Assessment of structurally-controlled slope failure in a steeply dipping Iron ore mine

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ABSTRACT: Excavating an open pit mine with a steep angle considering both productivity and safety is a major challenge. The current work proposes a framework for slope design for a large open-pit iron ore mine with complex geological conditions. The joint properties of the steeply deposited mine are collected through face mapping and laboratory tests are done to obtain the intact rock and joint properties. The kinematic analysis of the initial slope design showed wedges forming in the benches. As a remedial measure, the wedge failure analysis is done for the bench scale and the most suitable pit design is selected by changing the slope angle and pit orientation. It was found that the optimized slope design in terms of both safety and productivity can be achieved at an overall slope angle of around 35^0 with a stripping ratio of approximately 3.5.

Keywords: Pit slope design, Face mapping, Kinematic analysis, Wedge failure, Stripping ratio.

1 INTRODUCTION

Demand for mineral reserves has increased as a result of the world's rapidly growing population. For this reason, most of the open pit mines in the world are trying to excavate the ore up to maximum depth till the ultimate pit limit is not reached (Hoek & Bray, 1981). But, the likelihood of substantial slope stability issues, which could endanger the final pit slope, is one of the major concerns with the increasing depth of opencast mines (Read & Stacey, 2009). The main objective of any slope design in an open pit mine is to prevent the instabilities that could harm people and machines and could stop ore production. Any type of slope failure in open-pit mines has adverse impacts on the overall mine profitability, safety, and environment. Again, the stability of a slope of an open-pit mine is crucially influenced by many factors such as slope geometry, quality of the rock mass, presence of geological features, and their properties. The major geotechnical challenge for any slope design engineer is to determine the optimum safe overall slope angle, which will result in the least cost for overburden removal so that the profitability can be maximized (Ortiz et al., 2015). This task becomes tougher if the ore deposit is steeply dipping along with complex geological conditions in terms of multiple rock types in the surrounding region and discontinuities weakening the rock mass properties. Therefore, special attention must be given to the geotechnical parameter characterization and how the structural instabilities (planar, wedge, toppling, etc.) in rock slopes are getting affected by those properties. Considering these constraints, the main objective of the mining/geotechnical engineers is to excavate the ore deposit safely with a profit margin ensuring maximum recovery. The final pit slope design of the mine is designed in terms of overall slope angle and pit slope orientation which ensure the ore recovery in an economic method without any possibility of slope failure.

This current research work is being done in a steeply dipping iron ore deposit in Chhattisgarh, India which contains two iron ore veins dipping at an angle varying from 75^0 to 87^0 shown in Figure 1. This extremely steep deposition of the orebody with limited width, i.e., 25 to 40 m results in a high stripping ratio (waste to ore ratio) of the mine.

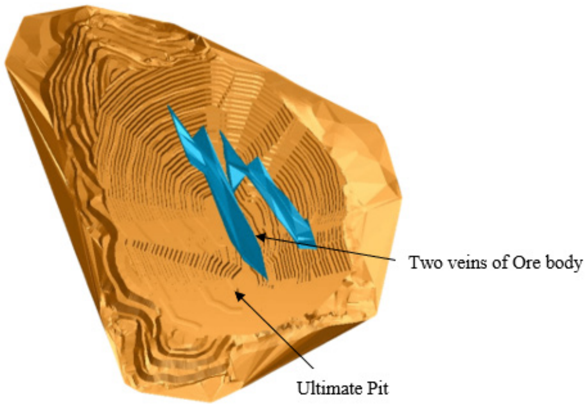

Figure 1. The proposed 3-D solid model of the mine showing the steep deposition of the orebody.

The stripping ratio of the mine along with the safety factor is a variable of many factors like overall slope angle, pit orientation, slope height, and the rock mass properties which are hugely dependent upon the geometrical and shear strength properties of the discontinuities present in the excavation area. Again, even though the economic excavation of the ore deposit is a variable of the slope angle, it should be combined with the geotechnical analysis and must be computed. In this context, the slope stability analysis should be done on both bench scale and global scale to observe how the structural stability of a mine is related to economic excavation.

Given the current geological conditions in this mine, this study intends to propose a methodology to evaluate the open pit stability in terms of both safety and productivity and how with the change of slope face angle and the orientation the same can be achieved. The first step of the slope stability analysis is to do the kinematic analysis from the face mapping data collected during the initial excavation stages and to find out the potential slope failure at different locations using Dips (Rocscience 2021). After that, the bench scale slope stability analysis is used to see how the slope face angle and the orientation is impacting the factor of safety and that can be utilized to reduce the chances of wedge failure. The final slope design is selected from multiple pit orientations considering the stripping ratio and the factor of safety as the design parameters.

2 GEOTECHNICAL CHARACTERIZATION

The geotechnical characterization of an open pit mine includes face mapping data collection from different surface outcrops, collection of rock samples to determine the rock mass properties, and use of all these structural data to perform the slope design analysis. The following sections describe the methodology and the results obtained from the mine site to conduct the geotechnical characterization.

2.1 Discontinuity Characterization

The discontinuities may directly affect the stability of the slopes because failure occurs more frequently along these surfaces, which are the weak planes in the entire rock mass. The main goal of face mapping is to identify a set or sets of discontinuities that will affect the stability on a given slope. The most common discontinuity feature encountered in this study area is joints, and the face mapping data covers all types of geometrical properties which can influence the slope stability analysis during the initial stages of excavation shown in Figure 2. The summary of the face mapping data collected for the discontinuity characterization is given below in Table 1.

Figure 2. Face mapping data collection for different rock types.

Table 1. Summary of the average face mapping data used for the slope failure analysis for the critical joint sets.

Rock Type		Magnetite		Schist		Granite	
Joint Set		J1	J2	J1	J2	J1	J2
Dip	[°]	85	45	82	40	67	41
Dip Direction		208 S-W	80 N-E	262 S-W	87 N-E	214 S-W	83 N-E
Strike		298 N	170 N	172 N	177 N	126 N	173 N
Aperture	[mm]	7	5	5	4	5	10
Persistence	[cm]	265	350	270	450	180	250
Spacing	[cm]	35	25	35	75	90	35

2.2 *Geomechanical Properties of the Rock Mass*

The intact rock properties like UCS, modulus of elasticity, Poisson's ratio, and tensile strength are calculated as per the ASTM-D7012 and ISRM, 1979 standards, and as per the GSI values of the rock types the equivalent rock mass properties are evaluated. The shear strength properties of the rock joints, i.e., cohesion and angle of internal friction are also evaluated for these rock types and a summary of all the geomechanical properties is given in Table 2.

Table 2. Summary of rock mass and shear strength properties determined from the laboratory testing and using RocLab (Rocscience, 2021).

Rock Type		Magnetite	Schist	Granite
UCS	[MPa]	52.2	48.5	125.0
Deformation modulus	[GPa]	4.2	1.5	11.4
Poisson's ratio		0.26	0.15	0.19
Tensile strength	[MPa]	0.28	0.12	0.30
Cohesion (joint)	[MPa]	0.04	0.13	0.20
Friction angle (joint)	[°]	34.6	36.5	39.1

3 ASSESSMENT OF FAILURE MECHANISMS THROUGH KINEMATIC ANALYSIS

The process of kinematic analysis involves the identification of possible failure mechanisms that may be structurally controlled for an existing or proposed rock slope. This analysis is typically conducted using stereographic projection techniques (Goodman, 1989), along with three tests suggested by (Markland, 1972), (Hocking, 1976), and (Goodman, 1976) which are used to determine planar, wedge, and toppling failure mechanisms, respectively.

The face mapping data that is being used for the kinematic analysis in this study includes the geometrical properties of the rock joints collected from different surface outcrops during the preliminary slope design stage. The data contains the properties of 210 no. of joints in total 77 m of length for the mentioned rock types. The results obtained from the kinematic analysis suggest that the wedge failure has the potential to occur at the intersection line of two joint sets and that can lead to some severe accidents in the mine (Hoek & Bray, 1981). The structurally controlled failure like planar and wedge failures occurring has some mandatory conditions to be fulfilled like the dip of the sliding plane or the line of intersection in the case of wedge failure must be less than the dip of the slope face given in Figure 3. This condition simply denotes that the sliding surface is created due to the presence of discontinuities that daylight in the slope face.

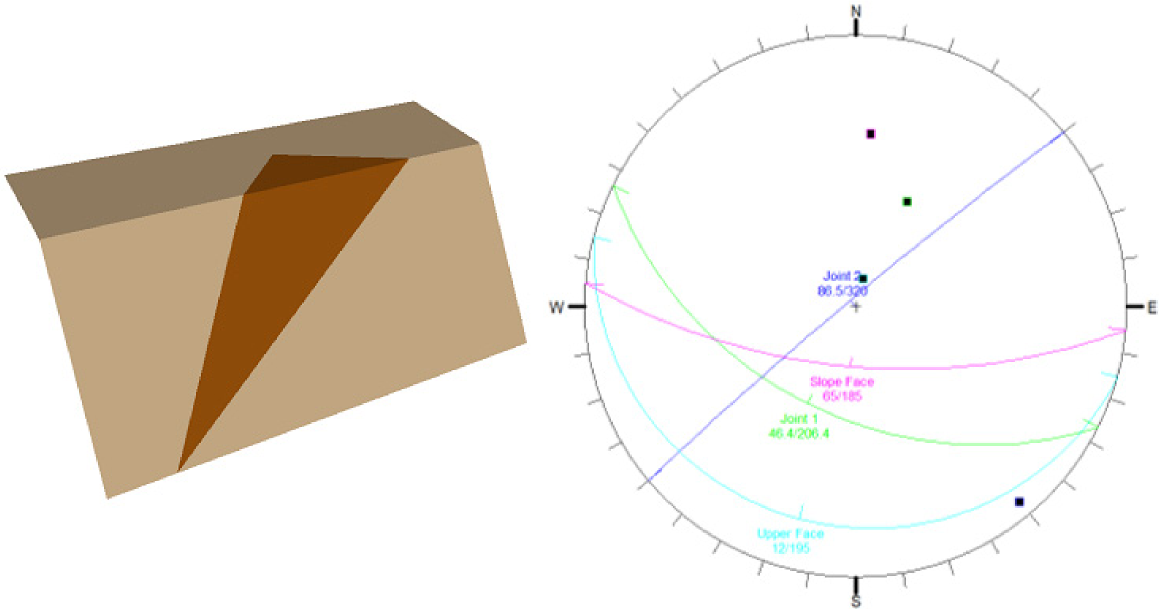

Figure 3. Wedge formation view along with the corresponding stereo net plot.

4 REMEDIAL MEASURES

4.1 *Bench scale slope stability analysis*

The geotechnical slope design of an open pit mine starts at the bench scale configuration by considering the orientations of joints. Then, the design of larger scale slopes, i.e., inter-ramp and global scale is focused on by considering the rock joint properties (both geometrical and shear strength) as well as the overall rock mass strength. In this section, the wedge failure analyses for the two rock types, i.e., schist and granite are done and the possible wedge formation is shown in Figure 4. The effect of changing the slope face angle and slope orientation on the factor of safety is also observed by varying the input data, i.e., the geometrical and shear strength properties of the rock joints.

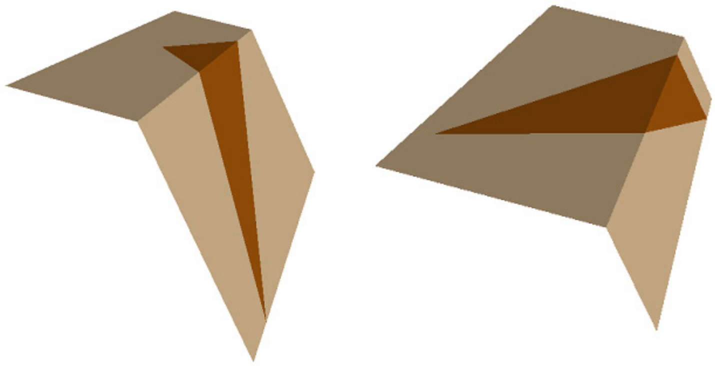

Figure 4. Wedge formations due to different critical joint orientations.

4.2 Effect of change in overall slope angle and pit orientation

The effect of change in overall slope angle and pit orientation on both economical excavation of orebody and safety is observed on bench and global scale. As shown in Figure 5 the overall slope angle has a huge impact on the stripping ratio as the excavation of waste reduces significantly but the factor of safety is also reducing at a higher rate. The FOS values are less than 1.25 after the overall slope angle goes beyond 45^0 which is not acceptable. Similarly, for bench scale configuration the slope angle was varied from 40^0 to 75^0 and the variation in the FOS values is observed. The pit orientation is also changed to observe the effect on both design parameters. The stripping ratio is slightly increasing because of the increase in the excavation of waste volume as shown in Figure 6. The change in pit orientation has a significant role to play in adjusting the slope stability which can be seen in the variation of FOS values. The small change in pit orientation can reduce the impact of the combination of joints for which the potential structural instability can occur.

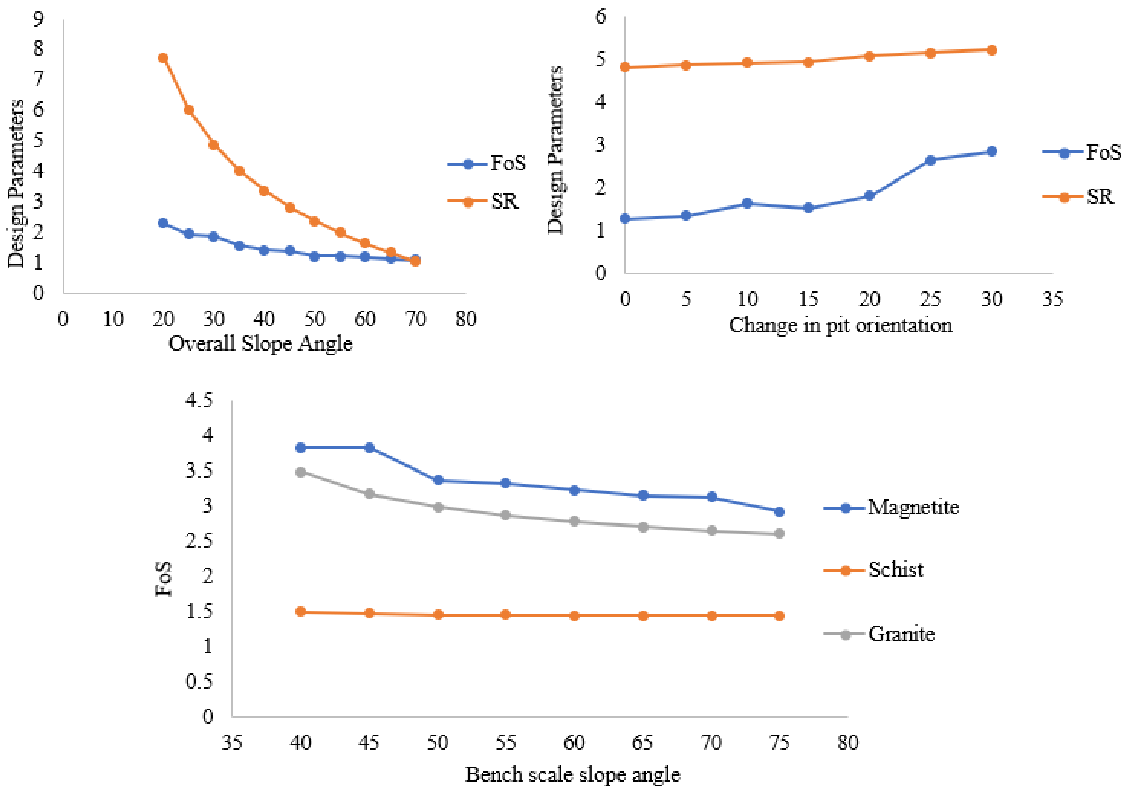

Figure 5. Variation of design parameters (FoS and SR) on both bench and global scale slope stability.

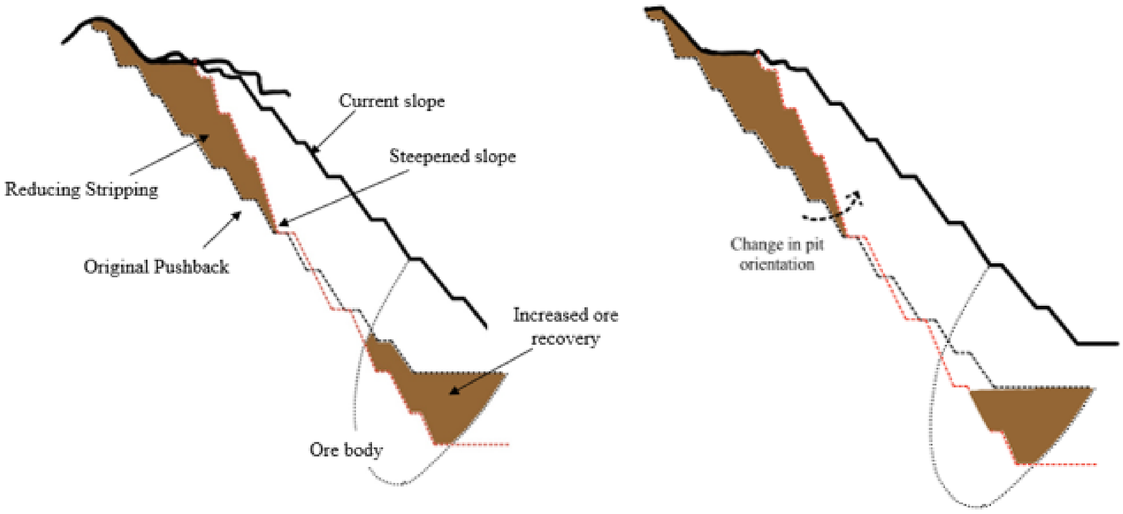

Figure 6. Variation of stripping ratio with change in pit orientation on a global scale.

5 CONCLUSION

In this study, a methodology is proposed for the extraction of ore with safety and profitability in an Indian iron ore mine with complex geological conditions. The best possible pit design for this case study is done where bench scale wedge failure analysis showed the factor of safety changing from 3.84 to 2.93 with the bench slope angle varied from 40^0 to 75^0. Similarly, for each slope angle, the pit orientation was also varied where the change in the stripping ratio values is not significant. The global scale analysis is done in the same way where the overall slope angle varied from 20^0 to 70^0, and the factor of safety changed from 2.27 to 1.06. Similarly, the overall slope angle has an impact on productivity as the stripping ratio changed from 7.72 to 1.02 for the same variation. Also, the pit orientation was changed to observe the variation in the stripping ratio on a global scale. The factor of safety changed from 1.27 to 2.84 and the stripping ratio varied from 4.80 to 4.71 with a change of 30^0 pit orientation both in clockwise (up to 15^0) and counterclockwise directions (up to 15^0). The final suitable pit for the mine is suggested with a 33^0-35^0 overall slope angle and stripping ratio of approximately 3.5 considering all the economic as well as the geotechnical constraints.

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