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Stability Evaluation of an Opencast Coal Mine with Difficult Ground Conditions: A Case Study

Hitesh Meel and R. D. Lokhande*

Department of Mining Engineering, VNIT, Nagpur – 440010, Maharashtra, India; riteshlokhande@mng.vnit.ac.in

Abstract

Any nation's ability to grow is reliant on the expansion of its various industries, each of which adds to the GDP of the nation. With a 2.5 % GDP contribution, the mining industry is one of the major sectors. In mining, coal is an important and abundant fossil fuel in India, and it accounts for 55 % of the country's energy needs. The increase in coal production can be largely attributed to the rapid increase in open-cast mining activities and intensified mechanization. This has resulted in the opencast mines going deeper day by day with a maximum stripping ratio of 1:15, at a depth of about 500 m. For any opencast mine, a safe, properly designed, and scientifically engineered slope is essential for the economical, safe, and successful operation. In this paper, the stability evaluation of the pit slope at Bhanegaon Opencast Mine of M/s Western Coalfields Limited (WCL), which is centrally located Coalfields in India has been carried out. The loose and saturated thickness (20 m to 57 m) of the alluvial deposit (mixed with Black Cotton soil and sludge) with Kamthi series formation has high transmissivity which creates a stability problem. In this study, the slope stability analysis has been performed by using the computer program RocScience two dimension (RS2) to assess the effect of difficult ground conditions on stress distribution pattern and safety factor of pit slope. Sections were obtained by Terrestrial Laser Scanner (TLS) and analysed with the help of RS2 software. From the analysis, it was found that the Stress Reduction Factor (SRF) of sections where sand/clay band is present was less compared to other working areas because the cohesion of the upper layer material was less.

Keywords: Failure Analysis, Numerical Modelling, Shear Strength, Slope Failure, Stress Reduction Factor

1.0 Introduction

The majority of the coal production is done through opencast mines in India. Opencast mining is cost-effective mining method allowing a high grade of mechanization and large production. In India, the fast increase in the output of coal can be largely attributed to the rapid increase in opencast mining activities and intensified mechanization[1,2]. The production of coal during 2023-24 was 997.83 MT and import was 261.0 MT[3]. India's surface mining industry is expanding quickly in order to close the supply and demand imbalance for coal in the energy sector[4]. To access the economically valuable minerals beneath the surface, opencast mines require surface excavation as a result the stripping ratio reached 1:15 at 500 meters below the surface which caused the mines to get deeper every day. On a previously plain earth surface, the cut slopes must be formed to begin the excavation process. For safe and profitable mining, the cut slopes' stability is essential[5].

Slope stability is a major concern in opencast mines. To ensure safety throughout the mines' lifespan the safe mining operation is the responsibility of mine management. The making of the steepest pit slopes

*Author for correspondence

assuming they do not collapse during the mine's life. Therefore, when designing the deep open pit slopes, the design engineer must balance the two opposing components i.e., stability and steepness.

The stability of slopes is very important for safe mining operations. For stability, proper slope design based on the safety factors, correctly dealing with dynamic loading and water problems makes mine stable. The steepening of the slope could cause a slope failure, which would result in lost production, additional stripping costs to remove failed material, bench reforming, haul road rerouting, and production delays. On the other side, Steepening the slopes can result in significant cost savings.

If unsafe conditions are established, the Directorate General of Mines Safety (DGMS) may even decide to close the mine. As such, it is imperative to strike a balance between safety and economics. Consequently, there will be a correspondingly high amount of waste mining and dumping, which greatly increases the risk of highwall and slope failures. Because most production areas are located near the excavation floor, there is a constant risk to the personnel and equipment stationed there, which could result in a catastrophic loss of life and property.

It is necessary to analyse steep slopes thoroughly so that the entire process is safe and profitable. These days, open pits from both large and small-scale industries are unstable because they are reaching greater depths, which is a major concern when designing the slopes. For managing or preventing slope collapse, slope stability analysis and slope monitoring are very important[6]. Conventional approaches like limit equilibrium, kinematic analysis, and numerical methods are most frequently used to design slopes. These methods are practical and can be applied to various failure modes[1,7].

The limit equilibrium approach can be used to determine the factor of safety for predefined failure modes under homogeneous ground conditions[8]. Limit equilibrium techniques are often used by geotechnical engineers to analyse slope stability. These techniques compute a safety factor, which is the ratio of the available shear strength to the shear stress at equilibrium, with respect to the rock's (or soil's) shear strength. Their primary feature is their simplicity and low parameter count (hydrogeological conditions, geotechnical parameters, geological parameters, and slope geometry). However, complicated issues related to stability in open pit mines are frequently difficult to resolve using limit equilibrium techniques[9,10]. Several authors have worked on the Limit equilibrium method[11-14] but the development of numerical modelling through the Finite Difference, Finite Element, etc. methods give a better understanding of safety factor[15].

In this study, the authors have investigated Bhanegaon opencast mine for slope stability purpose, is situated in the Bina block of Kamptee Coalfields, this coal block falls in the Nagpur District of Maharashtra State (Figure 1). The Bhanegaon Opencast Project is a mine of Western Coalfield Limited (WCL) and situated in the northern part. This Project is located at the confluence of Pench and Kanahan Rivers. There is danger associated during mining operations due to river flowing from three sides of mining area. Considering multi seams and steep gradient of seams which falls in the range of 1 in 4.5 to 1 in 6, the Horizontal Slicing Method of mining is being used for Bhanegaon OCP (Bina). All types of Gondwana formation from the Talchir formation of Upper Carboniferous to the Kamthi formation of Upper Permian were encountered in Bhanegaon opencast project area during the geological exploration. The entire block is covered by a thick layer of Alluvium including Black cotton soil and river sand. The loose and saturated thickness (20 m to 57 m) of alluvial deposit (mixed with Black Cotton soil and sludge) with Kamthi formation having high transmissivity may create a stability problem. Currently mine is being worked as per DGMS guidelines and bench profiles are maintained accordingly. Bench geometry for alluvial soil is of 3 m height and 9 m width, for coal is of 10 m height & 10 m width and for rock mass is of 10 m height and 20 m width.



Figure 1. Bhanegaon mine location.

2.0 Field and Laboratory Investigations

2.1 Field Investigations

All types of Gondwana formations from Talchir Formation of Upper Carboniferous to Kamthi Formation of Upper Permian are present in Bhanegaon OCM. The Bina block is generally covered by a thick layer of black cotton soil and loose sand with pebbles (alluvium) followed by a blanket of Kamthis. None of the geological formations are exposed on the surface of the block. The geological structure is therefore based on the sub-surface data generated from boreholes (Figure 2 and Figure 3).



Figure 2. Bhanegaon mine benches.

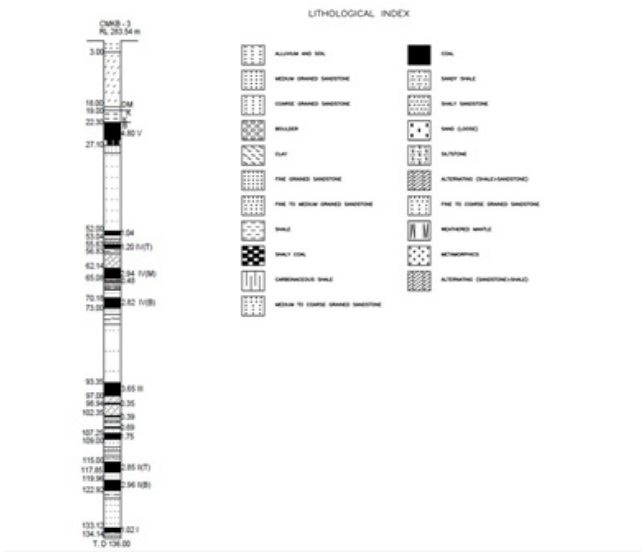


Figure 3. Borehole section and lithological index.

The drainage of the area is mainly controlled by the easterly flowing Kanhan River and Pench Rivers. The confluence of these two rivers is located just northeast of the block. A few seasonal nallahs originate within the block and drain into the Kanhan River. The Kamthi Formation along with Alluvial deposit (loose sand) represents the Shallow Aquifer. The thick bed of alluvium and current bedding seen in the mine cutting is indicative of recent alluvial deposition. Barakar Formation along with coal seam is lying below the Kamthi Formation/ Motur Formation represents the Deeper Aquifer. Water table was determined by Piezometric data.

2.2 Laboratory Investigations

In laboratory Density, Porosity, Poisson's Ratio, Young's Modulus (MPa), Peak Tensile Strength (MPa), Friction



Figure 4. Core cutting.



Figure 5. Core samples.

Table 1. Geo-mechanical properties of rock

Material Properties	Black Cotton	Alluvial Soil	Coal	Shale	Coarse Grain Sandstone	Medium Grain Sandstone	Fine Grain Sandstone
Unit Weight (MN/M^3)	0.015	0.018	0.015	0.020	0.018	0.020	0.021
Porosity Value	0.350	0.250	0.085	0.137	0.150	0.160	0.150
Poisson's Ratio	0.200	0.200	0.055	0.135	0.200	0.165	0.186
Young's Modulus (MPa)	10.000	20.000	1206.190	616.981	192.172	474.860	1051.400
Peak Tensile Strength (MPa)	0.050	0.100	2.290	1.800	0.384	0.785	1.137
Friction Angle (Degrees)	15.000	30.000	30.030	36.210	38.900	29.750	38.718
Cohesion (MPa)	0.050	0.020	18.663	13.326	8.424	12.110	29.300

Angle (Degrees), Cohesion (MPa) and Unconfined Compressive Strength were analysed by Stress-Strain analysis(IS 9221)[16], Brazilian Tenslile test(IS 10082)[17], triaxial test (IS 13047)[18], Porosity test (IS 13030)[19]. Samples of alluvial soil, black cotton soil, coal (from each coal seam) and sandstone (from coal seam parting) were collected from mine site to determine physio-mechanical properties. Samples against all 5 mine sections (Figure 6) were collected so that entire mine can be studied and analysed.

NX size cores were cut with Diamond core cutting machine (Figure 4 and Figure 5) and their properties were determined in the lab as mentioned in Table 1.

3.0 Numerical Modelling

To determine mine profile Terrestrial Laser Scanner (TLS) was used, and sections were created. Total 5 equidistance sections were created across the strike line to study the entire mine as these sections encompasses entire mining area (Figure 6). Sections are 550, 750, 950, 1150 and 1350.

For slope stability analysis models were created using the computer program RocScience two dimension (RS2). For model creation, first outer boundary was created with respective section co-ordinates and subsequently material layers were created with their properties as mentioned

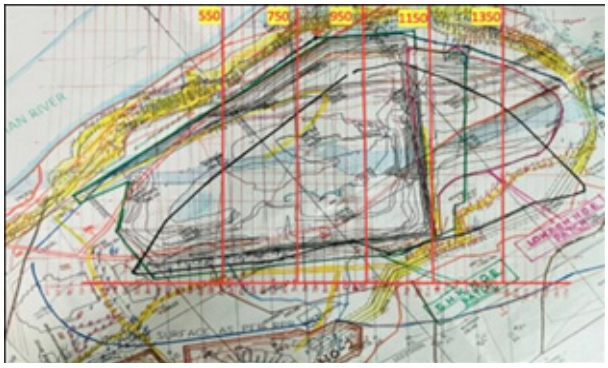


Figure 6. Mine plan with sections.

Table 2. Material and their colour representation in model

Material Name	Black Cotton	Alluvial Soil	Coal	Shale	Medium Grain Sandstone	Coarse Grain Sandstone	Fine Grain Sandstone
Material Color							

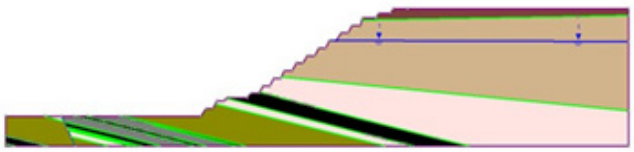


Figure 7. RS2 Model of section-1350.

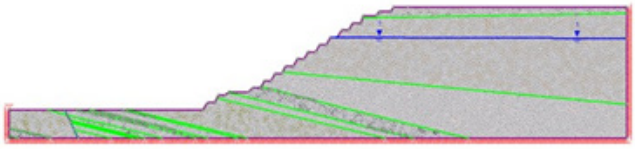


Figure 8. Model discretization and meshing.

in Table 1 (Figure 7). Details of different lithologies and their colour representation in models are shown in Table 2. Fault plane and Piezometric data were also used before Discretization and Meshing (Figure 8).

4.0 Results and Discussions

Stability of a mine section depends on a variety of factors including SRF, maximum displacement and maximum stress. A high SRF (>1) means that the structure is more resistant to failure, while a low SRF signals higher risk for collapse or movement. Maximum displacement helps identify areas where the mine section may be deforming excessively, signalling potential risks for instability. Monitoring and understanding the stress distribution is essential to prevent failure due to overstressed sections and to ensure that excavation activities do not introduce risks to stability. A low SRF combined with high displacement and high stress suggests that the mine section is at a high risk of instability. Conversely, a high SRF, low displacement and moderate stress would indicate a more stable condition.

The prepared models were analysed with maximum SRF tolerance 0.01 for precision in result. A small tolerance (0.01) would ensure more accurate Factor of Safety (FOS) by fine tuning the SRF value before failure occurs. After computation Critical SRF was determined with maximum displacement. At present mining operations are going smoothly without any safety disturbances as per DGMS guideline in soft material (106(4) of Coal Mines Regulations, 2017). Critical SRF obtained through RS2 modelling of sections 550, 750, 950, 1150 & 1350 are 1.95, 1.53, 2.09, 1.37 and 1.18 respectively, which showing the safe working conditions (Section 1350 shown in Figure 9).

In this analysis, all the sections were stable with more than one critical SRF (Figure 10). Further, the prepared sections were analysed based on their horizontal movement (displacement) and stress generated. Max.

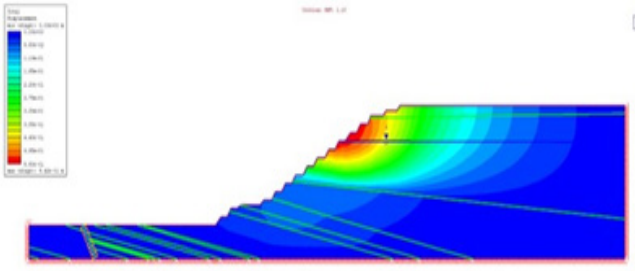


Figure 9. Critical SRF of section-1350.

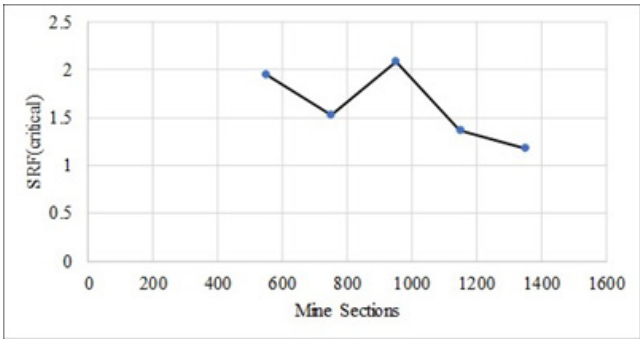


Figure 10. Critical SRF of all section.

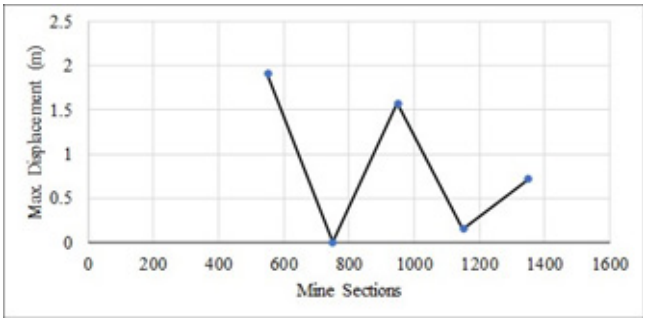


Figure 11. Max displacement of all section.

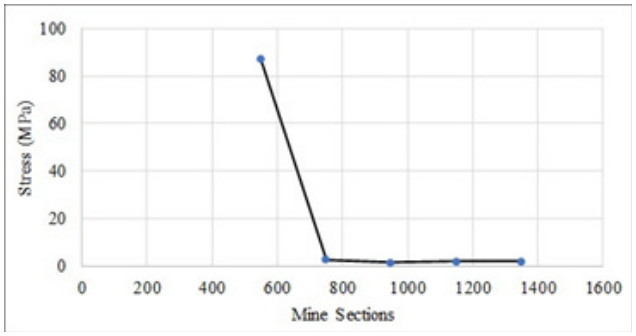


Figure 12. Max stress of all section.

displacement (meter) and max. stress (MPa) of sections 550, 750, 950, 1150, and 1350 are 1.900 and 87.38, 0.005 and 2.52, 1.570 and 1.33, 0.158 and 1.99, 0.718 and 1.83 respectively (Figure 11 and Figure 12). Section 550 (SW part of the mine) shows much displacement and stress due to geological discontinuity and higher alluvial cover as compared to the other part of mine.

5.0 Conclusions

In this study, the mine which was investigated had loose strata and water-bearing problems. Due to these conditions mine is very much prone to unstable but after analysing all the sections with difficult ground conditions (The loose and saturated thickness (20 m to 57 m) of alluvial deposit (mixed with Black Cotton soil and sludge) with Kamthi Formation) benches are completely safe to operate in current geometry with stable critical SRF (>1).

However, Section 550 showing much displacement and stress despite having critical SRF of 1.95 signifies that with current bench geometry working condition are safe but continuous bench monitoring is required in this part of mine. As per current Project Report (PR), mine is expending in eastern direction and final bench cutting has been done at section 550 and no mine working is going in this portion so, there is no danger to man and machinery in worst case scenario. As per the above study it's recommended to daily bench monitoring near section 550 as a precautionary measure.

6.0 Acknowledgements

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