Journal of Rock Mechanics and Tunnelling Technology (JRMTT)
31 (1) 2025 pp 31-43

Available online at www.isrmtt.com

Failure Mechanism of a Large Wedge in Open Cast Mine Composed of a Granite Porphyry Rock Mass of Aravali Region - A Case Study

Manish Kr. Meena*, Ashok Kr Singh, R. D. Dwivedi, J. K. Mohnot
CSIR-Central Institute of Mining & Fuel Research Centre, Roorkee, India
**E-mail: manishmeena@cimfr.nic.in*

ABSTRACT

The present study aims to investigate the mechanism involved in a massive wedge failure disaster at the Dadam Granite Mines in Haryana. This failure, with a block volume of about 2700 m³, occurred on the night of December 31, 2021. The wedge failure took place at the boundary junction of adjoining Pit Nos. 37 and 38, near the Aravali hills revenue forest area. In light of this accident, large wedges formation, initiation, and translation were studied. Field investigations revealed that kinematically unfavourable joints led to the massive wedge failure. Water inflow within the open and highly persistent joints (22 to 55 m) washed out the soft-infilled materials (clay and silts). This created a slip surface along the oblique joint, causing a sudden decrease in shear strength along the basal joint plane. The surface joint acted as a release plane, with flow imprints of the infilled materials visible on the leftover vertical and daylighted oblique joint walls. The back-calculated Slope Mass Rating (SMR) using the continuous function placed the kinematic potential wedge into Class IV and V, indicating entirely unstable conditions. Based on detailed field investigation and kinematic analysis, the study discusses the potential processes underlying such catastrophic wedge failures.

Keywords: Mine slope stability; Slope Mass Rating; Kinematic analysis; Wedge failure; Open cast mine

1. INTRODUCTION

Unstable pit walls in an opencast mine may lead to slope failures causing severe impact on mining operations and safety of the deployed men and machineries (Alejano et al., 2007). These failures usually result from bench collapse or the movement of rock masses within the mine. The consequences affect both mining efficiency and worker’s safety. This includes production disruptions, project delays, equipment idleness, fatal accidents, equipment damage, and psychological distress. Additionally, slope failures can trigger secondary failures, posing further safety threats and complicating recovery efforts (Alejano et al., 2007). Therefore, maintaining stable slopes is crucial in opencast mining operations. Selecting the overall pit geometry and pit slope angle is vital for the stability of the pit walls and the cost-effectiveness of mining operations.

The stability of mine slopes depends on various geo-mining factors. These include local and regional geological discontinuities, rock mass characteristics, pit geometry, blast loading, groundwater, and rainfall conditions (Hoek & Bray, 1981). Risk evaluation of mine slope failures is important in opencast operations (Terbrugge et al., 2006). Proper geotechnical study-based risk assessments of mine-pit and bench slopes help in identifying potential slope stability issues (Verma et al., 2022). Designing them can minimise the risk of accidents, and timely mitigation steps can be taken (Meena et al., 2023).

Stead and Wolter (2015) emphasized the role of geological structures in understanding rock slope failures in opencast mines. The orientation and strength of discontinuity structures are critical factors influencing rock slope stability. The strength of these discontinuities is affected by factors such as persistence, roughness, aperture, and the inherent strength of the rock (Singh & Goel, 2011). Chen and Cheng (2017) highlighted that even gentle rock slopes can fail if unfavourable planes are present. These unfavourable planes or the potential failure surfaces can significantly compromise rock slope stability. This understanding has led to recognizing the anisotropic behaviour of rock mass. Analysing the inter-relationship between these planes is crucial when assessing rock slope stability. Comprehensive consideration of geological structures and their orientations is essential for accurate pit slope stability assessments (Singh & Baliga, 1994).

Considering the role of geological discontinuities in large pit slope failures, the present study investigates the mechanism involved in a massive wedge failure disaster in an open pit mine in India. This fatal failure, with a block volume of about 2700 m^3, occurred in the Dadam Granite Mines in Hisar district of Haryana on the night of December 31, 2021. Following the incident, the mine authority invited CSIR-Central Institute of Mining and Fuel Research, Roorkee Centre to investigate the failure mechanism and assess the post-failure stability of the mine's high wall slopes. The study presented here is an updated version of the work of Meena et al. (2023) based on the detailed geological-geotechnical investigations of failed high wall slopes.

2. GEO-MINING CONDITION OF THE DADAM MINE & FAILED HIGHWALL SLOPE OF PIT NO. 37 & 38

Dadam Mine is located near Dadam village of Tosham Tehsil in district Bihawni of state Haryana, India. It is one of the isolated inselbergs including Khanak, Tosham, Riwasa, Dulheri, Nigana, Dharan, Kharkhari and Sohan. The area is covered by older alluvial deposits of quaternary age and aeolian sands limited to small parts of the district and is marked by Aravalli hill exposures. Older alluvium occurs extensively in the area consisting of inter-bedded, lenticular, inter-fingering deposits of gravel sand, soil, clay, and Kanker mixed in various proportions. Dadam hill is a part of the Tosham Ring Complex (TRC) which is the remnant of the outer ring of a fallen chamber of an extinct volcano around 732 million years ago equivalent to the lower Vindhyan group (Awasthi et al., 1981).

The geological province of TRC is an oval-shaped ring dyke on the fringes of a collapsed caldera from Khanak to Nigana Khurd on its NW- SE axis and Dadam to Tosham on its E-W axis. Except for the Tosham hill all other exposures of the TRC are intrusive rocks including Dadam hill (Bhushan, 1985). TRC is part of Malani igneous suit which is the largest felsic igneous province situated in the NW part of India. The lithological unit at Dadam resembles the second stage of discordant pluton of alkali and alkali feldspar granite (Bhushan & Khullar, 1998; Bhushan & Chitora, 1999). The granite at Dadam is hard, homogeneous and non-foliated. It is characterized by pink to grey-coloured medium-grained rocks consisting of quartz, feldspar and biotite as major minerals and porphyry texture. These granites are the host of minor minerals for the production of masonry stone.

The mine is composed of a granite porphyry rock mass that appears blocky and competent, intersected by persistently oriented joints. These joints make the rock mass vulnerable to weathering from environmental factors such as water and daily temperature fluctuations. Field observations indicate that the rock mass exhibits moderate to high weathering which can lead to strength degradation at the exposed joint surfaces (Goel & Mitra, 2021). The mine slopes have three to four major joint sets along with random joints, extending more than 20 m, highlighting the significant impact of joint conditions on slope stability. However, the unfavourable orientation of these joints makes the slopes prone to joint-controlled failures such as wedge, planar, and toppling failures. The progressive opening of these joints increases the susceptibility of overhanging blocks to dislodgement. Kinematic analyses reveal structural inhomogeneity due to the random occurrence of fractures, with wedges being the prevalent type of rock failure. The detailed joint characterization along with rock mass classification of the studied mine pit are given in the following sections.

3. CHARACTERISTICS OF FATAL PIT SLOPE IN DADAM MINE

The slope failure accident occurred in the slope section of Pit No. 37 & 38 adjacent to the revenue forest area in the eastern and western margin of the pit (Fig. 1). As the failure occurred at the boundary of Pit No 37 and 38, both the Pits are shown in Figure 1. The height of the slope is about 40 m with an almost vertical slope inclination towards $90^0/120^0\pm5^0$ (slope face direction). The rock mass of the failed slope appears very blocky and competent. The flow imprints of infilled joint materials (clay and silts) were quite visible on the remnant vertical and day-lighted oblique joint walls (Fig. 2a). This signifies the water inflow within the open joints that washed out the soft infilling materials and might create slip surfaces along the oblique joint resulting in massive wedge failure probably due to a sudden decrease in shear strength along the basal joint plane. The surface joint (J1) acted as a release plane for such a huge size (28 m × 12 m × 8 m) wedge failure (Figs. 2a & 2b).

Figure 1 - 3D view of Pit No. 37 & 38 with location of fatal wedge failure derived from LiDAR survey

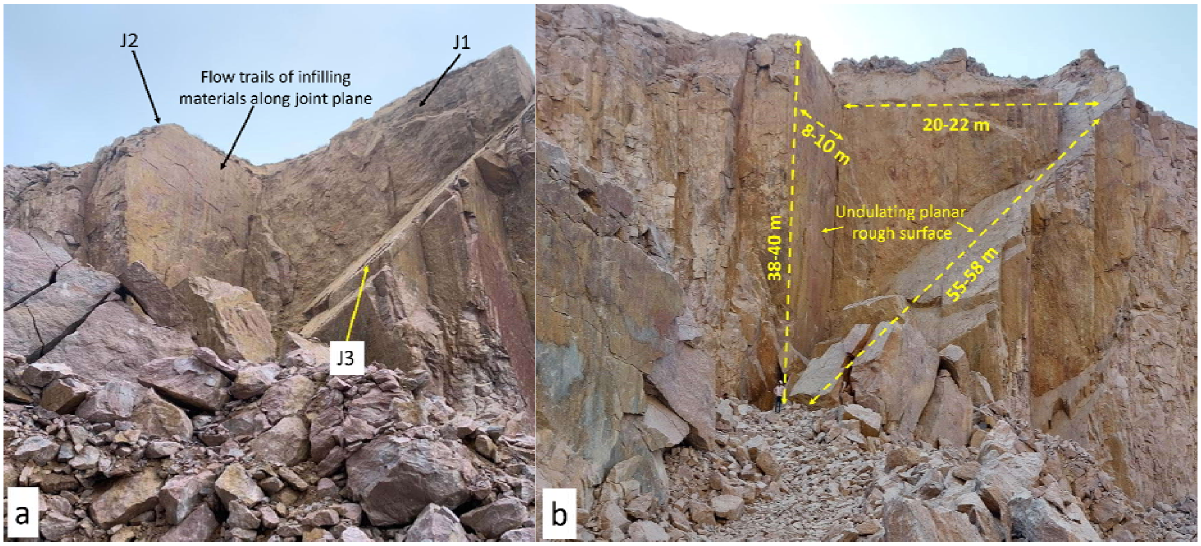


Figure 2 - (a) Failed wedge with relic flow trails of infillings along the major joints (b) Dimension of failed wedge

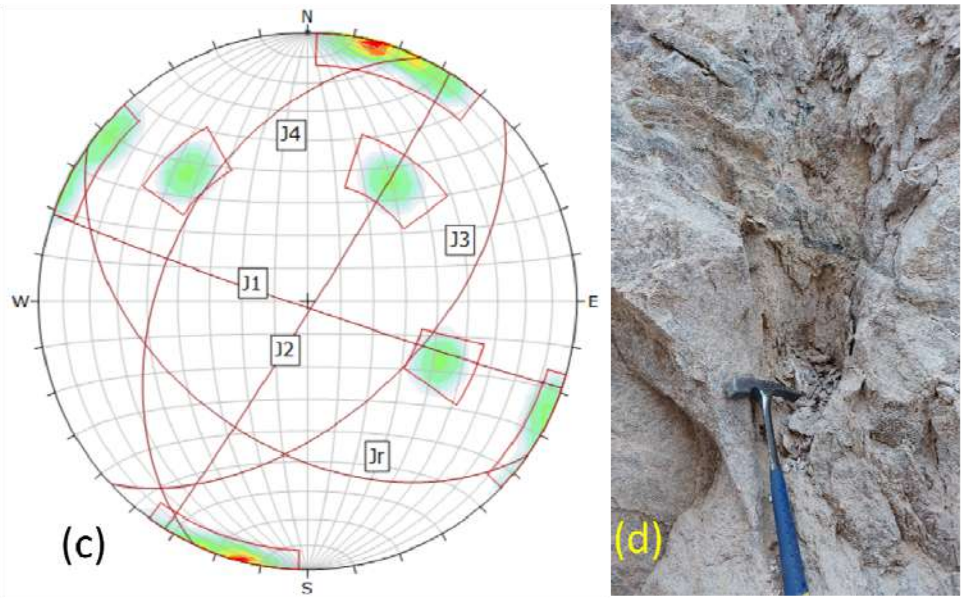


Figure 2 – (c) Stereographic projection of collected joints (d) highly weathered granite rock mass

The exiting slope section consists of three sets of major joints (J_1, J_2 and J_3) with random ones (Fig. 2a & c). The major joints (J_1, J_2, J_3) are quite persistent (varying from 22-55 m) with wide to very wide spacing (8-10 m) that instigates the occurrence of very large to extremely large in-situ blocks to failure. The major joints, J_1, J_2, J_3 are mutually orientated unfavourably leading to the formation of various unstable blocks that cause rock failure mainly wedges and toppling types (Fig. 2c). Joint J_3 acted as plane along the slided wedge (Fig. 2a). The stability condition degrades drastically as joints dilate due to progressive weathering (Fig. 2d) as suggested by Goel & Mitra (2021) due to geo-environmental agents such as water, temperature variations along with the destressing of rock mass because of excavation. The visual inspection suggests that pit slopes have the potential for joint-controlled block failures due to overhanging blocks.

4. METHODOLOGY

A detailed field investigation was conducted to understand the failure mechanism of the fatal wedge in the Dadam opencast granite mine. The geological and geotechnical data along with joint characteristics were collected from Pit No. 37 & 38, where the failure had occurred. Rock mass characterization, kinematic analysis and back-calculation of continuous slope mass rating were carried out to analyze the structurally controlled failures susceptibilities in the high vertical pit wall.

Rock mass characterization involves geological mapping, measuring joint characteristics such as orientation, spacing, persistence, roughness, and infilling of discontinuities for classification system like RMR, and Q-System for assessing the quality and properties of a rock mass to understand its mechanical behaviour and to predict the stability for improved design with the optimized safety and cost-effectiveness. The kinematic analysis and back-calculation of continuous slope mass rating helped in refined assessment of the slope with the potential for different types of slope failures (e.g., planar, wedge, toppling) based on the inter-relationship of the geometry and orientation of discontinuities relative to the excavated bench/slope face.

Furthermore, Q-slope analysis (Bar and Barton 2017) was also carried out to find out the optimum allowable safe pit slope angle in such challenging geo-mining scenario in Dadam opencast mine.

5. RESULTS AND DISCUSSION

Detailed geological and geotechnical investigations were conducted to assess stability scenario. During field investigations, rock mass parameters were collected to understand the prevailing geo-mining conditions. LiDAR survey provided a 3D geometrical configuration of the existing pit section.

5.1 Field Investigation

Geological & geotechnical data related to rock and joint parameters such as joint orientations, jointvolumetric count (J_v), joint compressive strength (JCS), joint roughness coefficient (JRC), persistence, spacing, aperture, infilling, weathering and groundwater conditions were collected using a window sampling method (Fig.3a & Table 1). Soft infilling of less than 5mm in moderately weathering conditions in completely dry conditions was observed. Additionally, light detection and ranging (LiDAR) survey of the pit slopes was also conducted to acquire the point cloud data of prevailing discontinuities and 3D geometrical configuration of existing pits as provided in Figure 1. Three major joints, J_1, J_2 & J_3 having mean orientations of 88°/199°, 88°/122° & 55°/137° respectively are responsible for large wedge formation and subsequent failure due to unfavourable joint, J_3 which is discussed in following sub-section 5.3. However, based on the collected mean subsequent failure due to unfavourable joint, J_3 which is discussed in following sub-section 5.3. However, based on the collected mean joints data from the Pit No. 37 & 38 (Fig. 2c), the influence of J_4 (45/295) and random joint (J_r) (45/215) is also critical in other section of Pit No. 37 & 38 for joint-controlled block failures.

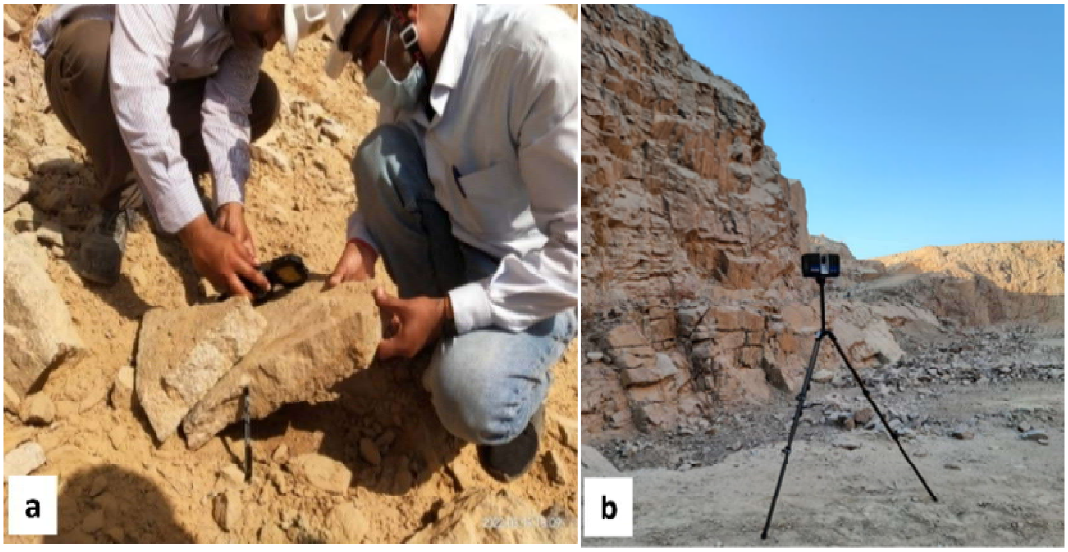


Figure 3 - (a) Measuring basic friction angle of joints at site (b) LiDAR Survey

Table 1: Parameters determined during the field investigation

Locations		Parameters					
		UCS (MPa)	RQD (%)	Spacing (mm)	Joint condition		
					Persistence (m)	Aperture (mm)	Roughness
Pit No. 37 & 38	West wall	146-171	72-80	60-200	>20	1-17	Rough to planar
	East Wall	50-100	50-75	60-200	>20	>5	Rough to planar/undulating

5.2 Rock Mass Characterization

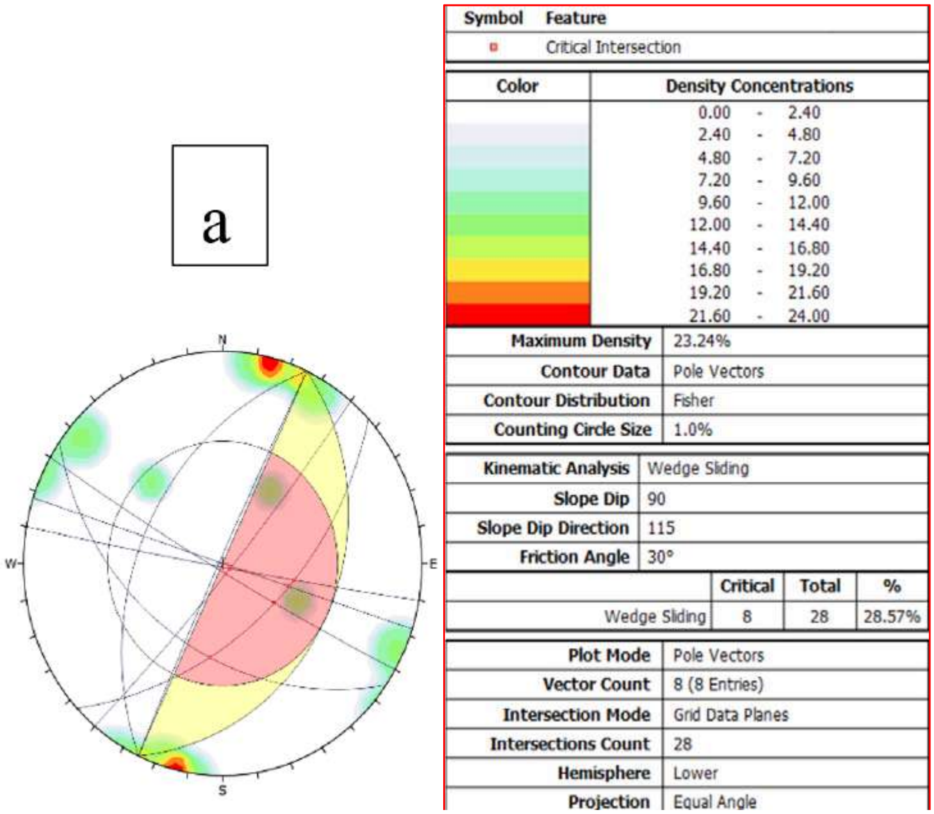
From the field investigation, it is found that the Rock Quality Designation (RQD) of the rock mass along the western wall of Pit no. 37 & 38 is around 70-80% depicting fair to good rock mass quality. The observed Rock Mass Rating (RMR) also falls in Class II and III (RMR ranging from 56 to 70) i.e., fair to good rock quality with prominent joint sets traversing the structure with the persistence of more than 20 m. However, joints are orientated unfavourably leading to the formation of various unstable blocks that can cause rock failures mainly wedges. The stability condition degrades drastically as joints dilate due to progressive weathering (due to geo-environmental agents such as water, temperature variation etc.). The visual inspection suggests that pit slopes have the potential for kinematically controlled block failures due to overhanging rock masses. The rock mass of the pit slope appears very blocky and competent. The rock mass parameters and their ratings for RMR of Pit No 37 & 38 are tabulated in Table 2. Wedge failure took place from East wall. Therefore, parameters collected from the East wall for unfavourable joint (J_3) has been given in Table2.

Table 2: RMR parameters with range and average rating

Parameters	Ranges	Ratings
UCS (MPa)	146-171	12
RQD (%)	72-80	13-17
Spacing (mm)	60-800	8-12
Persistence (m)	>20	0
Aperture (mm)	>5	0
Roughness	Planar/undulating to rough	3-5
In filling	Soft < 5 mm	2-4
Weathering	Moderate to slightly weathered	3-5
Ground water condition	Completely dry	15
RMR_{Basic}	56-70	

5.3 Kinematic Analysis

Kinematic analysis of the pit section suggests a high potential for large wedge-type failure released from the J_1 & J_2 having mean orientations of 88°/199° & 88°/122° respectively and gravitational sliding along the day-lighted joint, J_3 with the mean orientation of 55°/137° (Figs. 4a-d).



Symbol	Feature
▫	Critical Intersection

Color	Density Concentrations
⬜	0.00 - 2.40
⬜	2.40 - 4.80
⬜	4.80 - 7.20
🟩	7.20 - 9.60
🟩	9.60 - 12.00
🟩	12.00 - 14.40
🟩	14.40 - 16.80
🟨	16.80 - 19.20
🟧	19.20 - 21.60
🟥	21.60 - 24.00

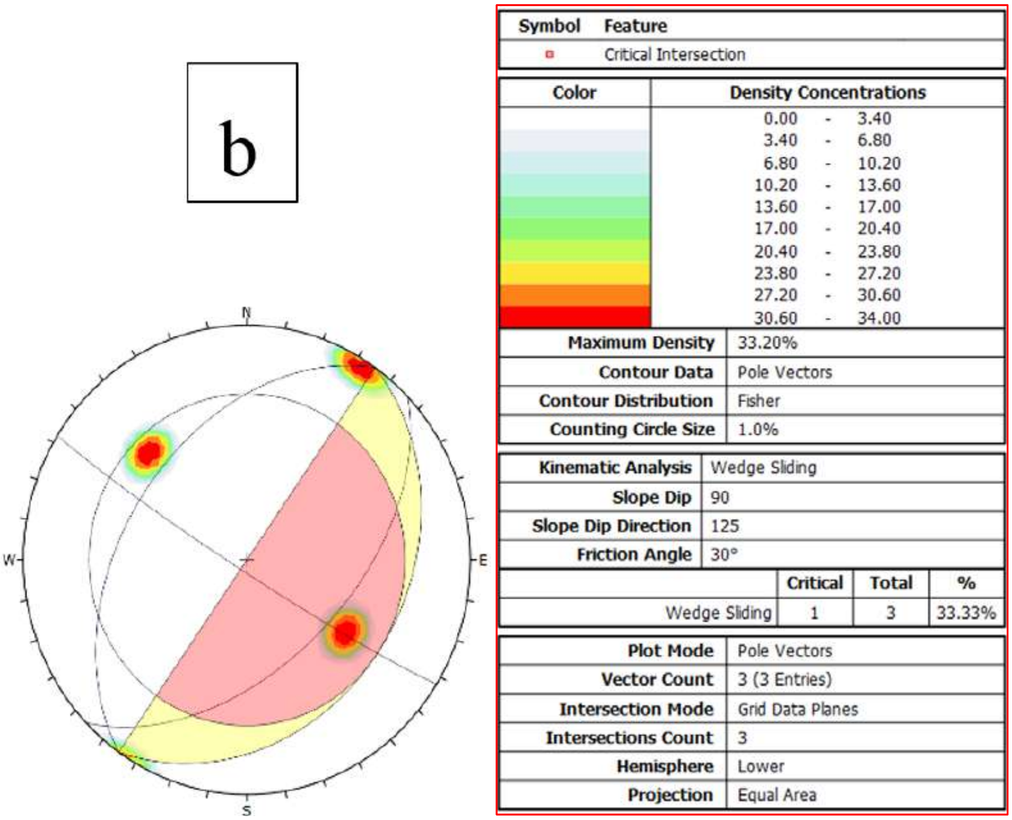
Maximum Density	23.24%
Contour Data	Pole Vectors
Contour Distribution	Fisher
Counting Circle Size	1.0%
Kinematic Analysis	Wedge Sliding
Slope Dip	90
Slope Dip Direction	115
Friction Angle	30°

	Critical	Total	%
Wedge Sliding	8	28	28.57%

Plot Mode	Pole Vectors
Vector Count	8 (8 Entries)
Intersection Mode	Grid Data Planes
Intersections Count	28
Hemisphere	Lower
Projection	Equal Angle

Figure 4 (a) - Potential wedges from all joint data

The kinematic analysis also suggests susceptibility for planar and direct toppling types of failure. The planar failure is prone along the inclined joint, J_3 towards vertical excavation (120°±5°). The calculated SMR using the continuous function is from 16 to 27 referring to class IV & V (Romana, 1985). Class IV refers to planar or big wedge failure, whereas class V refers to big planar or soil-like or circular failure. Exactly the same has happened at the site. The kinematic analysis predicts 8 critical wedge failures out of 28 from all the joint data (Fig. 4a). Based on the collected joint data and field evidence, the wedges formed by joints, J_1, J_2 & J_3 are most susceptible to failure as depicted by the kinematic analysis (Fig. 4a) which were involved in the failure. However, the individual criticality of each wedge has not been determined in this work.



Symbol	Feature
▫	Critical Intersection

Color	Density Concentrations
⬜	0.00 - 3.40
⬜	3.40 - 6.80
🟦	6.80 - 10.20
🟦	10.20 - 13.60
🟩	13.60 - 17.00
🟩	17.00 - 20.40
🟩	20.40 - 23.80
🟨	23.80 - 27.20
🟧	27.20 - 30.60
🟥	30.60 - 34.00

Maximum Density	33.20%
Contour Data	Pole Vectors
Contour Distribution	Fisher
Counting Circle Size	1.0%

Kinematic Analysis	Wedge Sliding
Slope Dip	90
Slope Dip Direction	125
Friction Angle	30°

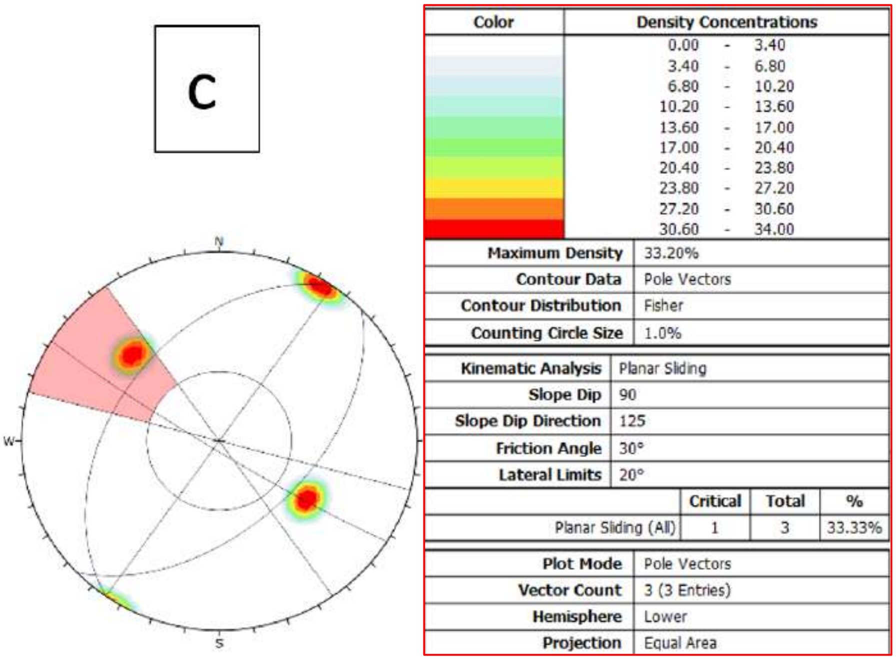
	Critical	Total	%
Wedge Sliding	1	3	33.33%

Plot Mode	Pole Vectors
Vector Count	3 (3 Entries)
Intersection Mode	Grid Data Planes
Intersections Count	3
Hemisphere	Lower
Projection	Equal Area

Figure 4 (b) - Potential wedges from mean joint

5.4 Slope Mass Rating & Q-Slope Analysis

Slope Mass Rating (SMR) is a useful qualitative tool for assessing slope stability, especially in the early stages of site evaluation. It helps in identifying potential hazards to slope areas and guides further investigations related to slope design and stabilization. The SMR values for all the joints were determined using the application "EasySMR" developed by Kundu et al. (2019, 2022) based on the developed continuous functions for each parameter of SMR proposed by Romana (1985) and later modified by Anbalagan et al. (1992). The application of "EasySMR" is used to determine the kinematic potentiality and associated SMR in terms of planar/wedge/toppling failure and total rock mass vulnerability simultaneously in percentage (Kundu et al. 2019, 2022). The evaluated SMR with kinematic and slope mass vulnerability is given in Table 3 which signifies the wedge susceptibility of 40.3% with an overall kinematic vulnerability of 37.6% along with a high slope mass vulnerability of 48.1%.



Color	Density Concentrations
⬜	0.00 - 3.40
⬜	3.40 - 6.80
⬜	6.80 - 10.20
⬜	10.20 - 13.60
🟩	13.60 - 17.00
🟩	17.00 - 20.40
🟨	20.40 - 23.80
🟨	23.80 - 27.20
🟧	27.20 - 30.60
🟥	30.60 - 34.00

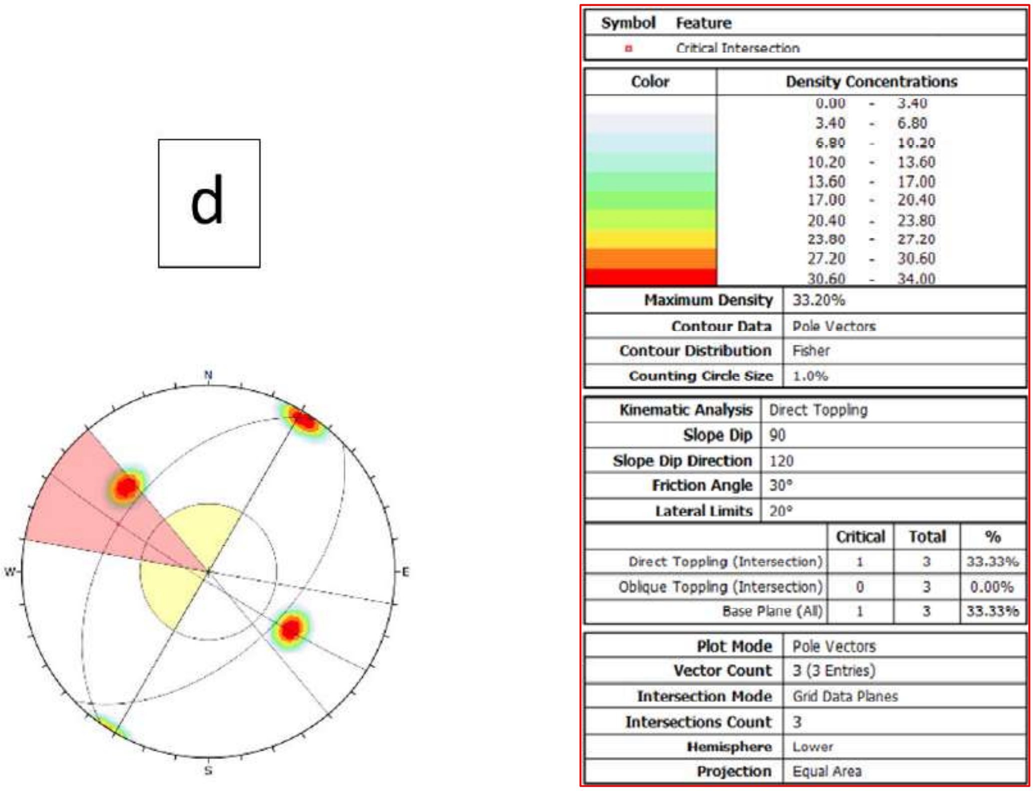
Maximum Density	33.20%
Contour Data	Pole Vectors
Contour Distribution	Fisher
Counting Circle Size	1.0%

Kinematic Analysis	Planar Sliding
Slope Dip	90
Slope Dip Direction	125
Friction Angle	30°
Lateral Limits	20°

	Critical	Total	%
Planar Sliding (All)	1	3	33.33%

Plot Mode	Pole Vectors
Vector Count	3 (3 Entries)
Hemisphere	Lower
Projection	Equal Area

Figure 4 (c) - Potential planar failure from mean joint



Symbol	Feature
▫	Critical Intersection

Color	Density Concentrations
⬜	0.00 - 3.40
⬜	3.40 - 6.80
⬜	6.80 - 10.20
⬜	10.20 - 13.60
🟩	13.60 - 17.00
🟩	17.00 - 20.40
🟨	20.40 - 23.80
🟨	23.80 - 27.20
🟧	27.20 - 30.60
🟥	30.60 - 34.00

Maximum Density	33.20%
Contour Data	Pole Vectors
Contour Distribution	Fisher
Counting Circle Size	1.0%

Kinematic Analysis	Direct Toppling
Slope Dip	90
Slope Dip Direction	120
Friction Angle	30°
Lateral Limits	20°

	Critical	Total	%
Direct Toppling (Intersection)	1	3	33.33%
Oblique Toppling (Intersection)	0	3	0.00%
Base Plane (All)	1	3	33.33%

Plot Mode	Pole Vectors
Vector Count	3 (3 Entries)
Intersection Mode	Grid Data Planes
Intersections Count	3
Hemisphere	Lower
Projection	Equal Area

Figure 4 (d) - Potential toppling from mean joint

A wedge susceptibility of 40.3% indicates the possibility of significant wedge failures, which occur when rock masses slide along intersecting planes of weakness. The overall kinematic vulnerability of 37.6% indicates a substantial risk of block failures, encompassing not just wedge failures, but planar and toppling failures as well. Additionally, the high slope mass vulnerability of 48.1% underscores the considerable potential for large-scale block movements, driven by the combined effects of material properties, slope geometry, and external factors such as rainfall and blasting. Based on the analysed SMR, the identified failure types are generally observed to lie in class IV & V. It also anticipates big planar and/or large wedges are likely potential for Pit no. 37 & 38. Collectively, these matrices suggest that the studied mine pit is prone to significant stability hazards, necessitating thorough monitoring and potential mitigation measures to ensure safety and stability.

Table 3: Slope mass rating (SMR) with kinematic and slope mass vulnerability

Parameters	Values	Parameters	Values
RMR_{basic}	56-70	Avg. SMR (lowest)	19
Slope angle	90°	Total failure count	23
Slope direction	120°	Planar	3
Angle of friction	30°	Wedge	18
Slope mass vulnerability (%)	48.10	Topple	2
Topple failure vulnerability (%)	3.40	Wedge failure vulnerability (%)	40.30
Planar failure vulnerability (%)	22	Overall kinematic vulnerability (%)	37.60

Parameters RQD, J_n, J_r, J_a, and J_w were evaluated for Q-slope considering the potential wedge failure with values of 74.5, 12, 3, 3, and 0.8 respectively with O-factor of 0.75 (Set A) and 0.8 (Set B). The SRF is taken as 5 based on the prevailing slope mass conditions. The Q-slope is found to be 0.59, which suggests the maximum safe slope angle for the studied pit is around 60° (Fig. 5).

The natural slope height on the western side of Pit No. 37 & 38, ranging from 38 m to 40 m, indicates that the Q-slope system's empirical ratings suggest an inherently unfavourable stability condition due to steep slope angles coupled with kinematically vulnerable slope mass (Fig. 5). The natural slope activity is also on the higher side due to the presence of an inherently high degree of jointing, the existence of over-hanged blocks, and open joints filled with soft materials (clay silt/sand). The weathering condition in the upper part of the slope and clay and silt coating in the open joints allowed the gravitational movement of an inverted loose wedge upon saturation conditions due to water. The shear strength along the rock joints decreases after the soft clay comes in contact with the water. Along with this, as mentioned earlier, several other geological and geotechnical aspects contributed to the movement of such substantial wedge failures.

6. DISCUSSION

The pit slope exhibited kinematic favorability for structurally controlled rock mass failure, with a large wedge failure vulnerability of approximately 40%. The basal joint plane's weathered materials, which became lubricated due to rainfall, intensified the situation. The saturation of infilled soft materials, such as clay, led to the progressive dilation of joints and initiated gravitational sliding along the basal plane. A back-calculated continuous SMR analysis indicated a high slope mass vulnerability of around 48%, suggesting a high probability of large to very large wedge and planar failures as per SMR classification. Additionally, empirical ratings from the Q-slope system highlighted an inherently unstable condition due to the steep slope angles and the kinematically susceptible slope mass along the high pit wall of Pit No. 37 and 38 at the Dadam open cast mine

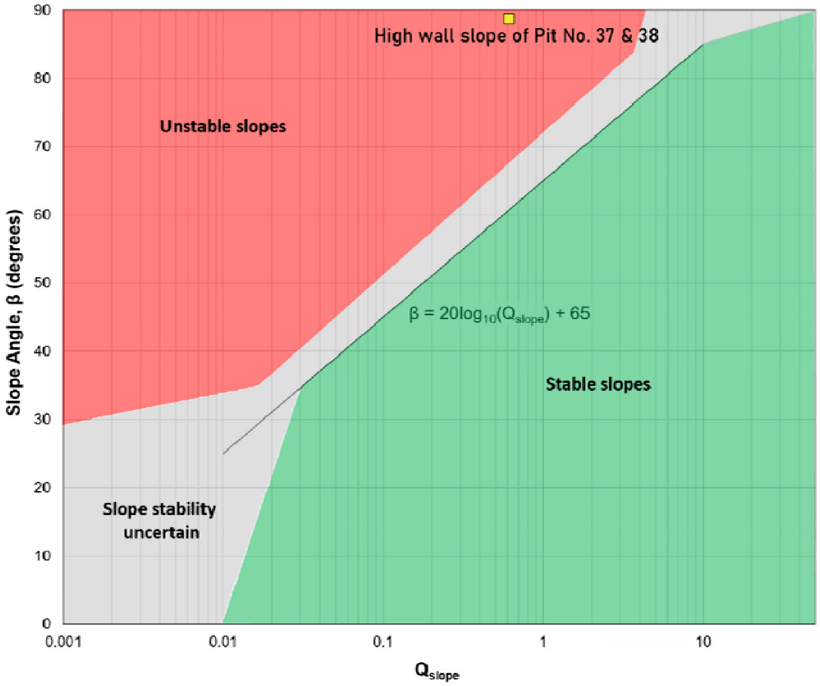


Figure 5 – High wall slope of Pit No. 37 & 38 plotted in Q-slope stability chart

The role of geological and structural factors is crucial in understanding the instability at the Dadam mine. The adverse orientation of joints acted as pre-existing weaknesses in the rock mass, making the mine susceptible to failure. These joints, being naturally spaced and aligned unfavourably, created potential planes for rock movement and detachment, particularly forming large wedges. The presence of weathered materials along these joints, especially at the basal plane, further complicated the stability. Rainfall-induced lubrication would have reduced the friction along these planes, increasing the likelihood of sliding. The average annual rainfall in the region is 450 mm. Around 75-80% of the annual rainfall is received during the monsoon season (June to September) i.e. approximately 354 mm and around 10-15% of the annual rainfall occurs during the winter season (Nov to Jan) due to western disturbances (WDs) i.e. approx. 45-67.5 mm. The rainfall particularly in the winter season might have caused the localised infiltration and washing out of the infillings. The infiltration of water into the clayey infill materials probably led to swelling and the subsequent dilation of the joints, diminishing the cohesion and stability of the rock mass. In addition to this, the steep slope angles at the site exacerbated these issues, as they increased the gravitational forces acting on the rock mass, making the slopes more prone to failure. The determined SMR using the continuous functions and Q-slope system ratings quantified the slope mass susceptibility, highlighting the high risk of large-scale wedge and planar failures. Together, the geological and structural factors interacted in a way that significantly compromised the stability of the mine, illustrating the complex and multifaceted nature of rock mass behaviour under prevailing geo-mining conditions.

Considering the prevailing field constrained due to the adjacent forest area at Pit No. 37 & 38, the benching would not be feasible. However, based on the preliminary conventional stability analyses, the drapery/rock netting along with systematic bolting on a kinematically vulnerable zone can improve pit safety in the long run.

7. CONCLUSIONS

The conclusions drawn from the study are as follows:

1. *Influence of Joint Orientation:* The adverse orientation of naturally occurring joints relative to the mine pit face was a primary factor in the failure observed at the Dadam mine. This unfavourable orientation (J_3) facilitated the detachment of a large wedge block formed due to widely spaced joints, which inherently compromised stability.
2. *Kinematic Suitability for Failure:* The kinematic analysis indicated a favourable condition for structurally controlled rock mass failure, specifically with a wedge failure vulnerability of around 40%. The spatial arrangement and characteristics of joints contributed to this significant risk level.
3. *Role of Weathering and Rainfall:* The presence of weathered materials along the basal joint plane, combined with rainfall-induced lubrication, played a critical role in the failure mechanism. This environmental impact decreased the shear strength, allowing the wedge block to slide along the basal plane.
4. *High Slope Mass Vulnerability:* The study revealed a high slope mass vulnerability, approximately 48%, indicating a substantial probability of large to very large wedge failures. This vulnerability underscores the necessity for safety precautions and slope stability management in the mine.
5. *Stability Challenges Due to Steep Slope Angles:* The empirical ratings from the Q-slope system suggested an inherently unfavorable stability condition due to steep slope angles. Combined with the kinematic susceptibility of the slope mass, these angles further contributed to the risk of failure along the high pit wall of Pit Nos. 37 and 38 at the Dadam opencast mine.

References

Alejano LR, Pons B, Bastante FG, Alonso E, Stockhausen HW (2007). Slope geometry design as a means for controlling rockfalls in quarries. Int J Rock Mech Min Sci, 44(6):903-921.

Anbalagan R, Sharma S, Raghuvanshi TK (1992). Rock mass stability evaluation using modified SMR approach. In: Proc of the 6th National Symp on Rock Mechanics, 258-268.

Awasthi SC, Prasad M, Anand VK (1981). Geology, structure and sulphide mineralisation of Tosham district Bhiwani, Haryana. Records of the Geological Survey of India, 112(2):7-16.

Bar N, Barton N (2017). The Q-Slope Method for Rock Slope Engineering. Rock Mech Rock Eng., 50(12):3307-3322.

Bhushan SK (1985). Malani volcanism in western Rajasthan. Indian Journal of Earth Sciences, 12:58-71.

Bhushan SK, Chittora VK (1999). Late Proterozoic bimodal volcanic assemblage of Siwana subsidence structure, western Rajasthan. Journal of Geological Society of India, 53:433- 452.

Bhushan SK, Khullar VK (1998). Geochemistry and tectonic significance of dyke swarm in Malani Igneous Complex around Sankra, district Jaisalmer, Rajasthan. B.S. Paliwal (ed.), The Indian Precambrian Scientific Publisher, Jodhpur, pp. 482-491.

Chen SL, Cheng CP (2017). Influence of failure probability due to parameter and anchor variance of a freeway dip slope slide - A case study in Taiwan. Entropy, 19:431.

Goel RK, Mitra S (2021). Weathering and its influence on rock slope stability in hilly areas. Journal of Rock Mechanics and Tunnelling Technology, 27(1):49-62.

Hoek E, Bray JD (1981). Rock slope engineering. Institution of Mining and Metallurgy, 3rd Edition, CRC press, 364p.

Kundu J, Sarkar K, Singh AK (2019). EasySMR: a computer program to check kinematic feasibility and calculate Slope Mass Rating. Geophys Res Abstr, 21:1540.

Kundu J, Sarkar K, Verma AK, Singh TN (2022). Novel methods for quantitative analysis of kinematic stability and slope mass rating in jointed rock slopes with the aid of a new computer application. Bull Eng Geol Environ, 81(1):1-19.

Meena MK, Singh AK, Dwivedi RD, Mohnot JK (2023). Study on the mechanism of a large wedge failure in Dadam opencast mine, Haryana. In: Proc of INDOROCK 2023: 9th Indian Rock conference, New Delhi, 268-273

Romana M (1985). New adjustment ratings for application of Bieniawski classification to slopes. In: Proc of Int Sym on the Role of Rock Mechanics and Int Soc Rock Mech, Salzburg, 49-53.

Singh AK, Kundu J, Sarkar K, Verma HK, Singh PK (2021). Impact of rock block characteristics on rockfall hazard and its implications for rockfall protection strategies along Himalayan highways: A case study. Bulletin of Engineering Geology and the Environment, 80:5347-5368.

Singh B, Goel RK (2011). Shear Strength of Rock Masses in Slopes. In: Engineering Rock Mass Classification, Eds: Bhawani Singh, R.K. Goel, (Pub) Butterworth-Heinemann, 205-210.

Singh VK, Baliga BD (1994). Slope design of an open pit copper mine. Int J Rock Mech Min Sci & Geomech Abstr, 31(1):55-69.

Stead D, Wolter A (2015). A critical review of rock slope failure mechanisms: The importance of structural geology. Journal of Structural Geology, 74:1-23.

Terbrugge P, Wesseloo J, Venter J, Stefen O (2006). A risk consequence approach to open pit slope design. J South Afr Inst Min Metall, 106:503–511.

Verma R, Verma HK, Singh AK (2022). Hazard analysis of rockfalls from high wall slopes in opencast mines - a case study of Dadam quartzite mine, Haryana, India. The Indian Mining & Engineering Journal, 61(09):12-17.