JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.81, June 2013, pp.804-812

Stability Analysis of an Open Cut Slope in Wardha Valley Coal Field

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Abstract: Open cast mines are the prime source of coal production in India. Due to an increase in coal demand, deeper surface mines are being planned to ensure better productivity with enhanced safety of these mines. The safe working environment and continuous production of the coal calls for the safe and stable design of cut slopes. The stability analysis of this slope requires in depth geotechnical investigation which are aided by result orientated stability assessment using empirical methods and numerical simulation. In the present study, a slope was examined to understand the mechanism and comparisons were made with field observations. The investigation has involved a 32m high cut slope from an open cast mine in Wardha valley coal field which has been analyzed using a two dimensional numerical simulation. The bench slope consisted of a low strength sandstones, shales and clay sequence. Hoek- Brown strength parameters established and used as input parameters in the model. The results indicate that the slope is critically stable and may lead to failure without warning and needs proper attention.

Keywords: Slope stability, Limit equilibrium method, Open cast mines, Factor of safety, Wardha valley coal field.

INTRODUCTION

Open cast mining has developed into a high prominence industry due to exponential rise in the demand for coal. Open cast coal mining's production share is more than that of the underground coal mining (Fig.1) and seeing the recent trends, it will continue to rise in the future too. This pressure on open cast mines to enhance the production has brought the issues of open pit safety and operational economics to the forefront. The stability of opencast mine slopes is significantly influenced by the presence of structural features within the rock mass. The slope design in such situations needs to be made keeping in view the relative orientation of these features. The optimum design of slope is vital to achieve the twin target of safety and economics. The task of designing optimum slope basically involves striking a balance between the conflicting requirements of safety and economics.

The primary objective of any rock excavation is to minimize the volume of rock to be excavated while providing an economic and safe environment for its intended function. The prime aim of economic and safe open pit slopes and dump slopes, as a rule, involve maximization of the angle of inclination of the slope while assuring stability. Stability assurance requires an appreciation for the potential modes of failure. Thus, a proper understanding of slope collapse mechanics at the same time astute monitoring and management of the slopes is essentially important to minimize the chances of slope failure. Therefore, the main aim of slope stability analysis is to design a slope that is stable, economical and has minimum chances of failure (Monjezi and Singh, 2000). The excavabilty of the material for the benching and the further slope stability are an important problem in geo-mechanical engineering and depending upon the physico-mechanical properties of the material. This holds for both at the design and construction stages. A number of methods have been used for the assessment of slope stability and excavatability (Hoek and Bray, 1981; Goodman, 1989; Pettifer and Fookes, 1994).

Analysis of a cut slopes in a 'inhomogeneous' rock mass along with use of rock mass classification methods is in widespread use for the determination of rock mass strength and deformational parameters. The rock mass classification numbers Q (Barton et al. 1974), RMR (Bieniawski, 1989) and, more recently, the Geological Strength Index (Hoek and Karzulovic, 2000), have been correlated with the rock mass modulus, rock mass strength parameters (for both Hoek-Brown and Mohr-Coulomb) and the 'unconfined compressive strength' of the rock mass. Correlation between Mohr-Coulomb strength parameters and geological strength index has recently been encapsulated in a computer package RocLab (Rocscience, 2002), allowing simplistic determination of cohesion and friction values of the rock

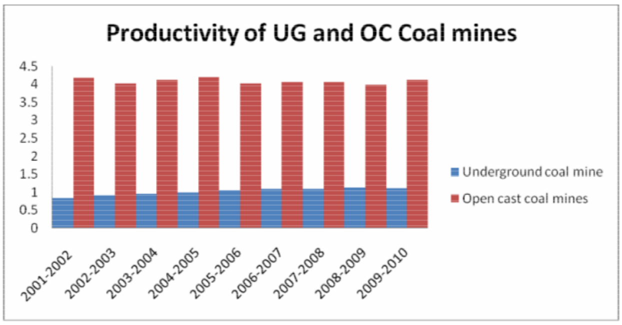


Fig.1. Comparison of coal production between opencast and underground coal mine (Source WCL, 2011).

mass from Hoek-Brown parameters. This package also provides for the determination of the uniaxial compressive strength of a rock mass and rock mass modulus, using an 'average' correlation from empirical results.

Singh and Dhar (1994) and Singh et al. (1995) based their rock mass input parameters on rock mass classification data and made use of a finite difference method to evaluate the stability of rock slope in open pit mines. In the former, the indication of failure was the 'plasticity indicators' contained within the program, while in the latter it was the localized factor of safety against the Mohr-Coulomb shear failure. In both the cases, limit equilibrium analysis were also carried out which provided similar indications of stability. Du Plessis and Martin (1991) also used similar methodology. However, they determined the appropriate cohesion and angle of friction for the rock mass by calibrating the model by slope monitoring data, and thereby used the model to assess the stability of the final pit.

Evaluation of the slope stability in the open pit mines at different stages of mining is important for the safe and economic mining operations (Sarkar et al. 2007). Slopes are normally designed based on the geotechnical data and physico-mechanical properties of the material. Using the rock mass properties, stability of the slopes is evaluated from various empirical, analytical and numerical techniques (Singh et al. 2007). Different researchers have emphasized on the various factors which play a key role in overall behavior of slopes. These factors can be broadly grouped as geological, geotechnical, hydrological, nature of material, slope geometry, physico-mechanical properties, drainage of slopes, erosion, temperature, state of the stresses, effect of blasting and dynamic loading and finally the time factors (Coates, 1964; Brawner et al. 1975, Brawner, 1978; Gupta and Singh 1985, Singh et al. 1989, Singh and Singh, 1996). Oztekin et al. (2006) had done stability analysis of cut slopes in limestone for 6 different cut slopes having high angle of inclination ranging between 71° to 84° and the factor of safety was observed to lie in the range of 1.19-3.83. Their analysis was done assuming a circular slip surface using automatic grid search which generates a slip centre grid from which various slip planes are analysed.

Scope of the study

The subject of cut slope stability assumes special significance in Wardha Valley Coalfield (WVC) where opencast mines are becoming deeper and deeper due to constraints of land availability and the deposits are encountered by various geological discontinuities in the form of joints and faults. The stability of open pit slopes in this coal field is greatly influenced by these structural features and the benching patterns. The slope is being monitored at Wardha Valley Coalfield (WVC) with the help of level and Electronic Distance Measuring (EDM) instruments for the measurements of vertical and horizontal displacements, respectively (Jhanwar et al. 1996; Jhanwar et al. 2008). The slope stability state in WVC is typically governed by several factors like the thickness of soil formation, condition of sandstone rock mass, presence of major and minor strike faults, infiltration of rainwater into slope, presence of external loads on slopes in the form of overburden dumps, etc. (Jhanwar and Thote, 2010). The average annual rainfall in this coalfield has been reported to be 1250 mm approximately (Jhanwar and Thote, 2011).

For quick and reliable estimation of the slope health the two dimensional LEM software have gained importance. These programs give the factor of safety of the rock and soil slopes based on limiting conditions i.e. the shear strength of the slope material and the shear stress acting on it.

This paper discusses the investigation conducted on one of the 32 m high cut slope in an opencast coal mine of WVC, using 2D limit equilibrium method. The analysis has been carried out using simplified Bishop's method and Janbu's corrected method using different slip search modes. The slope is formed of different lithologies having quite an erratic variation in strength. The measured rock mass strength parameters viz. cohesion, angle of internal friction, uniaxial compressive strength, geological strength index and material constants for the Hoek-Brown material have been used for the respective rock types in the limit equilibrium analysis model. The results have been scrutinized for the shear stress generation along the slip surfaces.

Location of the study area

The mine is located near Chandrapur and is well connected by road from Nagpur, India. The studied Ghugus mine falls under the area of Western Coalfields Limited, Nagpur (Fig.2). The Wardha River flows along the dip side

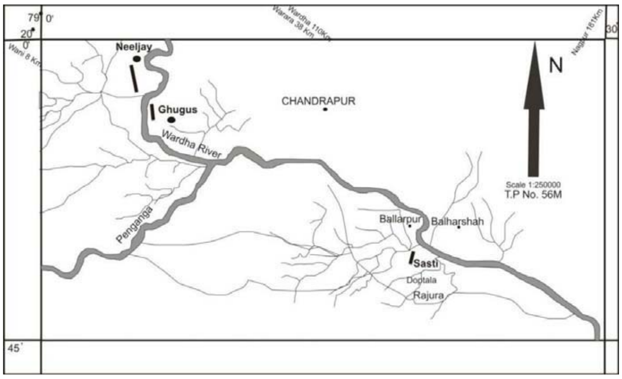


Fig.2. Location map of Ghugus Open Cast mine.

of this mine. Ghugus mine extends up to a length of 1.5 km, having an N-S strike. The Ghugus open cast mine lies exactly in east of the Wardha River. The depth of the open cast mine is around 95-100m. Some coal seams, particularly lower benches are submerged in water, throughout the year. WCL has adopted strip mining method for Ghugus and the other mines. They are operating on the 11th bench of mine working along the dip of the seam.

GENERAL GEOLOGY

The area is located in the Southern part of the Wardha Valley Coalfield. The coal field is broadly dipping towards the NNW. The mine has a strike along NNE-SSW, mostly covered with a thick mantle of soil. The gradient varies from 8^0 to 10^0 W. Geologically, Ghugus mine comes under the lower Gondwana Group and the dominant lithology includes sandstone, shale, clay, coal seam and soil forming the overburden. A general field view of slope is shown in Fig.3. The coal bearing Barakar Formation does not outcrop on Ghugus area as it is completely overlaid by Kamthi Formation and recent detrital mantle (Soil, black cotton,

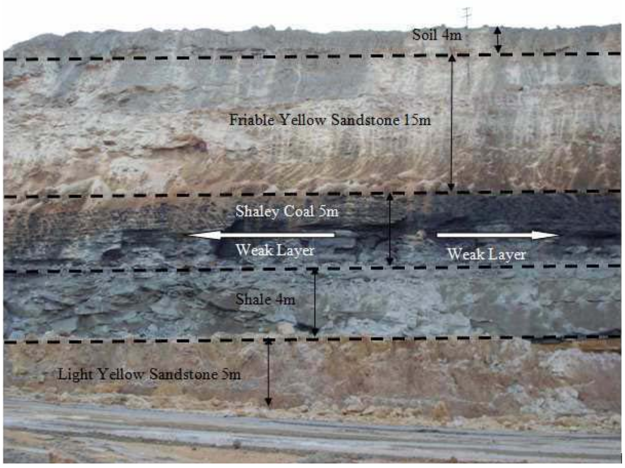


Fig.3. A field view slope of Ghugus Open Cast mine.

silt and clay). The soil forming the overburden at Ghugus mine has a thickness of 4-5 m and is red and brown in colour. The soil layers is underlain by a layer of friable yellow sandstone with a thickness of 18-20 m, followed by a compact layer of sandstone with a thickness of 8-10 m and having yellow colour. It is underlain by shaley coal having thickness of 3-4 m. The shaley coal is underlain by shale, which is 2-3 m thick, followed by light yellow colour sandstone below.with thickness of 15-20 m.

In between light yellow colour sandstone, there is a layer of bauxite of thickness of 1.5-2 m, underlain by a small layer of 2-3 m thick shale. Finally, coal seam of thickness 20-21m has been found and is currently being exploited. A bench geometry and general litho-log is given in Figs. 4 and 5 respectively. The broad stratigraphic sequence of the area is given in Table 1.

Table 1. Lithological sequence at Sasti Opencast mine (Jhanwar et al. 2006)

Formation	Lithology	Maximum thickness (m)
Detrital Mantle	Black cotton soil, sandy soil etc.	32.05
Kamthi	Sandstone, shale and clay	86.00
	Unconformity	
Barakar	Sandstone, shale, carbonaceous shale and coal seam	105.00
Talchir	Greenish grey shale and sandstone	Not ascertained

Cut-slope Morpho-geometry

A 32 m high, open cut slope was analysed using two dimensional limit equilibrium method to calculate the factor of safety. The cut slope consists of different sedimentary lithologies viz. soil, sandstone, shale and coal sequence (Fig.3). This shaley coal bed is a weak zone as evident from sporadic spalling from the slope wall along the bed. A 3m thick low strength shale bed was lying under the shaley coal seam. A 16m yellow sandstone bed was present below the shale bed. A 5m berm was developed below the shale bed on the yellow sandstone. A slender 3m shale bed and 17-20 m thick coal seams are present below the yellow sandstone layers. The rocks are moderately to highly weathered. The cut slope had an inclination of 78^0 towards east. The slope observed is damp to wet with water ingress at a few spots.

GEOTECHNICAL INVESTIGATION

A detailed geotechnical study was carried out for the assessment of the health of the high bench slope. The

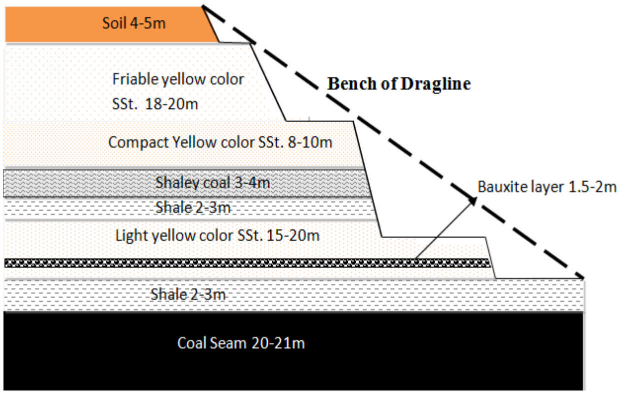


Fig.4. Bench geometry of Ghugus Open Cast mine

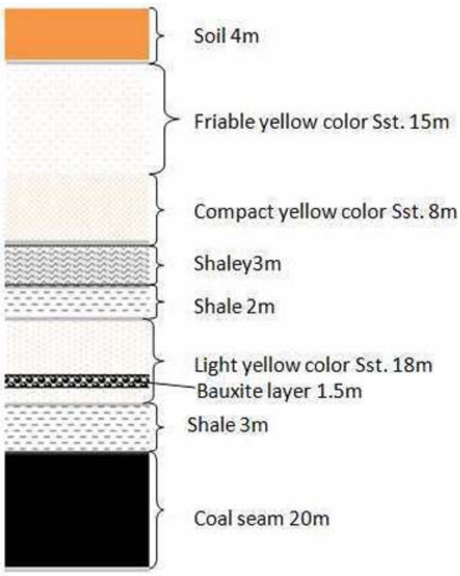


Fig.5. General litholog of Ghugus Open Cast mine.

representative rock samples were brought to the laboratory for measuring the geotechnical properties, which were used as input parameters for the LEM analysis of the cut slope. The rocks were tested with their natural moisture content for their uniaxial compressive strength, unit weight and estimation of the rock mass strength (Table 2). The rock masses delineated by the lithological contacts were assigned a Geological Strength Index (GSI) based on the respective geological conditions (Fig.6). GSI helps in the estimation of the reduction in strength parameters of a rock mass for different geological conditions (Hoek et al. 1998). The soil was assigned a GSI rating of 10. The material constant, m_i values were chosen based on rock type as described by Hoek and Brown (1994). The highest GSI rating of 43 was assigned to yellow sandstone. A disturbance factor of 0.5 was used for all the lithologies as the mining was being accomplished through controlled blasting.

Table 2. Average value of used geotechnical properties.

Litho-type	UCS (MPa)	GSI	Disturbance Factor	m_i
Soil	0.46	10	0.5	3
Yellow friable Sandstone	14	38	0.5	15
Shaley coal	19	35	0.5	4
Shale	16	30	0.5	8
Yellow sandstone	27	43	0.5	17
Coal	8	35	0.5	4

Two-dimensional Limit Equilibrium Analysis

The safety and cost effectiveness of the cut slopes is a major criterion for workability and safety of the mines. The open cut bench was analyzed for factor of safety using a two dimensional limit equilibrium technique. Two dimensional slope stability methods using limit equilibrium technique can be distinguished into the method of slices, circular methods, and non-circular methods (Rocscience, 2010). The method of slices is based on dividing the slope into different slices and analyzing the stability of the failing mass while taking into consideration, the static equilibrium of the slices separately and the overall equilibrium of the failing mass as whole. The static equilibrium of the slices can be attained by different assumptions viz. disregarding and considering the various interslice forces and the moment

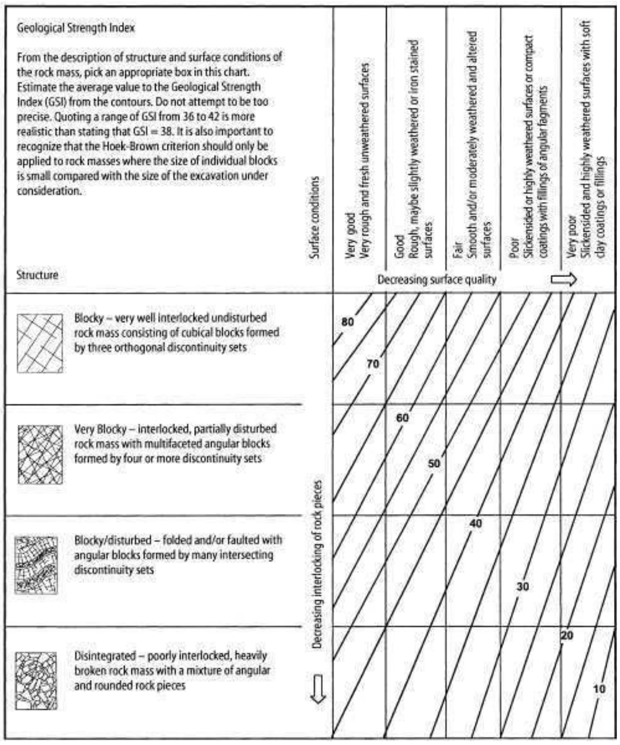


Fig.6. Characterization of rock masses on the basis of interlocking and joint alteration (Hoek and Brown, 1998 adjusted from Hoek, 1994)

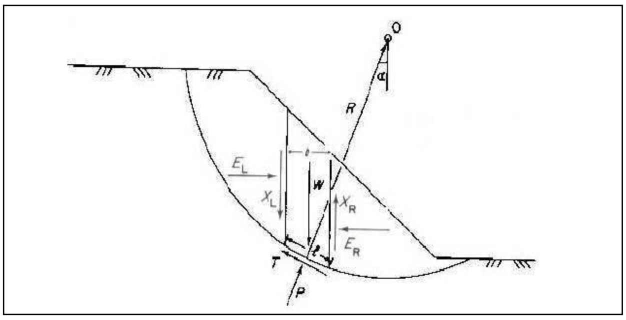


Fig.7. Bishop's simplified method of slices for the analysis of circular failure in slopes.

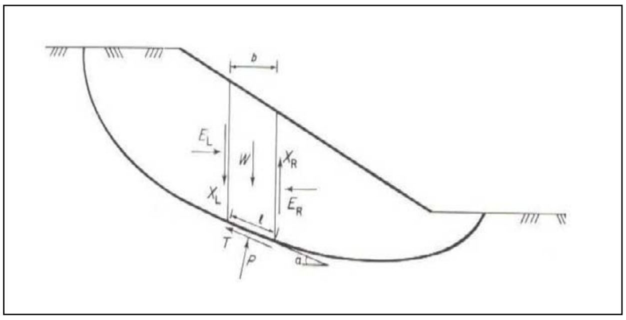


Fig.8. Janbu's method method of slices for the analysis of non-circular failure in slopes.

equilibrium of the slices. In circular and non-circular limit equilibrium analyses, the equilibrium of the whole failing mass is considered neglecting the internal equilibrium of the sliding mass. Bishop's and Janbu's methods were used for the analysis.

In the Bishop's method, the failure is assumed to occur by rotation of a mass of soil on a circular slip surface centered on a common point (Bishop, 1955). The shear stress between the slices is neglected as the forces on the sides of the slice are assumed to be horizontal. The total normal force is supposed to act at the center of the base of each slice, and is obtained by summing forces in a vertical direction (Fig.7). The simplified Bishop method does not satisfy the complete static equilibrium conditions but the analysis provides relatively precise values for the factor of safety. The factor of safety by the Bishop's method is obtained by the following equation:

$$F = \frac{\sum \left[\frac{c' l \cos\alpha + (w - ul\cos\alpha) tan\emptyset'}{\cos\alpha + (\sin\alpha \, tan\emptyset')/F} \right]}{\sum W \sin\alpha}$$

Janbu's method is applicable to non-circular failures. This method too assumes horizontal interslice forces and zero shear forces. For the present analysis Janbu's corrected method, which takes into account the interslice shear forces (f_o), was used for the factor of safety calculations (Janbu, 1954, 1968):

$$F_o = \frac{\sum (c' l + (P - ul) \tan\emptyset') \sec\alpha}{\sum W \tan\alpha}$$

$$F = f_o . F_o$$

where, c' = cohesion, ϕ' = angle of internal friction, α = angle at the base of sliding slice W = effective weight of the slice, u = pore water pressure, l = width of the slice, P = Normal force acting at the base of the slice, E & X= Normal and tangenial forces acting on the sides of the slice.

The limit equilibrium analysis of open cut slope was performed using the software SLIDE 6.0 (Rocscience, 2010). The software generates a number of probable slip surfaces and safety of factor is calculated for all of them to achieve the failure surface with global minimum safety factor.

The bench slope was analyzed using both simplified Bishop Method and Janbu's corrected method, for the factor of safety. Three types of slip criteria were employed viz. Circular surface, Non-circular surface (auto-generated) and Non-circular surface (path-generated). In the circular slip surface, an automatic grid was generated whose each node was used as a center of rotation for the probable failure surfaces. For non-circular slip failure surfaces, a path search and auto refine methods were used. In the path search mode, generation of slip surface is based on the generation of random numbers. For the path search random numbers are used to generate the slip surface initiation points, the angle of the first slip surface segment and the angle of all subsequent slip surface segments. The slide 6.0 divides the range in half and uses the range closest to the toe of the slope, to generate the slip surface starting points.

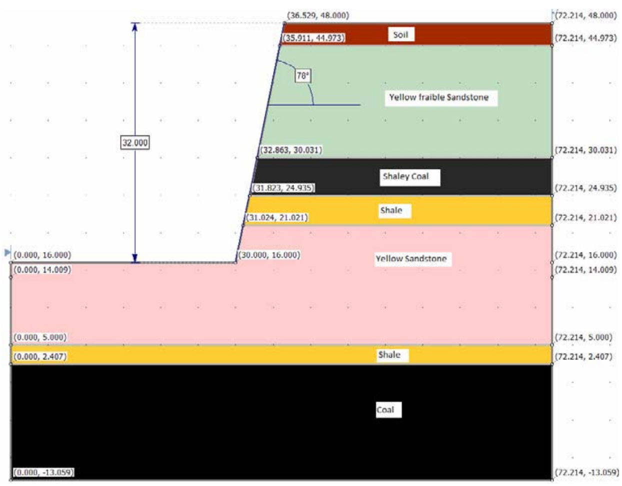
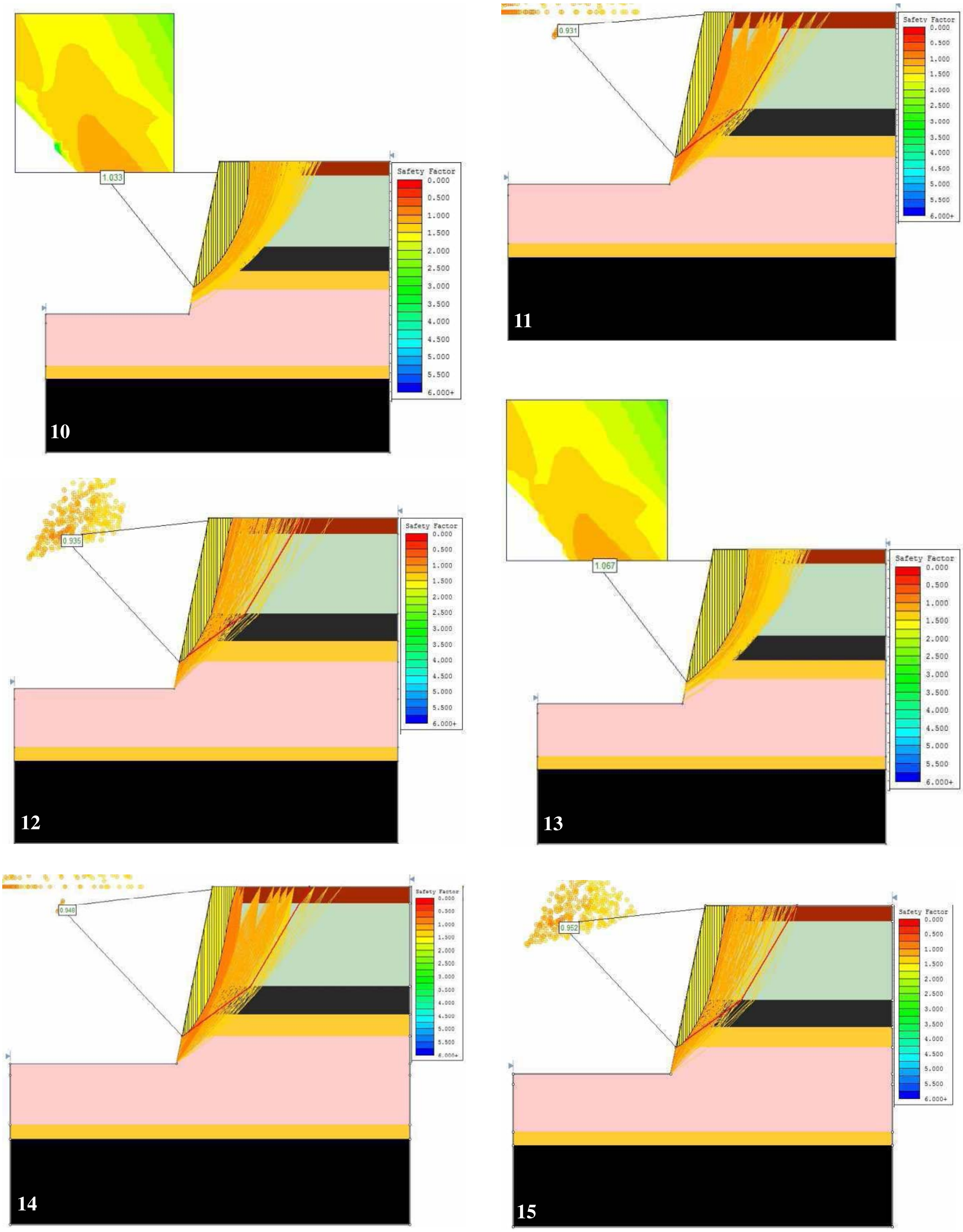


Fig.9. 2-D model for the analysis of the cut slope.



Figs10-15. An analyzed cut slope: **(10)** Bishop's method, circular slip surface). **(11)** Bishop's method, auto slip surface. **(12)** Simplified Bishop's method, path slip surface. **(13)** Corrected Janbu's method, circular slip surface. **(14)** Corrected Janbu's method, auto slip surface. **(15)** Corrected Janbu's method, path slip surface

Table 3. FOS obtained through different methods for the cut slope

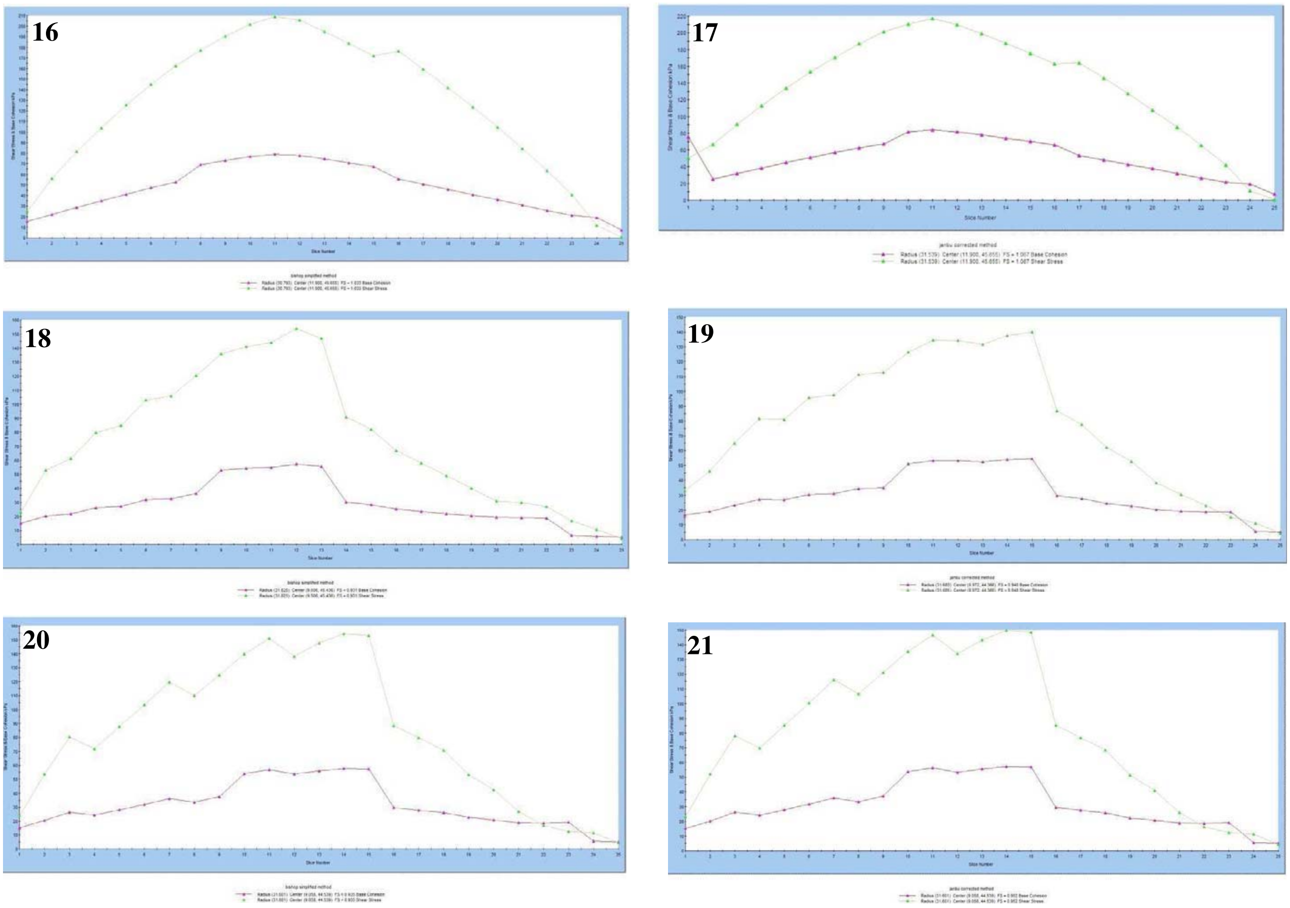
Method	Computed FOS	Remarks
Bishop Circular	1.033	Critically Stable
Janbu-corrected Circular	1.067	Critically Stable
Bishop non-circular (auto)	0.931	Unstable
Janbu-corrected non-circular (auto)	0.944	Unstable
Bishop non-circular (path)	0.935	Unstable
Janbu-corrected non-circular (path)	0.952	Unstable

The non-circular slip surface criterion was also used in the auto search mode in which the slope surface, as defined by the slope limits, is divided into a number of divisions, according to the value of the divisions along slope. Circles are then generated between each pair of divisions, according to the value of the circles per division. The safety factors are then calculated for these circles, and the average safety factor associated with each division along the slope, is recorded (Rocscience, 2010). A two dimensional model including the varied lithologies, thickness and slope inclination, was simulated for the stability assessment of the studied cut slope (Fig.9).

The slope was analyzed using the estimated and measured geotechnical properties (Table 2). The analysis was first carried out with Bishop's method circular slip surface, which gave a FOS of 1.033 (Fig.10). The analysis was carried to adopt the auto refine and path search slip surface criteria which gave a FOS of 0.931 and 0.935 respectively (Figs. 11 and 12). The slope was also examined using corrected Janbu's method for refinement and better comparison of the results. The bench slope, when using circular failure criterion gave a FOS of 1.067 (Fig.13). Numerically, there was a slight reduction in FOS when the auto refine and path slip surfaces were used for the scrutiny of the slope up to a value of 0.944 and 0.952, respectively, while in the critical observation stable slope became unstable (Figs. 14 and 15).

RESULTS AND DISCUSSION

The analytical results of 2D LEM methods were quite



Figs.16-21. Variation of base cohesion and shear stress w.r.t slices **(16)** Simplified Bishop's method, circular slip surface. **(17)** corrected Janbu's method, circular slip surface. **(18)** Simplified Bishop's method, auto refine slip surface. **(19)** corrected Janbu's method, auto refine slip surface. **(20)** Simplified Bishop's method, path slip surface. **(21)** corrected Janbu's method, path slip surface.

close to each other. The circular slip surface mode for both Bishop's method and Janbu's method gave comparatively higher factor of safety (Table 3) which can be attributed to satisfying the movement equilibrium and overall force equilibrium upto various degrees. The variation in FOS has ranged from 3% to 12%. A maximum shear stress of 209 KPa at the shaley coal had developed, using the both the simplified Bishop's method and corrected Janbu's method in circular failure mode giving a FOS of 1.033 and 1.067, respectively. The maximum base cohesion of 77 KPa had generated along the global minimum factor of safety surface in corrected Janbu's method while only 15 KPa had been generated in simplified Bishop's method using the same slip surface mode (Figs. 16 and 17).

A maximum shear stress of 155 KPa had developed along the failure surface from simplified Bishop's method in auto refine slip search mode, whereas only 148 KPa had been recorded in corrected Janbu's method. The base cohesion calculated along the slip surface had been almost similar when using auto refine path mode for both the methods (Figs. 18 and 19).

In path search mode, the shear stress generated along the failure surface was higher by 5 KPa from simplified Bishop's method compared to Janbu's corrected method (Figs. 20 and 21). The base cohesion in both the cases was identical.

The 2D analysis has given the factor of safety in a close range with minimum FOS of 0.931 to a maximum FOS of 1.067. The analysis has rendered the cut slope, unstable to very critical which can be exemplified from incessant spalling of the rock pieces from the cut slope.

CONCLUSION

The 32 m high, open cut slope from an opencast mine of WVC was analyzed for stability and safety using the limit equilibrium analysis under different calculation methods and different slip surface search modes. The analysis has shown that the cut slope is in a very critical state. The FOS has varied in a very narrow range, mean FOS being 0.977. The analysis has also shed light on the varied shear stress generation for the FOS calculation using the simplified Bishop's method and corrected Janbu's method. The shear stress generated in the former method has been higher compared to the latter method. The present study indicates that the slope requires immediate treatment to ensure long term stability, productivity and excavability of the mines.

Acknowledgements: The authors are indebted to Prof. S S Gupte and admistration of Western Colafields Limited, India for their assistance to carry out the field work. The views expressed in the paper are solely of authors'.

References

Barton, N., Lien, R. and Lunde, J. (1974) Engineering classification of rock masses for the design of tunnel support. Rock Mechanics, v.6(4), pp.189-236.

Bieniawski, Z.T. (1989) Engineering Rock Mass classifications: a complete manual for engineers and geologists in mining, civil and petroleum engineering, Wiley, New York, 251p.

Bishop, A.W. (1955) The use of the slip circle in the stability analysis of slopes. Geotechnique, v.5, pp.7-17.

Brawner, C.O., Pentz, D.L. and Compbell, D.B. (1975) Ground Stability in surface coal mines. Mining Congress Jour. v.61(6), pp.42-53.

Brawner, C.O. (1978) Stability in open pit and strip mining coal project, 1st International Symposium Stability in coal mining. Vancouver, pp.13-28.

Coates, D.F. (1964) Classification of rock for rock mechanics. Internat. Jour. Rock Mechanics & Mining Sci., v.1, pp.421-429.

Du Plessis, L. and Martin, D.C. (1991) Numerical modelling studies for design of high rock slopes at Palabora Copper Mine, Proceeding. 7th International Congress. International Society Rock Mechanics. Aachen, v.1, pp.799-804.

Goodman, R.E. (1989) Introduction to Rock Mechanics. 2nd edition. Wiley, New York, 562p.

Gupta, K.K. and Singh, D.P. (1985) Input parameters for rock slope design in open cast mine, 3rd Rock Mechanics Symposium. Roorkee, pp.27-37.

Hoek, E. and Bray, J.W. (1981) Rock Slope Engineering, 3rd ed. Institute of Mining and Metallurgy, London, 358p.

Hoek, E. and Brown, E.T. (1998) Practical estimates of rock mass strength. Internat. Jour. Rock Mechanics & Mining Sci., v.34, pp.1165-1186.

Hoek, E. and Karzulovic, A. (2000) Rock mass properties for surface mines. *In:* McCarter and Van Zyl (Eds.), Slope Stability in Surface Mining, Hustrulid, SME, Colorado, pp.59-70.

Hoek, E., Marinos, P. and Benissi, M. (1998) Applicability of the geological strength index (GSI) classification for very weak and sheared rock masses. The case of the Athens Schist Formation. Earth Environ. Sci. Bull. Engg. Geol. Environ., v.57(2),pp.151-160.

Janbu, N. (1954) Application of composite slip surface for stability analysis. *In:* Proc. European Conf. Stability of Earth Slopes, Stockholm, Sweden, pp.43-49.

Janbu, N. (1968) Slope stability computations. Institute for Geotknikk og Fundamenteringslære, Norges Tekniske Høgskole, Soils Mechanics and Foundation Engineering, the Technical University of Norway.

JHANWAR, J.C., CHAKRABORTY, A.K. and THOTE, N.R. (2008) Investigation into the slope failure in an opencast coal mine—a case study. *In:* M.K. Mishra and H.B. Sahu (Eds.), Proceedings of Conference on Emerging Trends in Mining and Allied Industries. NIT Rourkela, pp.137-143.

JHANWAR, J.C., SAINI, G.S. and JETHWA, J.L. (1996) Ground movement monitoring and stability assessment for a coal handling plant and workings of an opencast coal mine—a case study. *In:* R. Nath and B.P. Pandey (Eds.), Proceedings of National Conference on Ground Control in Mining. BHU-Varanasi, pp.433-444.

JHANWAR, J.C. and THOTE, N.R. (2010) Investigation into slope failure in an opencast coal mine of Wardha Valley Coalfield—a case study. Indian Mining Engg. Jour., v.49(4), pp.36-40.

JHANWAR, J. C. and THOTE, N. R. (2011) Slope Failures in the Opencast Coal Mines of Wardha Valley Coalfield in Central India: A Study, Rock Mechanics & Rock Engineering. DOI 10.1007/s00603-011-0139-4.

MONJEZI, M. and SINGH, T.N. (2000) Slope instability in an open cast mine. Coal International, pp.145-147.

OZTEKIN B., TOPAL T. and KOLAT, C. (2006) Assessment of degradation and stability of a cut slope in limestone. Ankara-Turkey. Engg. Geol., v.84(1-2), pp.12-30.

PETTIFER, G.S. and FOOKES, P.G. (1994) A revision of the graphical method for assessing the excavatability of rock. Quart. Jour. Engg. Geol., v.27, pp.145-164.

ROCSCIENCE, (2002) RocLab–Rock mass strength analysis using the Hoek-Brown failure criterion.

ROCSCIENCE, (2010) Slide 6.0 (http://www.rocscience.com)

SARKAR, K. and SINGH, T.N. (2007) Evaluation of Instability Analysis of Slope – A Numerical Approach, Mining Engg. Jour., v.8(10), pp.11-31.

SINGH, P.K. and SINGH, T.N. (1996) Prediction of slope of open cast mine situated in fault rock mass by equivalent material modeling, 2nd National conference on Ground control in mining. India, pp.39-47.

SINGH, T.N., SHARMA, P.K. and PANDEY, V. (2007) Numerical Approach for Evaluation of Instability of Slopes. International conference on Regional Rock Mechanics Symposium, Sri Lanka, pp.1-5.

SINGH, T.N., ULABHAJE, A.V., SINGH, D.P. and GUPTA, K.K. (1989) Planning of slope stability in opencast mine- A model study, 3rd National Seminar on Surface Mining. Indian Mining & Engineering Jour., Dhanbad, pp.5.2.1-5.2.10.

SINGH, V.K. and DHAR, B.B. (1994) Stability analysis of open-pit copper mine by use of numerical modelling methods, Trans. Institute of Mining and Metallurgical (Section A: Min. Industry), v.103, pp.A67-A74.

SINGH, V.K., PRASAD, M., SINGH, S.K., RAS, D.G. and SINGH, U.K. (1995) Slope design based on geotechnical study and numerical modelling of a deep open pit mine in India, Internat. Jour. Surface Mining, Reclamation and Environ., v.9, pp.105-111.

(Received: 9 June 2011; Revised form accepted: 9 May 2012)