CHEMICAL ENGINEERING TRANSACTIONS
VOL. 66, 2018

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Songying Zhao, Yougang Sun, Ye Zhou

ISBN 978-88-95608-63-1; **ISSN** 2283-9216
DOI: 10.3303/CET1866206

A Critical Review of Stability Analysis and Design of Pit Slopes in Indian Opencast Coal Mines

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The design of the optimum pit slope is one of the major challenges in Indian opencast coal mines. The aim of open cast mines should be to attain steepest possible slope angle without compromising safety in order to maximize profits. The important factors like geology, groundwater and slope angle play a critical role in the stability and behaviour of pit slopes in Indian opencast coal mines. Although mining engineers have long recognized the importance of these factors, it remains a significant challenge to integrate stability analysis and design of pit slopes into opencast mining operations during the entire life cycle of the project. This paper emphasizes the importance of these factors to slope stability assessments, reviewing how they control slope failure mechanisms, how mining engineers measure and include them in slope stability analyses, and how numerical simulations of slopes incorporate these parameters.

1. Introduction

In mining, open pits account for the major portion of the world's mineral production. Opencast mining is a very cost-effective mining method allowing a high grade of mechanization and large production volumes. The benefit of opencast mining largely depends upon steepness and stability of the pit slopes which should not fail during the life of the mine. In India, fast increase in output of various minerals can be largely attributed to rapid increase in opencast mining activities and intensified mechanization. This has resulted in the opencast mines going deeper day by day with the maximum stripping ratio being planned currently looking upto 1:15, at a depth of about 500 m. As a direct consequence, the amount of waste mining and dumping will also be commensurately very high thereby increasing the risks of highwall slope failures tremendously. Under such situations, with most production areas concentrated close to the excavation floor, there is a constant danger to the men and machinery deployed thereat with a potential to cause catastrophic loss of life and property. An analysis of the accidents in opencast mines revealed that slope failures have started assuming an upward trend in the recent times (DGMS Report, 2010).

The Indian Opencast Coal Mining Industry has experienced the pit slope failures at Dorli OC- I of M/s SCCL, SRP OC-I of M/s SCCL, GK OCP of M/s SCCL, RKP OCP of M/s SCCL, KTK OC sector-I of M/s SCCL and Kawadi OCP of M/s WCL. So, The Indian Coal Mining Industry has identified stability analysis and design of pit slopes as one of the thrust areas.

(1) Concept of Slope Stability

Unlike slopes in civil engineering, open pit slopes are typically designed with a lower factor of safety due to their reduced operating life span and a high level of monitoring provided by the mine. The benefits of steepening the slope angle are, however, counteracted by increased operational risks arising due to the reduced slope stability. So, the design engineer is faced with the two opposite requirements, stability and steepness, in designing the open pit slopes. Many slope failure incidents in Indian mines have taken place due to uneconomic and lack of sound design of slopes.

So, Slope stability is the greatest problem faced in the open cast mining, the scale of which is divided into two types:

Please cite this article as: Satyanarayana I., Sinha A.K., 2018, A critical review of stability analysis and design of pit slopes in indian opencast coal mines, Chemical Engineering Transactions, 66, 1231-1236 DOI:10.3303/CET1866206

(2) Gross stability problem: It refer to large volumes of materials which come down the slopes due to large rotational type of shear failure and it involves deeply weathered rock and soil (Fig.1). In India, regional failure of coal benches occurred at Jayanth Open cast Project, M/s NCL and Umrer Opencast Project, M/s WCL.

Figure 1: Regional Failure of benches at Umrer OCP, M/s WCL

(3) Local stability problem: This problem which refers to much smaller volume of material and these types of failure effect one or two benches at a time due to shear plane jointing and slope erosion due to surface drainage. Most of the pit slope failures occurred are local in nature. One example of bench failure at Dorli OCP-I, M/s SCCL is given in the following figure (Fig.2).

Figure 2: Local Failure of bench at Dorli OCP-I, M/s SCCL

2. Types of Slope Failure

Most of the geotechnical failures take place over a period of time, and can produce sufficient warning signs before the catastrophic failure. The failure process starts with a failure initiation phase, progresses through a propagation phase, and ends in the rock mass collapse. The sequence of rock mass behaviour leading to the regional failure is shown in Fig. 3.

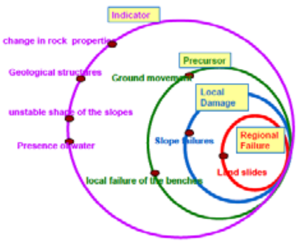

Figure 3: Sequence of rock mass behaviour leading to the regional failure

Rock being the stronger material does not fail in circular path rather rock slope does fail in the presence of weak strata like soil, clay, etc. and structural discontinuities like faults, joints, etc. Most of the cases, a tension crack on the crest of the slope and undrained conditions causes plane sliding along a joint or fracture plane. Based on the failure mode, slope failure has classified into main four topics. Circular failure is the basic mode of slope instability in weathered slope material, whereas plane - wedge - toppling failures occur in the hard rock mass.

3. Effects of geology, groundwater and slope angle on pit slope stability

Slopes need to be engineered considering the factors that influence slope design like depth of the pit, slope angle, geology, rock strength, ground water pressures, etc. (Tripathy et. al., 2010). The difficulty in determining the optimum pit slope design stems from the existence of uncertainties associated with the stability of the slopes. Table 1 summarizes the main sources of uncertainty in pit slopes. These uncertainties are accounted for during the process of design of the slopes.

Table 1: Main sources of uncertainty in pit slopes

Slope Aspect	***Source of Uncertainty***
Geometry	*Pit Slope Angle, Depth*
Geology	*Cohesion, Friction Angle, and density of different types of strata and structural discontinuities*
Groundwater	*Rainfall and Water table*

Design of slopes must be optimized in open pit mines with a well-oriented methodology, especially when the experience clearly shows that the rock mass is characterized uniquely by its geological structure, and therefore there exists no standard principle that can achieve the correct solution with certainty (Fleurisson, 2012).

The effect of water on the slope can be considered into two fold. One is groundwater below the surface that generates porewater pressure and the other is rainwater infiltration that seeps through surface and flows along the slope generating water pressure. Ground Water alters the cohesion and frictional parameters and reduce the normal effective stress. Therefore, the assessment of the effect of groundwater on stability of rock slopes is a critical component of open pit design and operation (Naghadehi et. al.2013). It is related to the surrounding precipitation levels, topography, nearby water masses, and the geo-hydrological characteristics of the rock mass (Sjöberg, 1999). The effect of ground water present within the rockmass surrounding an open pit can be detrimental to the stability of the slope (Hoek and Bray, 1981). Therefore, it is expedient to constantly monitor groundwater levels as well as pore pressure to assist in the assessment of slope stability (Ding et al. 1998). Piezometers are important for monitoring the effectiveness of mine dewatering programmes (Girard and McHugh, 2000). Measurement or calculation of water pressure is an integral part of site investigation for slope stability studies. Information on water pressures is essential for designing and maintaining safe slopes (Girard, et al. 1998). The water table or the phreatic surface will change constantly depending upon the development of the excavation (Morgenstern, 1971; Sharp et al., 1977). Erosion brought about by flowing water could also result in reduced strength (Morgenstern, 1971; Sage, 1976; Sharp et al., 1977; Hoek and Bray, 1981). Engineering judgments must be based on assessing the results of analyses considering acceptable risk or safety factors (Abramson et al., 2001).

4. Pit slope failures-case studies

Although, various researchers have investigated numerous ways of predicting the mechanism of failure of mine slopes, there is still no universally acceptable model for failure, and the mechanisms behind large scale failure are not well known, particularly in hard and strong rocks (Read et al., 2009). Consequently, proper understanding of the peculiarity of each rock formation and the underlying mechanisms driving instability is essential in analysing and predicting deformation and failure mechanisms.

4.1 Case Study-1: Dorli opencast project-I (Dorli OCP-I)

The Dorli opencast project-I (Dorli OCP-I) of M/s Singareni Collieries Company Limited (SCCL) is located in North western extremity of Godavari valley coalfield. A satellite view of the plan of mine area of Dorli OCP-I and boreholes section are shown in Fig.4 which depicts configuration of benches in Dorli OCP-I and weak strata.

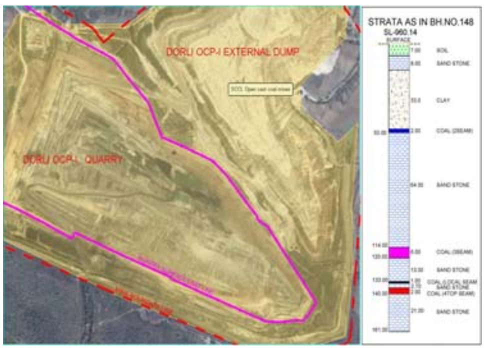

Figure 4: A borehole section and satellite view of the plan of mine area of Dorli OCP-I

The mine is operating at rated capacity of 2.0 MTPA (Million Tonnes Per Annum). The mining technology adopted in this mine under prevailing geo-mining conditions is shovel-dumper technology. The surface RL of the mine is 960 RL. The pit bottom RL of the mine is 840 RL. There are fourteen benches on dip side. The height of slope on dipside of the mine is 120m. The top four benches in loose strata are 5m high whereas the remaining 10 benches are 10m high with overall pit slope angle of 45^0. The average rainfall at this mine was about 1160 mm.

As the area is hilly and no seepage holes were drilled to drain-out water from the slope, the water table got charged near to surface due to continuous rainfall. Due to increase in water table and flow of rain water over the benches, the soil and clay at the crest of the pit became soft with the passage of time and the strata were weathered. During visual monitoring of slope, it was observed that there was no displacement of slope before 04.06.2014. A small tension crack was observed from 04.06.2014 at a distance of around 40m from crest of the pit on dip side due to continuous rainfall (273mm) for eleven days (Stage-I) (Fig.5, Fig. 6 & Fig. 7). There was no drainage system to divert rain water and the slope material got weathered and became soft. Gullies were formed along the benches due to flow of rain water and ultimately, water was accumulated at pit bottom (Fig. 6). The total station was positioned at a fixed point and measured displacement of the crack with the help of monitoring stations. Daily monitoring of the crack was being carried out.

On 17.06.2014, there was again a heavy rain fall recorded i.e. 68 mm at this mine (Stage-II) (Fig.5 & Fig. 7). The maximum portion of strata from surface (960 RL) to 50m depth (910 RL) consist of soil and clay (Fig.8). The vertical and horizontal displacements recorded by total station were 0.609m and 0.225m respectively due to erosion of weak strata by rain water (Stage-II) (Fig.9 & Fig.10). The measured length of the tension crack was about 400m. During the month of June 2014, the rainfall recorded at this mine was about 249mm which severely caused the weathering of weak strata in slope. Due to the flow of rain water into the crack, it got widened and deepened by eroding soil and clay. The vertical and horizontal displacements recorded were 0.812m and 0.382m respectively on 28.06.2014 due to erosion caused by rain fall of 36mm (Stage-III) (Fig. 5, Fig. 6 & Fig. 7). The effects of rainfall and progressive widening and deepening of crack in the remaining stages (stage IV to stage VI and final stage) are represented in Fig. 5, Fig. 6 & Fig. 7. The average rainfall recorded from the month of May 2014 to October 2014 was about 1160 mm which was very high. As the area is hilly and there was no drainage system or seepage holes to drain rain water away from the mine, the water table got charged near to surface. Due to increase in groundwater pressure and flow of rain water over the benches, the soil and clay in the slope were eroded with the passage of time. Subsequently, the crack was progressively got deepened and widened. The variation of vertical and horizontal displacements of tension crack with time is shown in Fig.9. The visual representation of different stages of deepening and widening of tension crack is shown in Fig.10. Due to the rainfall (41mm) on 13.10.2014, the crack was got displaced by 2.765m horizontally and 5.24m vertically. As a result, all the seven benches consisting of soil and clay from surface to 50m deep were collapsed and the bottom benches from 910 RL to pit bottom (840RL) were merged with the loose material of soil and clay (Fig.6). After collapse, the monitoring stations got disturbed. The rainwater flow channels are also observed near the failed zone. The rainwater of the adjacent catchments was infiltrating down below, which must have caused increase in hydrostatic pressure behind the weak slope mass. Fig. 7 shows the daily and total recorded precipitation as a function of the time elapsed during the monitoring period. In particular, daily average rainfall amounts of 25mm were recorded on ten days before the onset of tension crack on 04.06.2014 and the maximum daily rainfall was 114 mm on 06.09.2014 due to which the crack was widened and deepened extensively.

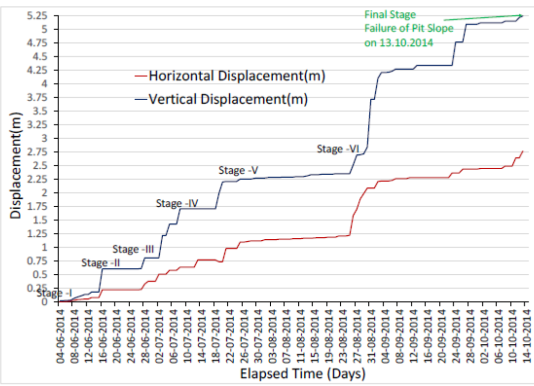

Figure 5: Variation of vertical and horizontal displacements of tension crack with time monitored by total station

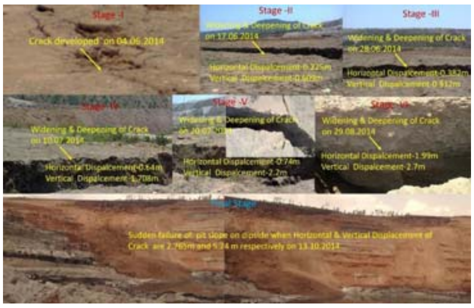

Figure 6: Photographs depicting different stages of deepening and widening of tension crack at Dorli OCP-I

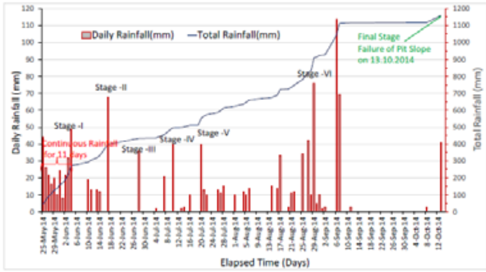

Figure 7: Photograph depicting formation of gullies due to rain water and its accumulation at pit bottom

Similar failure was occurred in 170m pit slope of Medapalli opencast project of M/s SCCL on 19.09.2015 (Fig.8) and 150m pit slope of Goutham Khani Opencast Project of M/s SCCL on 31.07.2012 (Fig. 9) in India.

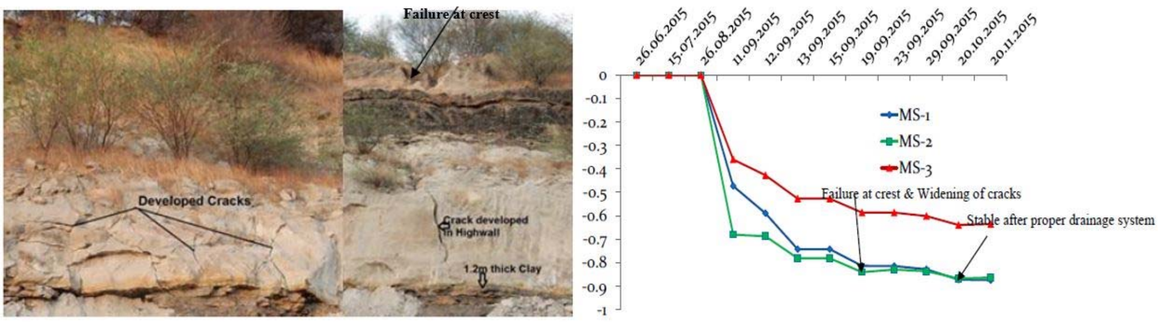

Figure 8: Photograph depicting failure and displacement in Medapalli opencast project

Figure 9: Photograph depicting failure and displacement in Goutham Khani Opencast Project

Based on slope profile, field observations and previous experiences of slope failures, it is found that slope angle, groundwater, weak strata like soil, and clay, and rainfall are the major influencing parameters for causing failure of pit slope at this mine.

5. Conclusions

An analysis of the accidents in opencast mines revealed that slope failures have started assuming an upward trend in the recent times. Mining depths in open pits are steadily increasing from time to time which has the increased risk of large scale slope failures. The case studies on the slope stability indicated that most of the slope failures occurred due to poor strata, structural discontinuities, improper design of pit slope angle and groundwater pressures.

The slope stability analysis and slope monitoring studies are not yet included as an integral part of the optimum pit design in India. The subject gets significant importance only when slope failure takes place putting in danger the entire mining activities or when a failure is imminent. Till date, most of the design methods are purely based on field experience and thumb rules followed by sound engineering judgment.

The most common method of evaluation of pit slope angle and groundwater in open cast mines is based on calculating factor of safety and comparing these results to defined acceptability criteria, thus reaching an acceptable slope angle design. These acceptability criteria are intended to ensure that the slope will be stable enough to have a safe mining operation. Till now, general guidelines are not developed for acceptable value of FOS for pit slope design in India.

Therefore, there is urgent need for stability analysis and scientific design of pit slopes in India and continuous intensive slope monitoring to detect any instability well in advance. Efforts should be made by statutory bodies to have more application of numerical modelling in this field to make slope analysis and design scientific. Based on these studies, the guidelines and acceptability criteria for acceptable value of FOS should be developed.

Acknowledgements

The authors are obliged to Director General, DGMS for his permission to present this paper. The authors are indebted to the CGM (R&D), the top management of M/s SCCL, and CIMFR, for providing the necessary data required for this manuscript. The views expressed in this paper are those of the authors and not necessarily of the institute to which they belong and also express their sincere gratitude to all those who help directly or indirectly in preparing this manuscript. The work reported in this paper forms the part of PhD work of the first author.

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