Kinematic Analysis of Slopes in the Western and Eastern Walls of the Karowe Open Pit, Botswana

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ABSTRACT

The Karowe Diamond Mine is an open pit mine located in the Central District of Botswana and it exploits the AK6 kimberlite which is part of the Orapa Kimberlite Field (OKF). The main focus of this study is to identify potential movement of critical structures or discontinuities such as joints, faults, bedding. Structural Discontinuity mapping and Geophysical Data Collection, Maptek 3D analysis and Kinematic analysis through the RocScience Dips.8 software were used to generate data and further evaluation using stereographic projection for the Karowe open pit. Through kinematic analysis, critical failure modes including Planar failure mode (1.65% of joints causing failure), flexural failure mode (1.65% of joints causing failure), Direct Toppling (12.43% of joints capable of causing failure) and Wedge Failure (12.09% of joints capable of causing failure) were identified. Direct toppling and wedge failure are prominent on the north-eastern and south-eastern slopes of the mine. Recommendations for slope stability enhancement include adjusting slope angles or pit geometries to align with critical discontinuity orientations, developing support structures for slope reinforcement, implementing regular drainage measures, and conducting tension crack mapping exercises. These proactive strategies aim to optimize slope stability, reduce potential failure risks, and ensure long-term safety and productivity in mining operations. This study emphasizes the significance of kinematic analysis for understanding and predicting potential failure modes related to structural parameters in mining operations. By incorporating these findings into slope stability assessments and engineering strategies, mining companies can enhance safety measures and optimize operational efficiency in challenging geological environments like the Karowe Diamond Mine.

Keywords: Karowe Kimberlite Field, Maptek, Dips.8, Kinematic analysis, Failure modes,

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INTRODUCTION

Background of the problem

The Karowe Diamond Mine is an open pit mine located in the Central District of Botswana and it exploits the AK6 kimberlite which is part of the Orapa Kimberlite Field (OKF). Production started in 2012 to date, in which commercial production commenced in July and full production capacity being achieved by August 2012. The mine life is expected to reach 2026. As the main diamond pipe continues deep below the final open pit depth, Karowe is developing an underground system to transition from open pit mining to underground mining method after 2026, extending the mine life to 2040. The location map of the Karowe mine is shown in Fig.1. Figure 2 shows an aerial photograph of the Karowe Diamond Mine and other Surrounding Mines with a Representation of The Kimberlite Pipes in the Area (Karowe Mineral Resource Update, 2018).

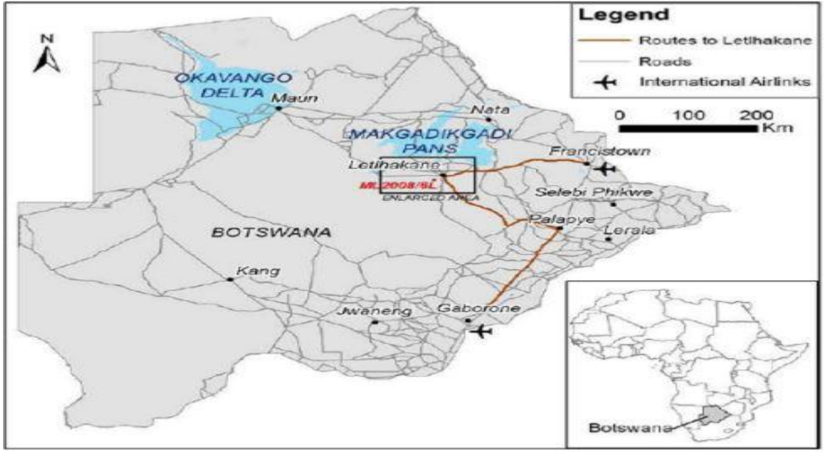


Fig. 1: Location of Karowe Diamond Mine

(Karowe Mineral Resource Update, 2018).
Different mining sites are displayed in Fig.2 below.

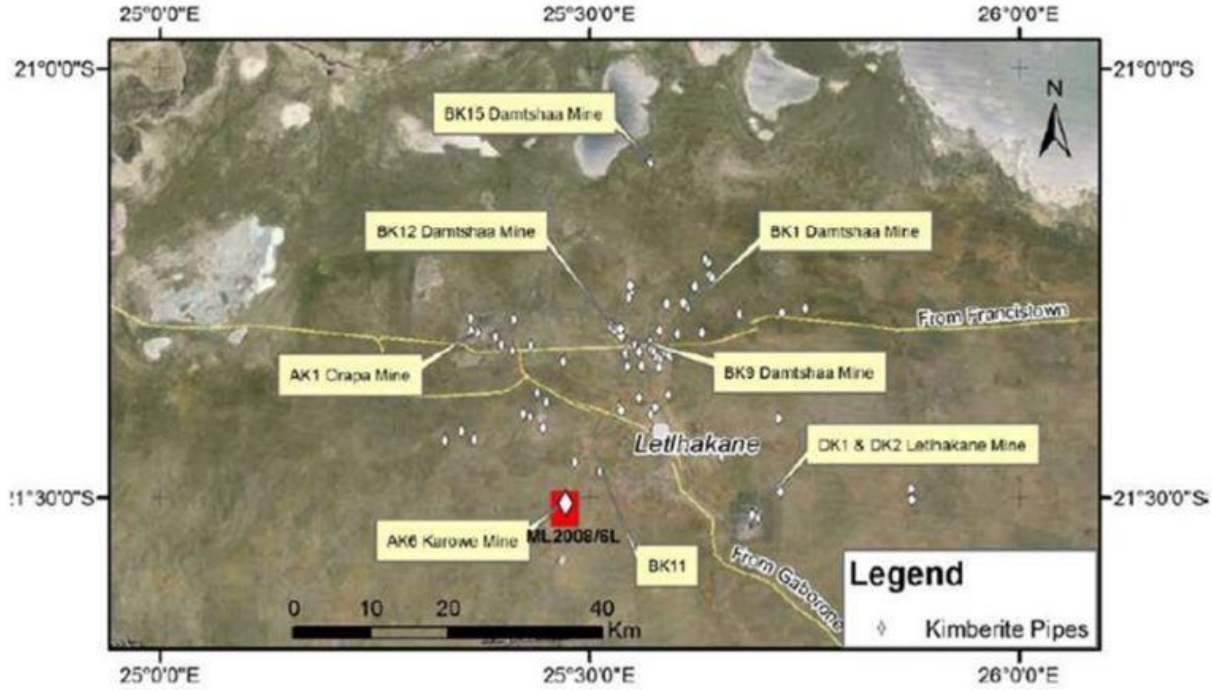


Fig. 2: Karowe Diamond Mine and other Surrounding
(Karowe Mineral Resource Update, 2018).

GLOBAL CONTEXT

Lefu & Hingston, (2019) presents a study of kinematic analysis conducted in the eastern kimberlite slope of the Main Pit at Letšeng Diamonds. Cluster analysis, which uses fuzzy clustering in Rocscience DIPS program, revealed three major joint sets J1 (63°/335°), J2 (45°/043°), and J3 (32°/265°). According to the analysis, it is evident that J1 promotes the potential for planar failure, while the intersection of J1 and J2 promotes potential for wedge failure. Moffitt at al., (2007) have conducted stability analysis in Diavik Diamond Mines has led to the exploration of new techniques to estimate the im-pact of intact rock bridges within pervasive fracture sets on the factor of safety for the pit slopes. The kimberlite pipes being mined from the A154 pit are hosted in a strong, moderately fractured granitic rock mass. Although located within the zone of continuous permafrost, the pipes are being mined in unfrozen rock below the shallow waters of Lac De Gras.

Grenon et al., (2007) provides the framework for integrating slope stability considerations in the early stages of mine planning for surface mine operations. The block model and the resulting pit optimisation shells are linked to a series of algorithms that are used to identify potential instability areas in any particular pit of the mining push-backs. The algorithms have been developed to facilitate limit equilibrium stability analyses and to construct and visualise 3-D susceptibility maps. This has resulted in an integrated process that allows for continuous updating of the stability and mine models from feasibility to production.

Dyson et al., (2020) used Dip 6.0 software in carrying out kinematic analysis of the Songwe open-pit mine in Malawi based on the attributes of discontinuities. The results show that there is a 16% likelihood of planar failure in the divided slope sections of the planned pit. Thus, slope angle optimisation to 41° has been proposed as a counter-measure to minimise the potential risk of planar failure.

REGIONAL GEOLOGY

The Orapa Kimberlite Field (OKF) is located on the northern margin of the Central Kalahari Karoo Basin, where the Precambrian rocks of the Makgadikgadi Depression are offset against the Karoo sequence and dip gently to the south-southwest. Its country rock is the sub-outcropping flood basalt of the Stormberg Lava Group, which is about 130 meters thick. Lebung Group's Ntane Sandstone Formation of up to 60 m thick and Mosolotsane Sandstone Formation comprising sandstone, siltstones and red mudstones sequence of up to 60 m thick, the ~70 m thick Tlhabala Mudstone Formation of the Beaufort Group comprising massive mudstone, the approximately 120 m thick Ecca Group made up of the Tlapana Carbonaceous Mudstone Formation (delta) comprising the carbonaceous mudstones, carbonaceous shales, coal and arkose and the basal Mea Arkose Formation comprising arkosic conglomerates and coarse-grained arkose with carbonaceous shale interbeds (Apter, et al., 1984). The Mea Arkose Formation has been observed from geological logs from the drilling to be localised with the regional stratigraphy around Karowe Diamond Mine. The basement formation underlying the Karoo Supergroup sedimentary rocks is the Archean Granite comprising granites, granitoids and gneisses (Carney et al., 1994). Figure 3 shows a picture depicting the regional geology of the mine.

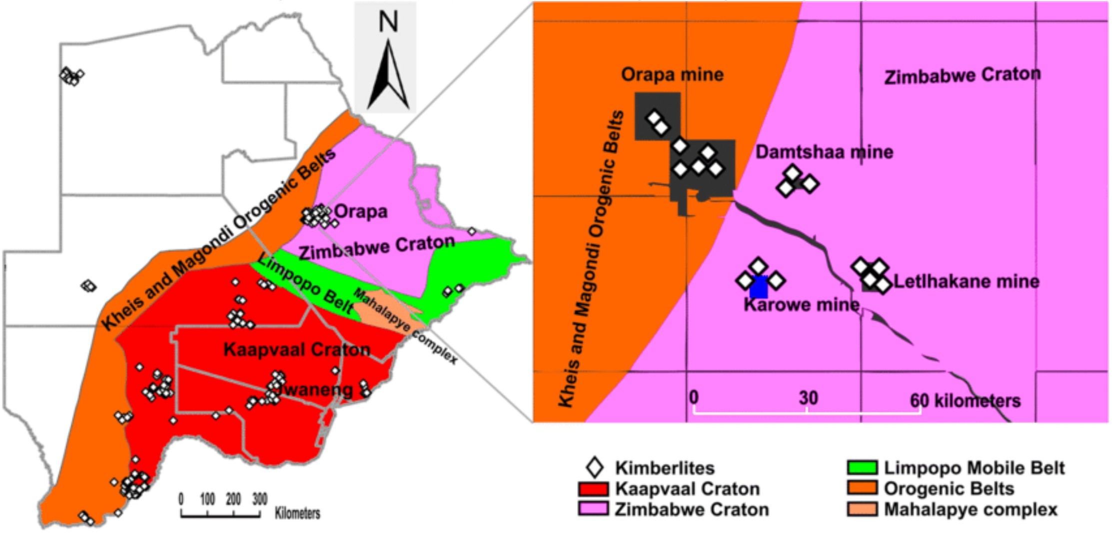


Fig. 3: Geological Setting of the Karowe Diamond Mine
Motsamai, & Harris (2018).

General stratigraphy of the region is shown in figure.4.

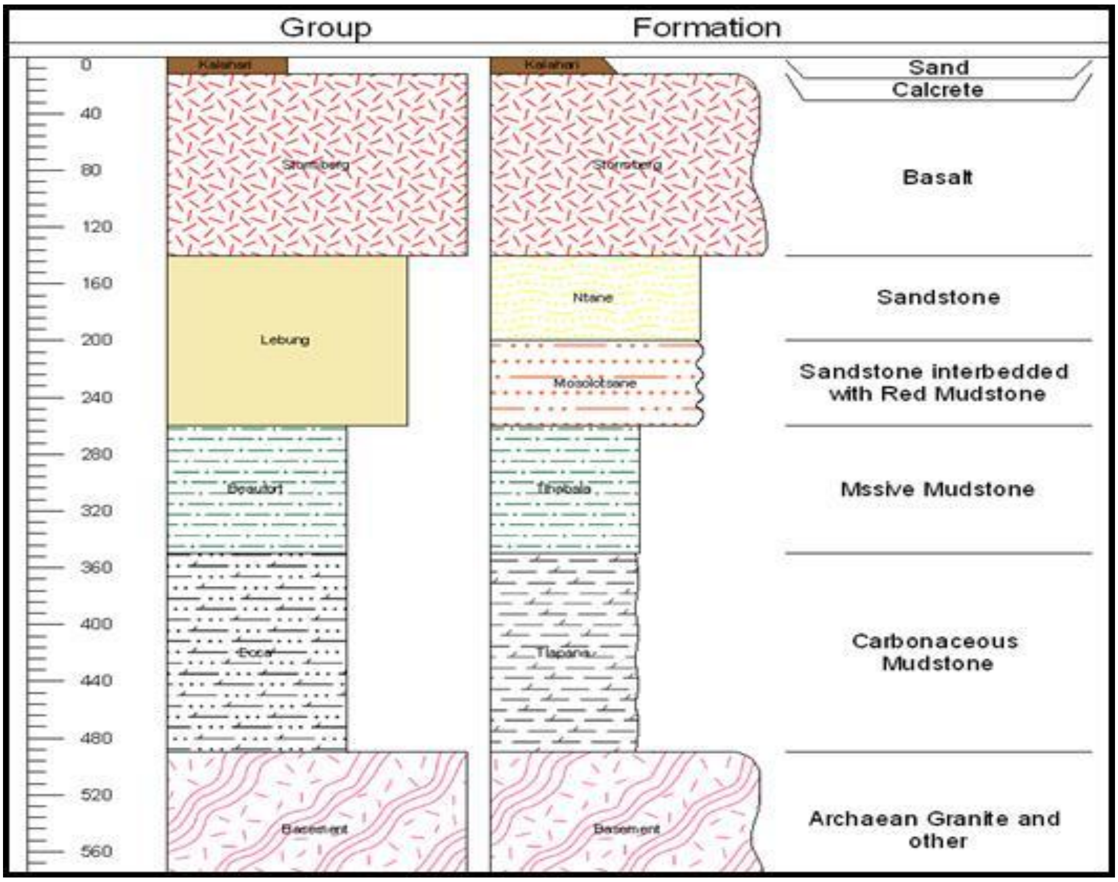


Fig. 4 : Stratigraphic Succession of the Karowe Mine

Carney et al., (1994).

3D Geological Model

According to Karowe Mineral Resource Update (2018). & Barnett, (2007) developed the current structural model using data gathered from borehole core study conducted in 2007 for project-related objectives, with specific emphasis on characterizing fracture zones. Figure 4 displays this model, though it has not yet been confirmed through in-pit investigations.

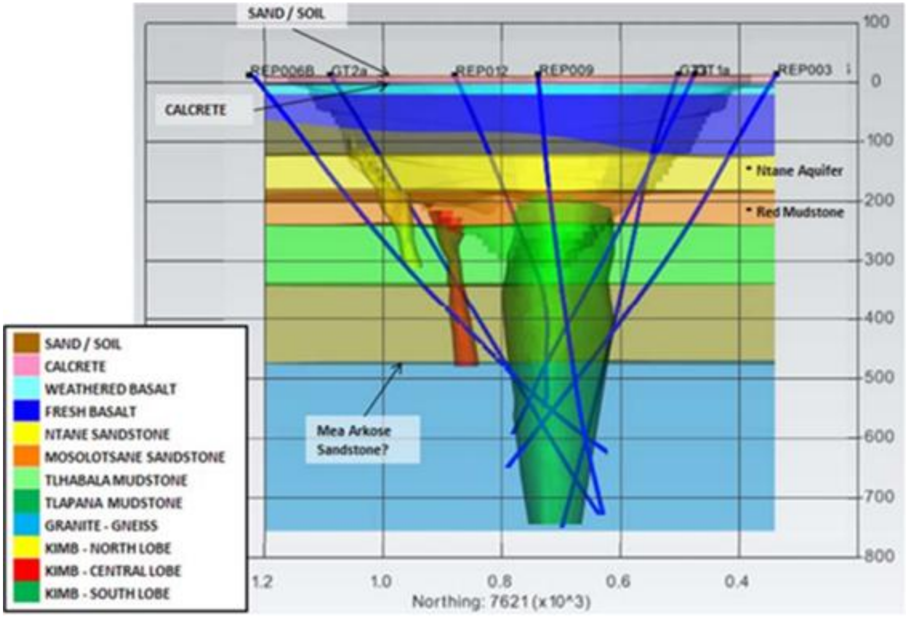


Fig.5: 3 D Country Rock Geological Model

Barnett, (2007)

STATEMENT OF THE PROBLEM

Karowe mine has not experienced any bench failures but there are signs of some probable failures to occur in the future, and these are mostly controlled by geological structures. The eastern and western slopes have more prominent geological structures, and they can dramatically affect the mechanism of failure in the future. In the present mining phase, the exposure of Red-mudstones presents a significant risk of slope failure due to their tendency to crumble and topple after prolonged exposure. As the excavation advances, a substantial amount of water has been encountered, a considerable portion of which permeates through the final walls. This leads to chemical degradation and weathering of the rock mass, a critical concern that heightens the risks of slope failure.

There is an urgent need to have a better understanding of the potential critical zones, failure mechanisms and their locations. They will also be used to update the geological model of the mine for further use in the future. The results will assist in the design and implementation of appropriate mitigation measures as well as in ground-movement monitoring. The data will also be used to develop an empirical method for assessing risks of rockfalls known as the Rockfall Risk Assessment for Quarries.

Objectives of this research:

The aims of this study are to:

1. Use kinematic analysis to identify and describe rock displacement of critical structures in the western and eastern slopes of Karowe Diamond Mine.
2. Determine the type of failure mechanisms related to the structure's parameters.
3. Suggest safety measures

METHODOLOGY

The main focus of this study was to identify potential movement of critical structures or discontinuities such as joints, faults, bedding which were evaluated using stereographic projection. The methodology is consisting of the following components:

1. Structural Discontinuity mapping and Geophysical Data Collection
2. Maptek 3D analysis
3. Kinematic analysis through the RocScience Dips.8 software

1) Structural and Geophysical Data Collection

Discontinuity mapping was carried out using a Maptek 3D laser scanner to obtain joint orientation data. Secondary pore-pressure data was acquired from the mine with the help of a hydrogeologist on-site and secondary rock strength data was obtained from the mine geotechnical team.

1.1) Discontinuity Mapping

Discontinuity mapping within the mine primarily utilized a Maptek 3D Laser Scanner (Fig.6). Initially, a comprehensive orientation scan was conducted using ground control points (GCPs) to encompass the targeted mapping areas, essentially covering the entire pit. The data collected by the tablet was stored and later downloaded for transfer and processing using Maptek software. This software was employed to clean and geo-reference the scan data, aligning it geographically with its original capture position in the pit. Structures within the scans were digitized and either saved or exported for utilization in other third-party applications.

Fig.6 : Maptek Laser Scanner

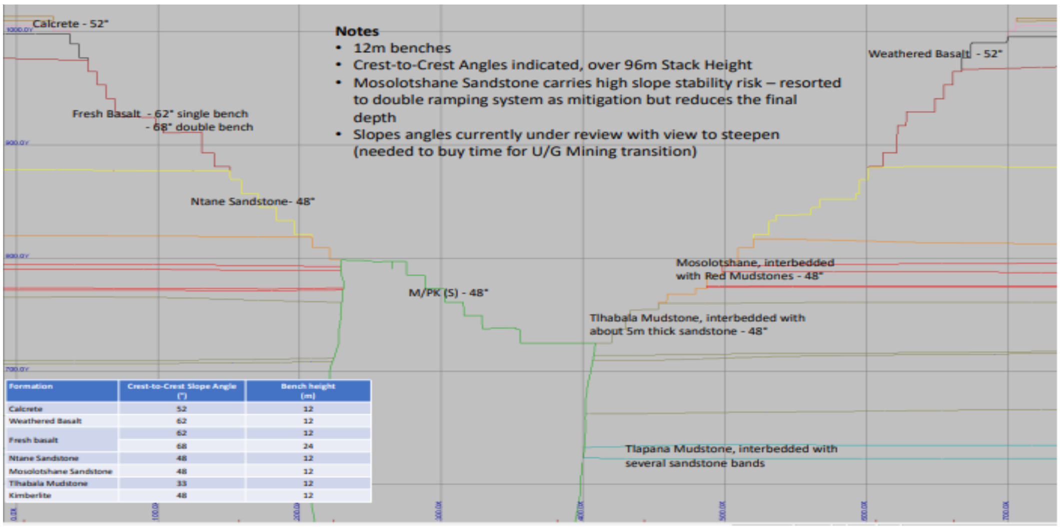
Fig. 7: A Piezometer Station

1.2) Pore - Water Pressure Data

The mine utilized vibrating wire piezometers (Fig.7) installed at specific depths within drilled boreholes in the ground to accurately measure groundwater pressures within subsurface formations. These piezometers were equipped with sensors designed to measure water pressure. The signal from the vibrating wire sensor was transmitted to a signal conditioning unit, which amplified and processed the signal to accurately measure the resonant frequency shift caused by the pressure change. Subsequently, the processed signal was sent to a remote data logging system where it was recorded at regular intervals. The recorded data was later retrieved and interpreted to determine variations in pore water pressure over time.

Rock Strata Data

Secondary rock strata data was acquired from the mine geotechnical team. This data provided details on the crest-to-crest angles of the various rock types within the pit (Fig.8). Values such as density, intact compressive strength, tensile strength, and others are depicted in Fig.9 (A & B).



Notes

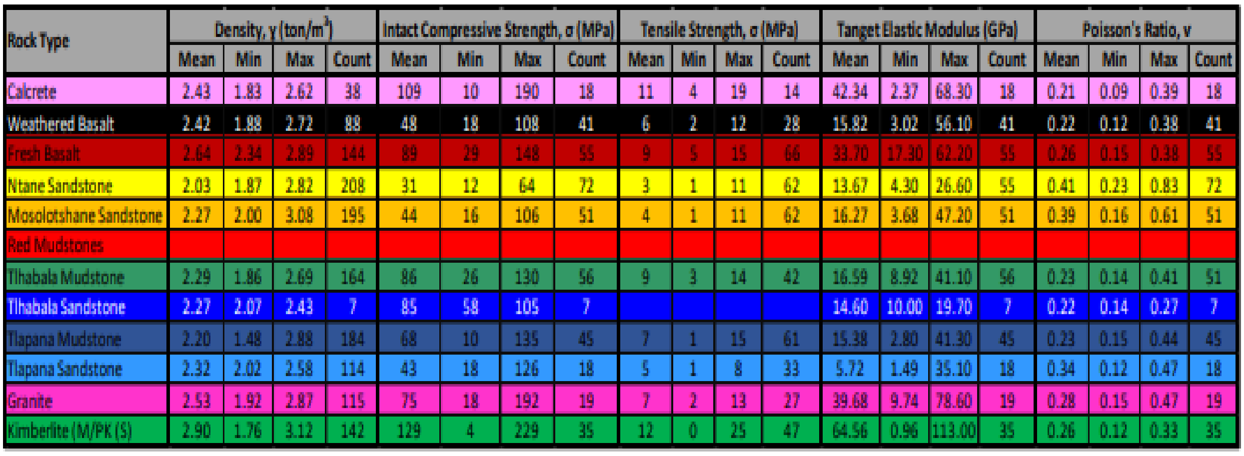
- 12m benches
- Crest-to-Crest Angles indicated, over 96m Stack Height
- Mosolotshane Sandstone carries high slope stability risk – resorted to double ramping system as mitigation but reduces the final depth
- Slopes angles currently under review with view to steepen (needed to buy time for U/G Mining transition)

Formation	Crest-to-Crest Slope Angle (°)	Bench height (m)
Calcrete	52	12
Weathered Basalt	62	12
Fresh basalt	62	12
	68	24
Ntane Sandstone	48	12
Mosolotshane Sandstone	48	12
Tlhabala Mudstone	33	12
Kimberlite	48	12

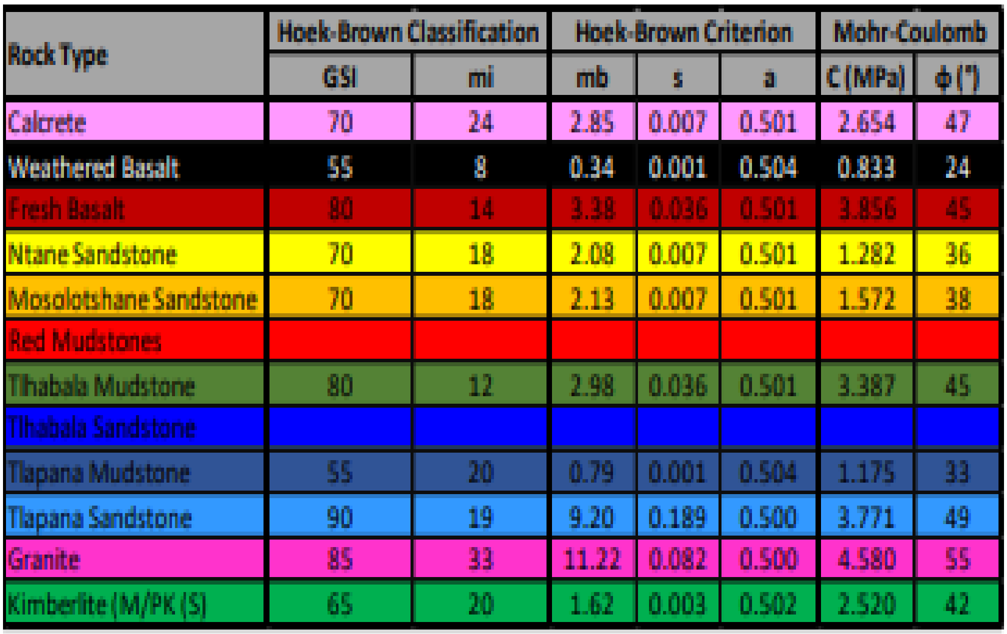
Fig. 8 : Crest to Crest Angles

Karowe Mine, 2020.

Fig. 9 A: Rock Types and Properties
Karowe Mine, 2020.



Rock Type	Density, γ (ton/m^3)				Intact Compressive Strength, σ (MPa)				Tensile Strength, σ (MPa)				Tanget Elastic Modulus (GPa)				Poisson's Ratio, ν			
	Mean	Min	Max	Count	Mean	Min	Max	Count	Mean	Min	Max	Count	Mean	Min	Max	Count	Mean	Min	Max	Count
Calcrete	2.43	1.83	2.62	38	109	10	190	18	11	4	19	14	42.34	2.37	68.30	18	0.21	0.09	0.39	18
Weathered Basalt	2.42	1.88	2.72	88	48	18	108	41	6	2	12	28	15.82	3.02	56.10	41	0.22	0.12	0.38	41
Fresh Basalt	2.64	2.34	2.89	144	89	29	148	55	9	5	15	66	33.70	17.30	62.20	55	0.26	0.15	0.38	55
Ntane Sandstone	2.03	1.87	2.82	208	31	12	64	72	3	1	11	62	13.67	4.30	26.60	55	0.41	0.23	0.83	72
Mosolotshane Sandstone	2.27	2.00	3.08	195	44	16	106	51	4	1	11	62	16.27	3.68	47.20	51	0.39	0.16	0.61	51
Red Mudstones																				
Tlhabala Mudstone	2.29	1.86	2.69	164	86	26	130	56	9	3	14	42	16.59	8.92	41.10	56	0.23	0.14	0.41	51
Tlhabala Sandstone	2.27	2.07	2.43	7	85	58	105	7					14.60	10.00	19.70	7	0.22	0.14	0.27	7
Tlapana Mudstone	2.20	1.48	2.88	184	68	10	135	45	7	1	15	61	15.38	2.80	41.30	45	0.23	0.15	0.44	45
Tlapana Sandstone	2.32	2.02	2.58	114	43	18	126	18	5	1	8	33	5.72	1.49	35.10	18	0.34	0.12	0.47	18
Granite	2.53	1.92	2.87	115	75	18	192	19	7	2	13	27	39.68	9.74	78.60	19	0.28	0.15	0.47	19
Kimberlite (M/PK (S)	2.90	1.76	3.12	142	129	4	229	35	12	0	25	47	64.56	0.96	113.00	35	0.26	0.12	0.33	35



Rock Type	Hoek-Brown Classification		Hoek-Brown Criterion			Mohr-Coulomb	
	GSI	mi	mb	s	a	C (MPa)	ϕ (°)
Calcrete	70	24	2.85	0.007	0.501	2.654	47
Weathered Basalt	55	8	0.34	0.001	0.504	0.833	24
Fresh Basalt	80	14	3.38	0.036	0.501	3.856	45
Ntane Sandstone	70	18	2.08	0.007	0.501	1.282	36
Mosolotshane Sandstone	70	18	2.13	0.007	0.501	1.572	38
Red Mudstones							
Tlhabala Mudstone	80	12	2.98	0.036	0.501	3.387	45
Tlhabala Sandstone							
Tlapana Mudstone	55	20	0.79	0.001	0.504	1.175	33
Tlapana Sandstone	90	19	9.20	0.189	0.500	3.771	49
Granite	85	33	11.22	0.082	0.500	4.580	55
Kimberlite (M/PK (S)	65	20	1.62	0.003	0.502	2.520	42

Fig. 9 B: Rock Types and Properties
Karowe Mine, 2020.

2) MAPTEK 3D Analysis

Maptek 3D Point Studio is a software application developed by Maptek, a company specializing in mining and geological software solutions. It is designed to work with point cloud data captured from various sources such as LiDAR (Light Detection and Ranging) scanners and laser scanning. The software is primarily used for processing, visualizing, analysing, and interpreting 3D point cloud data, including discontinuity mapping in geological applications.

Discontinuity Identification and Mapping:

Discontinuity data from the Maptek 3D laser scanner was cleaned to a higher resolution using the Maptek 3D Point Studio software at the mine. The software automatically detected and classified the discontinuities, and they were inspected by visually inspecting a 3D-generated model of the pit. Orientation data was analysed to give the strike, dip, and dip direction of discontinuities to understand geological structures and their spatial distribution. Statistical parameters such as spacing, persistence, roughness, and clustering of discontinuities were calculated within the software to characterize the rock mass behavior. The figure 10 below show a brief description of the process undertaken:

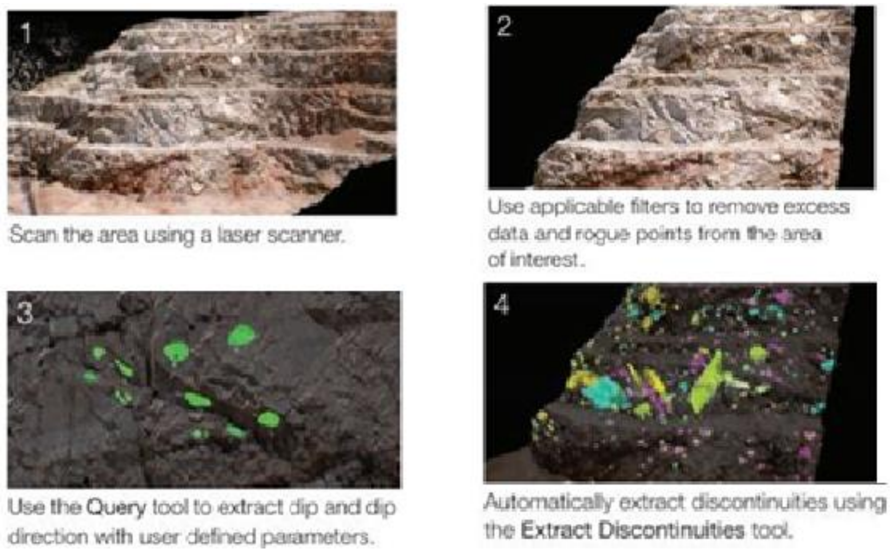


Fig.10 :Maptek Discontinuity Process
https://www.maptek.com/forge/september_2020/2020-vision-for-the-future/

The extracted discontinuities for the western and eastern walls were derived from the software to be used for various applications, in this case kinematic analysis.

3) Kinematic analysis through the RocScience Dips.8 software

Dips.8 software was used to carry out kinematic analysis of the discontinuity data collected. Dips is a stereographic projection program for the analysis and presentation of orientation-based geotechnical data with visualization of vectors, density contours, plane intersections and traverses. It was employed to determine joint sets and perform kinematic analysis of slope stability and determine the possibilities of planar or wedge sliding, or direct and flexural toppling failure modes.

Jointing analysis with Dips

Three analysis options within DIPS software were utilized: Joint Spacing to determine true or apparent spacing between joints within a set, RQD Analysis for evaluating Rock Quality Designation, and Joint Frequency for quantifying joint occurrences along specified distance intervals. (https://www.maptek.com/forge/september_2020/2020-vision-for-the-future/).

RESULTS AND ANALYSIS

The comprehensive review of the qualitative and quantitative data, encompassing the analysis and synthesis of the quantitative findings obtained from the study are presented herein. Additionally, it contextualizes these findings within the existing body of research and literature to discern parallels and distinctions between this study and prior scholarly work.

DIPS

Joints sets Identification.

After importing structural data from excel spread sheet into dips the first aim was to identify the joint sets of which was achieved. The J1 runs from north-west to south-west. Table 1 represent the joint set identified in the stereo net below.

SET ID	DIP	DIP DIRECTION
J1 (1m)	75	232

Table 1: A table stating the identified joints with their dip and dip direction.

Joint Set Analysis

Following the identification of the joint set, a secondary analysis was conducted to determine potential failure mechanisms. Dips were plotted for all discontinuities (joints) to observe their general trend. The resulting rosette plot below indicates a northwest to southeast trend of discontinuities.

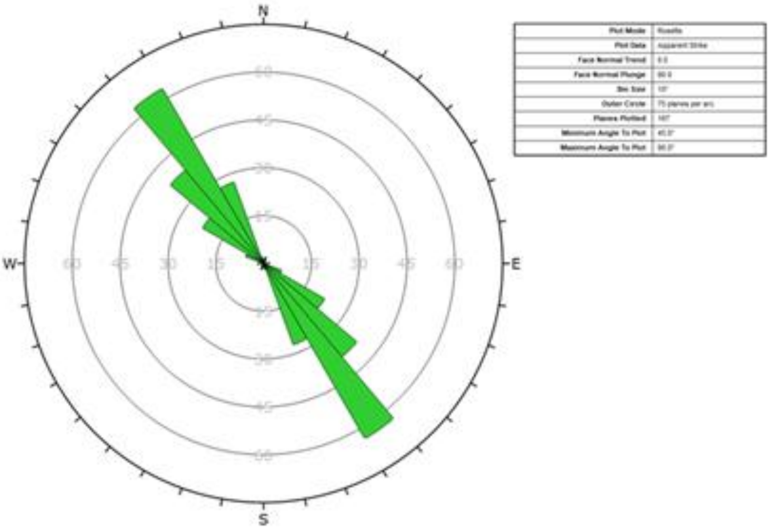
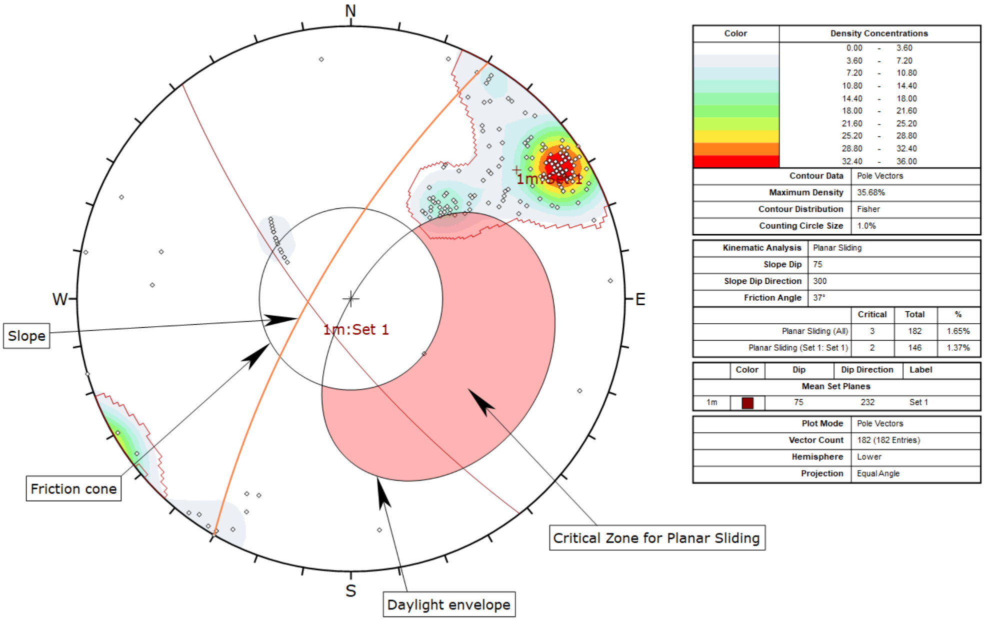


Fig. 31: Rosette Diagram Showing General Discontinuities Direction Trends.

Identification of Potential Failure Mechanisms

1. Planar Sliding

The eastern section of the Karowe pit reveals conditions conducive to potential planar failure modes, attributed to critical joint intersections that are exposed on the slope face. Conversely, the western side shows no such potential for planar failure. Analysis of dip plots within a daylight envelope allows for a kinematic assessment: poles falling within the highlighted pink envelope are kinematically free to slide if frictionally unstable. Additionally, a friction cone with a 37-degree angle is depicted, signifying that poles outside this cone represent potential sliding planes if kinematically feasible.



Color	Density Concentrations
⬜	0.00 - 3.60
▨	3.60 - 7.20
▨	7.20 - 10.80
🟩	10.80 - 14.40
🟩	14.40 - 18.00
🟩	18.00 - 21.60
🟨	21.60 - 25.20
🟨	25.20 - 28.80
🟧	28.80 - 32.40
🟥	32.40 - 36.00

Contour Data	Pole Vectors
Maximum Density	35.68%
Contour Distribution	Fisher
Counting Circle Size	1.0%

Kinematic Analysis	Planar Sliding		
Slope Dip	75		
Slope Dip Direction	300		
Friction Angle	37°		
	Critical	Total	%
Planar Sliding (All)	3	182	1.65%
Planar Sliding (Set 1: Set 1)	2	146	1.37%

	Color	Dip	Dip Direction	Label
Mean Set Planes				
1m	🟥	75	232	Set 1

Plot Mode	Pole Vectors
Vector Count	182 (182 Entries)
Hemisphere	Lower
Projection	Equal Angle

Fig. 12: A Dips Stereo Net Demonstrating a Planar Failure Mechanism.

Table 2: A

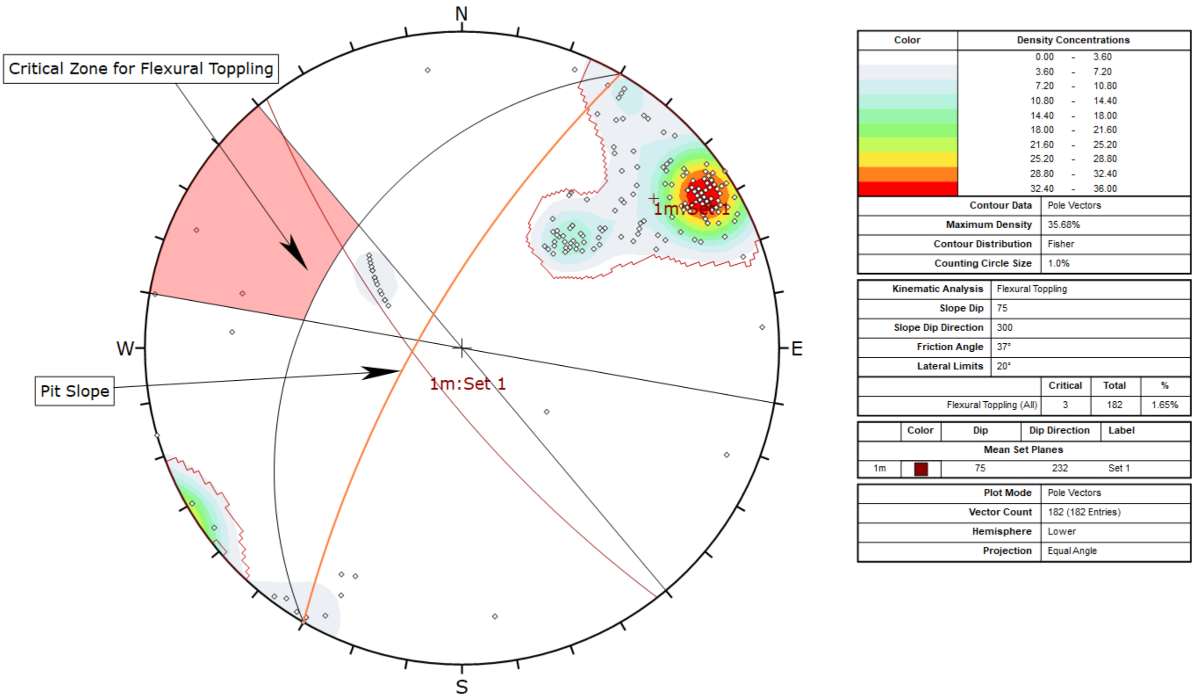
Kinematic analysis	Planar sidling		
Slope dip	75		
Slope dip direction	300		
Friction angle	37		
	Critical	Total	Percentage
Planar sidling (all)	3	182	1.65%
Planar sidling (set 1)	2	146	1.37%

Summary of Planar Sliding of Kinematic Analysis Results

The crescent-shaped area delineated by the Daylight Envelope and the pole friction circle defines the region of Planar Sliding, indicating planes capable of and likely to slide. Figure 19 illustrates the critical zone for planar failure assessment, while Table 2 presents the legend of results, representing percentages of all poles in the dataset (2 out of 146) for Set 1.

2. Flexural Toppling

The western and eastern side of the pit show no evidence of potential flexural toppling as the critical zone is at the northwestern side of which there are very minimal joints at the region. This shows that there are no critical joint intersections found in relation to slope face since the split planes cannot topple if they cannot slide with respect to one another. Figure 13 gives an illustration of no significant risk of Flexural Toppling on the northeastern and southwestern side of the pit. Table 3 as the Legend provides results as a percentage of all poles in the file (3/182. For Set 1 the toppling probability is 1.65 percent.



Color	Density Concentrations
⬜	0.00 - 3.60
⬜	3.60 - 7.20
⬜	7.20 - 10.80
⬜	10.80 - 14.40
🟩	14.40 - 18.00
🟩	18.00 - 21.60
🟨	21.60 - 25.20
🟨	25.20 - 28.80
🟧	28.80 - 32.40
🟥	32.40 - 36.00
Contour Data	Pole Vectors
Maximum Density	35.68%
Contour Distribution	Fisher
Counting Circle Size	1.0%

Kinematic Analysis	Flexural Toppling		
Slope Dip	75		
Slope Dip Direction	300		
Friction Angle	37°		
Lateral Limits	20°		
	Critical	Total	%
Flexural Toppling (All)	3	182	1.65%

	Color	Dip	Dip Direction	Label
Mean Set Planes				
1m	🟥	75	232	Set 1

Plot Mode	Pole Vectors
Vector Count	182 (182 Entries)
Hemisphere	Lower
Projection	Equal Angle

Fig. 13: A Stereo Dips Net Demonstrating a Flexural Toppling Failure Mechanism

Kinematic analysis	Flexural Toppling		
Pit Slope dip	75		
Slope dip direction	300		
Friction angle	37		
	Critical	Total	Percentage
Flexural Toppling (all)	3	182	1.65%

Table 3: A Summary of Flexural Toppling Kinematic Analysis Results

3. Direct Toppling

Direct Toppling and Flexural Toppling are based on differing sets of assumptions. On the eastern side, the highest potential for direct toppling failure mode is indicated by critical joint intersections. Figure. 14 delineates primary and secondary critical zones, with the pink-highlighted area (Zone 1) representing the primary critical zone for direct toppling (including intersections and base plane poles). The yellow-highlighted area (Zone 3) is the secondary critical zone, where oblique toppling considerations are taken into account (involving intersections and base plane poles). Generally, oblique toppling analyses suggest a lower potential for failure across all slope faces.

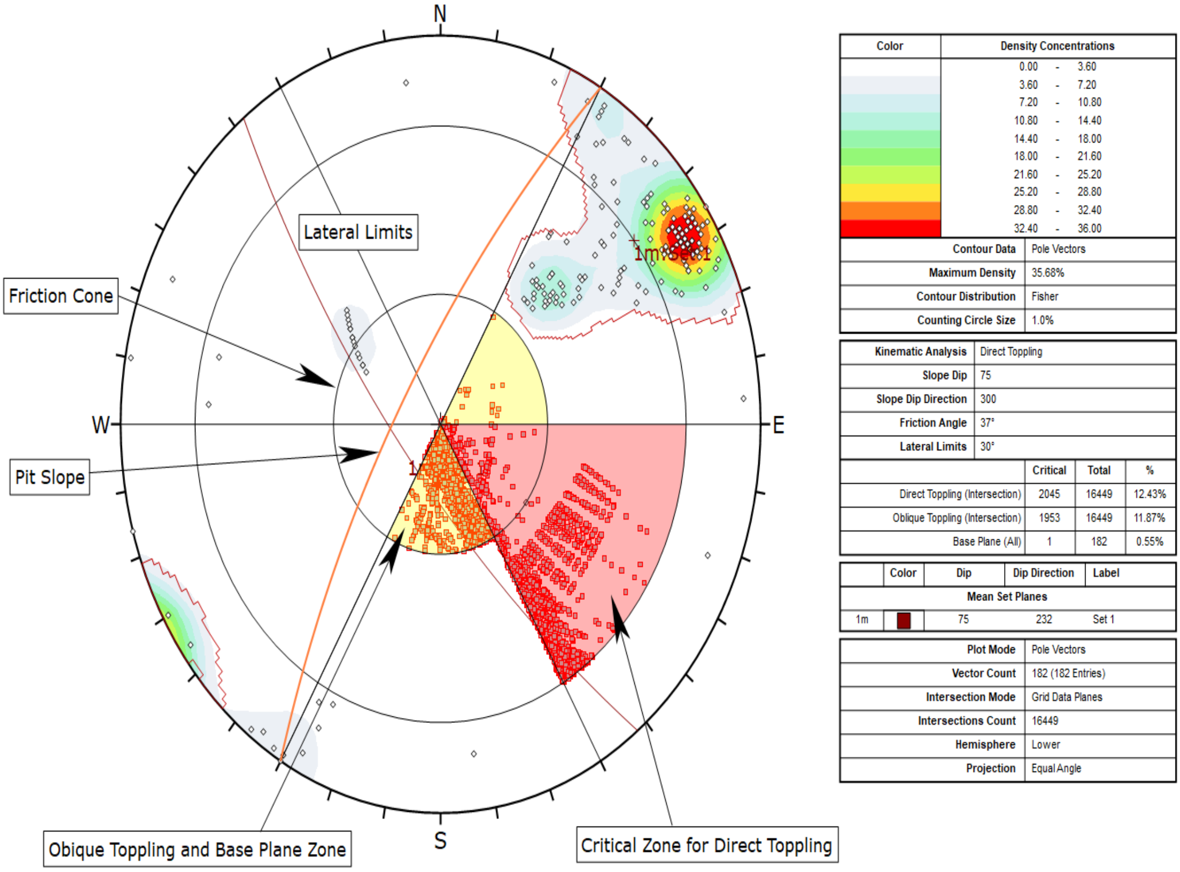


Fig. 4: A Dips Stereo Net Demonstrating a Failure Mechanism on The Southeastern Side

Kinematic analysis	**Direct Toppling**		
Pit Slope dip	75		
Slope dip direction	300		
Friction angle	37		
	Critical	Total	Percentage
Direct Toppling (intersection)	2045	16449	12.43%
oblique Toppling (intersection)	1953	16449	11.87%
Base plane (all)	1	182	0.55%

Table 4: A Summary of Direct Toppling Kinematic Analysis Results

4. Wedge Sliding

The northwestern sector of the Karowe pit reveals a potential for wedge sliding failure modes along the slope, as evidenced by critical joint intersections exceeding 12.09%, indicating a heightened risk of wedge failures. The Primary Critical Zone for Wedge Sliding is represented by a crescent-shaped area within the plane friction cone of the slope plane (highlighted in red in Figure 15). Intersections falling within this zone denote wedges that meet both frictional and kinematic conditions for sliding. The Secondary Critical Zone (highlighted in yellow in Figure 15) lies between the slope plane and a plane (great circle) inclined at the friction angle. Critical intersections within these zones signify wedges that slide along a single joint plane. In this area, the intersections are inclined at angles less than the friction angle, but sliding is likely to occur on a joint plane with a dip vector greater than the friction angle.

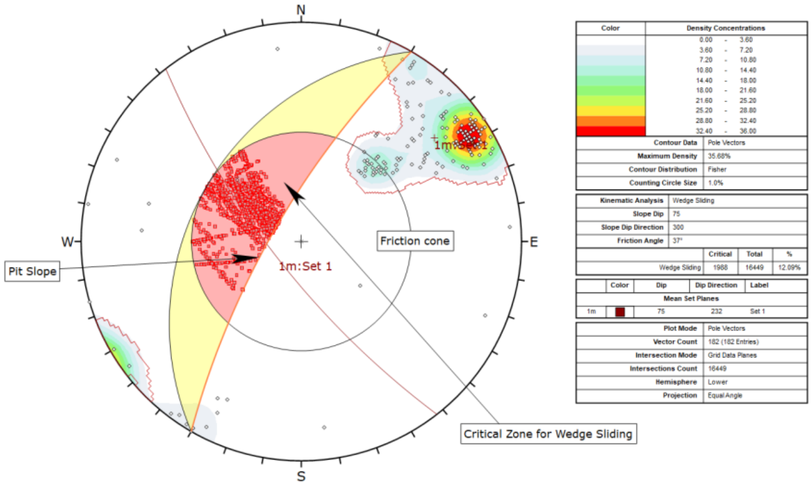


Fig. 15: A Wedge Sliding Mechanism on The Northwestern Side of The Karowe Pit

Kinematic analysis	Wedge Sidling		
Pit Slope dip	75		
Slope dip direction	300		
Friction angle	37		
	Critical	Total	Percentage
Wedge Sidling	1988	16449	12.09%

Table 5: A Summary of Direct Toppling Kinematic Analysis Results

Kinematic Analysis indicates Direct toppling failure (12.43%) and Wedge failure mode (12.09%) being the most prominent across the northwestern and southeastern regions of the pit.

DISCUSSION

The results of the kinematic analysis highlight significant findings regarding potential failure modes in specific regions of the Karowe open pit. On the north-eastern side, the analysis reveals a 12.43% of joints capable of Direct Toppling failure. This indicates a notable risk of rock masses or blocks detaching and toppling directly downslope. Conversely, the south-eastern side shows a 12.09% of joints cable of Wedge Failure mode, suggesting a substantial risk of wedge-shaped rock masses or blocks sliding or toppling along planes inclined towards the slope.

The occurrence of Direct Toppling failure on the north-eastern side is the result of critical joint orientations or geological conditions that favour block detachment and toppling. Factors such as joint orientations, rock mass properties, and slope geometry could contribute to this mode of failure. Understanding these factors is crucial for designing effective slope stabilization and mitigation measures. On the other hand, the prevalence of Wedge Failure mode on the south-eastern side is the result of specific structural discontinuities that promote wedge-shaped failures. These failures can occur due to stress concentration along inclined planes, leading to sliding or toppling of wedge-shaped rock masses. Assessing the geometry and kinematics of these wedges is vital for evaluating stability and implementing appropriate engineering interventions.

The contrasting nature of these failure modes underscores the complexity of slope stability in the Karowe open pit. It highlights the importance of detailed geological and geotechnical investigations to characterize joint sets, rock mass properties, and structural features influencing slope stability. Incorporating these findings into comprehensive slope stability analyses can aid in predicting potential failure scenarios, optimizing slope designs, and implementing targeted mitigation strategies to enhance overall safety and productivity in mining operations.

Even if a Kinematic Analysis indicates risk of failure, it does not necessarily mean that failure will occur, since factors other than kinematics and friction angle may work to increase stability (e.g., joint cohesion, joint persistence etc.,). Conversely, other factors may decrease stability (e.g., water pressure) of kinematically safe slopes. It is important to look beyond statistical results (e.g., mean set plane orientations) and consider major discrete structures such as shear zones which may have a dominant effect on stability due to low friction angles and inherent persistence.

CONCLUSION

In conclusion, our study aimed to employ kinematic analysis to assess rock displacement in critical structures on both the western and eastern slopes of the Karowe Diamond Mine, with a focus on identifying and describing potential failure mechanisms. Through rigorous kinematic analysis, we were able to shed light on the distinct failure modes prevalent in these areas. The findings indicate a notable 12.43% of joints will cause Direct Toppling failure on the north-eastern side and a 12.09% of joints will cause Wedge Failure mode on the south-eastern side of the mine. These results are in line with our objectives of determining the type of failure mechanisms based on structural parameters.

The occurrence of Direct Toppling failures on the north-eastern side suggests critical joint orientations or geological conditions favering block detachment and toppling, while Wedge Failure on the south-eastern side is indicative of stress concentration along inclined planes leading to sliding or toppling of wedge-shaped rock masses.

This study underscores the importance of kinematic analysis in understanding and predicting potential failure modes related to structural parameters in mining operations. By integrating these findings into slope stability assessments and engineering interventions, mining companies can enhance safety protocols and optimize operational efficiency in challenging geological environments like the Karowe Diamond Mine. Continued monitoring and adaptation of slope management strategies based on such analyses will be essential for maintaining safe and productive mining practices over time.

RECOMMENDATION

Engineers are advised to consider several strategies to enhance slope stability in the optimization of the Karowe pit. Firstly, they should consider reducing the slope angle or adjusting the pit geometry to align perpendicularly with the orientation of J1 discontinuities. This alignment can help minimize potential instability along these discontinuities.

Secondly, the development of support structures (shotcrete, rock bolts and wire mesh) to reinforce the slope should be explored as a remediation method. Implementing regular drainage measures, particularly on the eastern side of the Karowe pit, can effectively manage groundwater levels and mitigate associated stability challenges. It is crucial to conduct tension crack mapping exercises to identify and mitigate potential failures caused by elongated tension cracks leading to wedge failures, particularly on the on the southeastern and northwestern side of the Karowe pit. These initiative-taking measures will contribute significantly to ensuring long-term slope stability and safety within the mining environment.

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