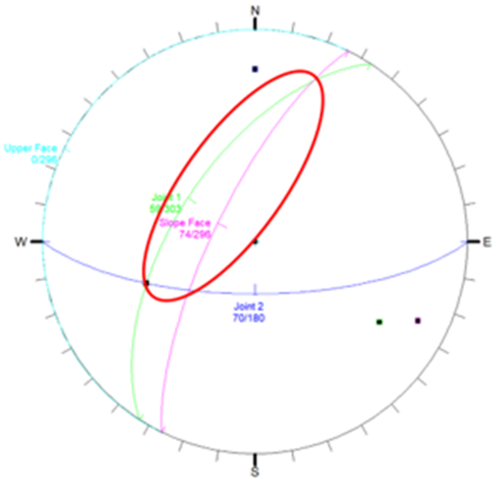

Figure 22 Stereo net of TF3 vs J3 combination.

5.2.2 Combination of TF3 vs J5 SWedge

When TF3 and J5 are assigned as the joint 1 and 2 governing wedge failure, respectively. The results show, amongst other results, that most importantly the SF is 2.562, as presented in Figure 23.

Figure 23 J3 vs J5 combination show 0.95 SF.

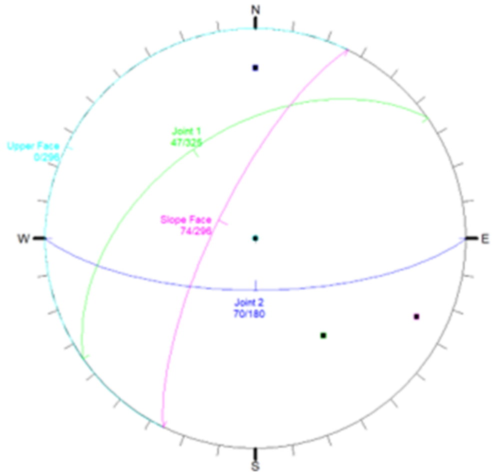

Figure 24 Stereonet of J3 vs J5 combination.

5.2.3 Combination of TF3 vs J1 in SWedge

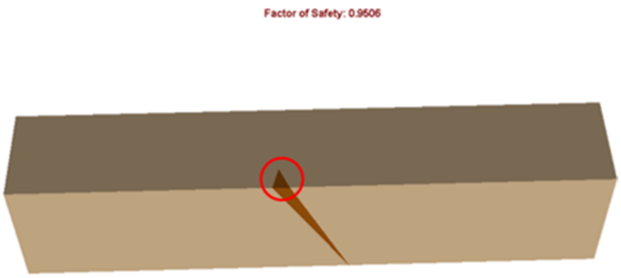

Figure 25 J3 vs J1 combination show 0.95 SF.

Figure 26 Stereonet of J3 vs J1 combination.

5.2.4 Combination of TF3 vs J2 in SWedge

Figure 27 SF 0.4776 but very small wedge.

Figure 28 Stereonet of J3 vs J2 combination.

5.2.5 Combination of J1 vs J5 in SWedge

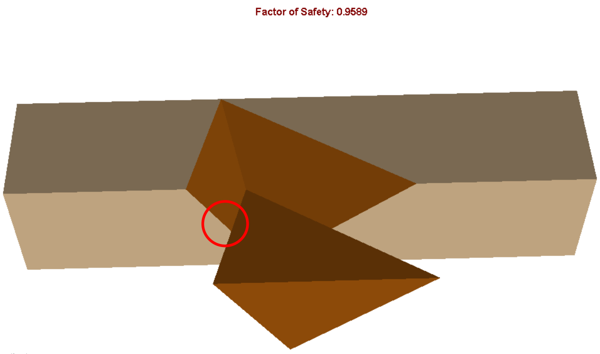

Figure 29 J1 vs J5 combination show 0.95 SF.

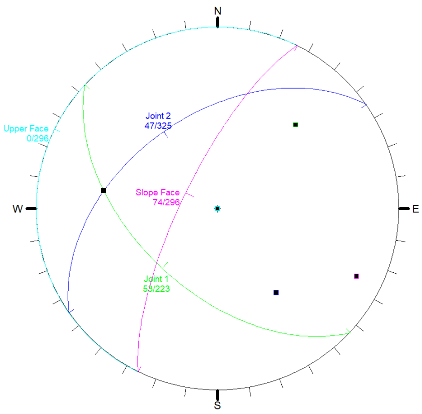

Figure 30 J1 vs J5 combination stereo net.

5.2.6 Combination of J2 vs J5 in SWedge

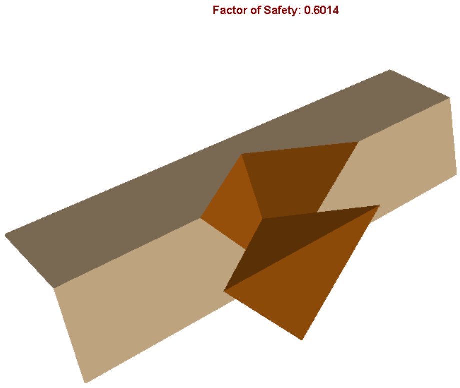

Figure 31 J2 vs J5 combination show 0.6 SF.

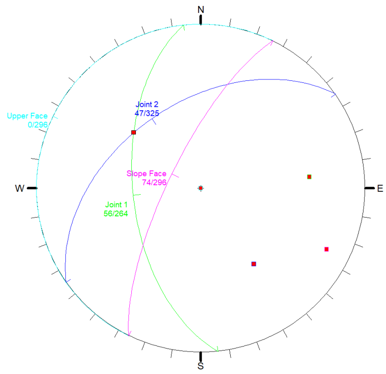

Figure 32 J1 vs J5 combination stereo net.

5.2.7 Combination of J5 vs J3 in SWedge

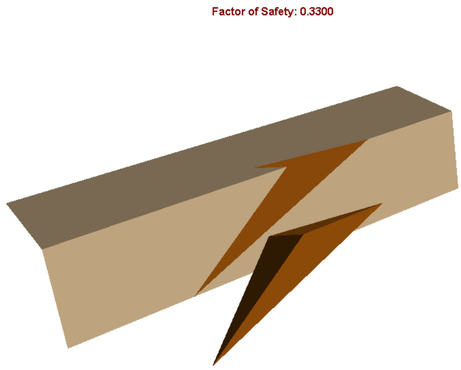

Figure 33 J5 vs J3 combination show 0.33 SF.

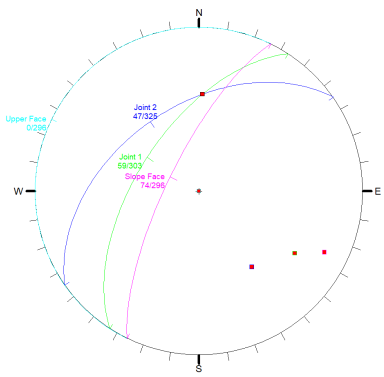

Figure 34 J1 vs J5 combination stereo net.

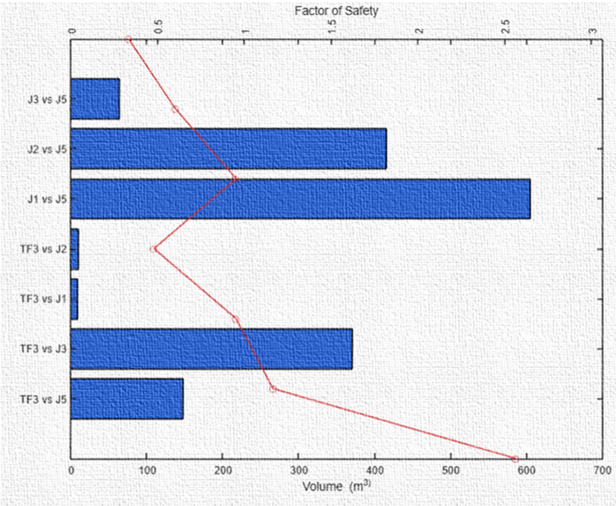

Figure 35 Joint combinations in Swedge and the related factor of safety and volume in m³.

In Figure 35, several joint combinations for wedge formation are shown in relation to the volumes they can generate and the related factors of safety. The following discussion interprets these results.

TF3 vs J3 (371 m³, SF: 1.1624): Although this combination surpasses the SF threshold of 1, it is closer to the threshold and has a larger volume, signifying a wedge that may approach critical stability. While it is relatively safer than the threshold, the larger volume could still pose risks in certain conditions or under stress. Also, ~~it~~ J3, as mentioned earlier, may have some noise in the mapping.

J1 vs J5 (605 m³, SF: 0.95): This joint combination presents a considerable wedge volume and falls below the SF threshold, indicating a potentially dangerous configuration. The substantial volume and the SF below 1 imply a notable risk of failure and instability within this wedge formation. This is the main possible big wedge in this analysis

J2 vs J5 (416 m³, SF: 0.6): With a sizeable wedge volume and an SF well below the safety threshold, this combination stands out as more precarious. The larger volume combined with a significantly low SF indicates a higher likelihood of instability and potential failure.

J3 vs J5 (64 m³, SF: 0.33): Although this combination represents a smaller wedge volume, its SF is substantially below the safety threshold, highlighting a critical safety concern. Despite the smaller size, the SF well below 1 signals a very unstable and potentially dangerous configuration.

The analysis underscores that larger wedge volumes, combined with SF values below the threshold of 1, significantly increase the risk of potential failure within wedge formations. Configurations like J1 vs J5, J2 vs J5, and J3 vs J5, despite varying in volume, all exhibit SF values below the safety threshold, indicating the critical importance of reinforcement action to maintain pitwall safety and risk of failure.

5.3 Results from SBlock probabilistic approach

The structural data for the sp5 132 21 in Table 10 was also used in SBlock as well, a computer program which uses joints orientation, persistence and spacing statistics was implemented to develop a probabilistic approach which allows rapid determination of the probability of failure of blocks/wedges for different benches geometries (Hormazabal, 2013). The probabilistic approach failure analysis using SBlock is shown in Figure 36.

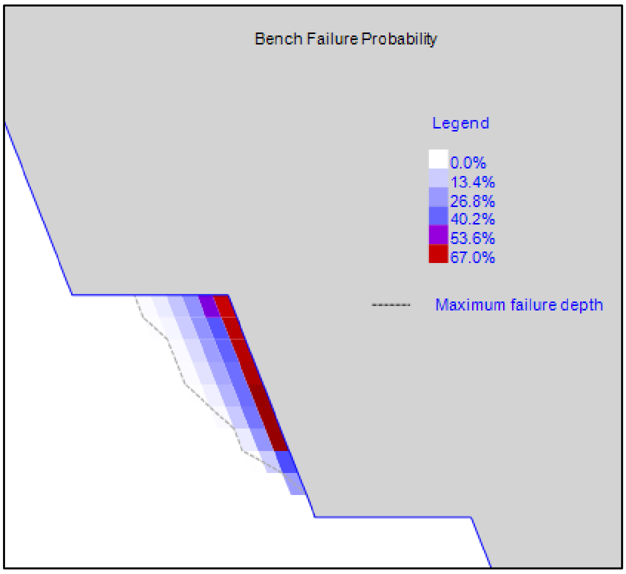

Figure 36 Probabilistic approach Failure analysis using SBlock.

In Figure 36, the possibility of the wedges to fail lies mostly on the crest and part of the wall. This is confirmed by the comparison of reality and 3D simulated results of wedge formation on this blast as shown in Figure 39. Figure 38 shows that the effective catch bench in this blast would be lost up to 6.26m from the planned 10m due to backbreak.

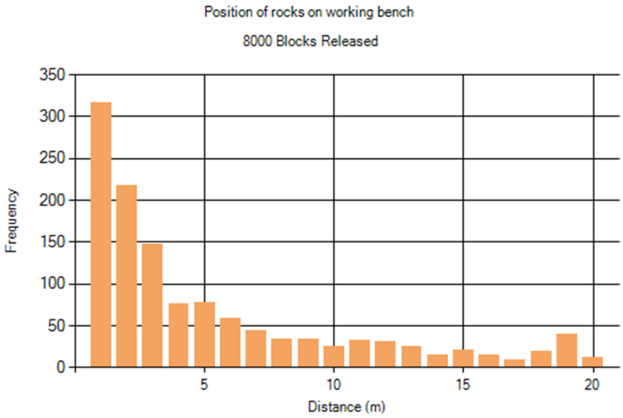

Figure 37 Rockfall results from SBlock.

Figure 39 illustrates a computer-generated 3D simulation that represents how wedges may form within assumed conditions for this study, particularly sp5 132 21. This virtual representation is contrasted and validated against the results obtained from the SBlock program, which utilizes structural data and statistics to predict the probability of wedge failures in mining scenarios.

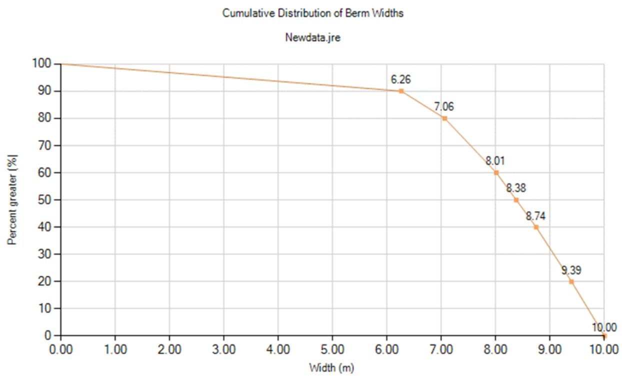

Figure 38 Backbreak and loss of crest results from SBlock.

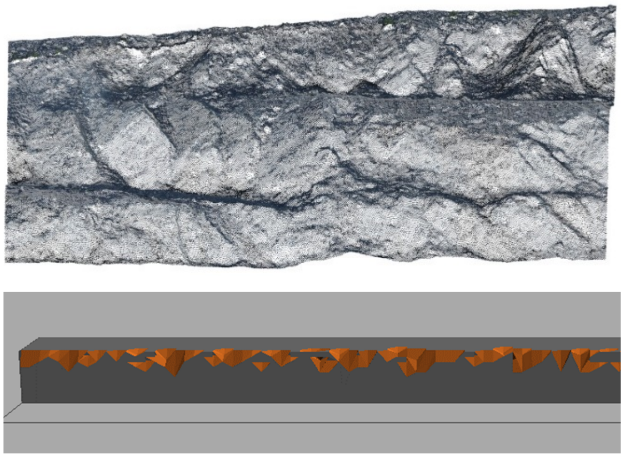

Figure 39 3-dimensional simulation of wedge formation in relation to the slope on compared to reality SBlock.

6 CONCLUSIONS

The study employed a detailed structural mapping approach to analyse pitwall stability, offering critical insights into potential failure scenarios. The data, categorized into five classes based on joint characteristics and filtering levels, unveiled the multifaceted influences of blasting noise, joint sizes, and faults on pitwall stability. This thorough analysis informs decision-making for stability enhancement and safety implementation, with critical wedge sliding possibilities ranging from 48.85% to 69.23% across different classes. The unfiltered data in SBlock demonstrated a 67% sliding possibility, emphasizing the significance of accurate data classification in predicting and mitigating risks.

Swedge analysis explored joint combinations, highlighting configurations like J1 vs. J5, J2 vs. J5, and J3 vs. J5 with safety factors below the threshold, indicating higher risks of instability and potential failure. The probabilistic approach through SBlock provided a comprehensive understanding of failure probabilities.

Addressing a critical issue in rock mechanics and open pit mining, this research contributes practical guidance for enhancing stability in diverse operational contexts. The integration of advanced software tools, the constructive collaboration between DIPS, Swedge, and SBlock, and the consideration of multifaceted factors position this study as a valuable resource for engineers, regulators, and stakeholders in open pit mining. The outcomes extend beyond the specific project, offering a broader guide for future endeavours facing similar geotechnical challenges in pursuing responsible and sustainable mining practices.

7 LIMITATIONS

The study's reliance on UAV and photogrammetry for structural mapping is challenged by the extreme weather conditions at Tapuli pit, especially during winter, which can obscure pitwalls and affect data accuracy. Additionally, the inability of photogrammetry to capture infill characteristics between critical joints necessitates supplementary borehole logging data, highlighting a gap in comprehensively assessing the properties of joint infills, which are crucial for understanding slope stability.

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