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Stability evaluation of highwall slope in an opencast coal mine – a case study

The stability analysis of slopes is an integral part of the opencast and highwall mining operations during the entire life cycle of the project. 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 up to 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 and dump failures tremendously. Safe, properly designed, and scientifically engineered slope is essential for economic, safe and successful operation of opencast mine. Engineering of safe and stable slopes is of significant importance and is normally carried out by empirical, observational or analytical techniques. While less than 3% of mine accidents are associated with slope stability problems, slope failure accidents were responsible for more unproductive work, loss of equipment and poor economic performance. Massive highwall failures containing a million cubic metres of material or more can be dangerous for heavy-equipment and persons working over there. Several remote sensing technologies are being evaluated as tools to monitor slope stability to assess hazards in advance. This paper makes an attempt to review the important factors affecting slope stability and analyze stability of slopes with a case study from the Singareni Collieries Company Limited (SCCL).

Keywords: *Shear strength, slope failure, failure analysis, numerical modelling, monitoring, safety factor.*

1. Introduction

The design, analysis, monitoring, and stabilization of slopes are integral part of the opencast and highwall mining operations during the entire life cycle of the project. Safe, properly designed, and scientifically engineered slope is essential for economic, safe and successful operation of opencast mine. Engineering of safe and stable slope is of significant importance and is normally carried out by empirical, observational or analytical techniques. Engineering judgments must be based on assessing the results of analyses considering acceptable risk or safety factors (Abramson et al., 2001).

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. 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 up to 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 there 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 upwards trend in the recent times (DGMS Report, 2010). Therefore, the evaluation of the stability of rock slopes is a critical component of open pit design and operation (Naghadehi et al.2013).

Mining depths in open pits are steadily increasing from time to time which has the increased risk of large scale slope failures. Since it is impossible to maintain stable vertical slopes, the pit slopes must thus be inclined to prevent failure. With the increasing depths of open pit and opencast mines, design of opencast slope angles and prediction of the behaviour of the rock mass is necessary in order to design mine slopes that are safe, both for the workers and the equipment. Small changes in the overall pit slope angle have significant influence on the overall economy of the mining operation.

The Indian coal mining industry has experienced the pit slope failures at Dorli OC-I; SRP OC-I; Medipalli OCP; KTK

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TABLE 1: ACCIDENTS DUE TO SLOPE FAILURE IN INDIAN OPENCAST COAL MINES (DGMS REPORT, 2016)

Year	State	Name of mine	Name of company	Date of accident	No of persons killed	No. of persons seriously injured
2007	Jharkhand	Chasnalla	IISCO	21-Aug 07	1	0
2008	Madhya Pradesh	Jayant colliery	NCL	17-Dec 08	5	0
2009	Maharashtra	Sasti OCP	WCL	04-Jun-09	2	0
2010	Maharashtra	Umrer OCP	WCL	28-Sep 10	1	1
2011	Jharkhand	Chasnalla	IISCO	9-Mar-11	1	1
2011	West Bengal	Dalurband OCP	ECL	14-Jun-11	1	0
2013	Odisha	Bharatpur OCP	MCL	21-Apr-13	1	1
2013	Odisha	Kulda OCP	MCL	10-Aug 13	13	0
2014	Madhya Pradesh	Dhanpuri OCP	SECL	01-Jul-14	2	0
2015	NIL					
2016	Jharkhand	Rajmahal OCP	ECL	29-Dec-16	23	0

OC sector-I of SCCL and Kawadi OCP of WCL. The Indian coal mining industry is moving towards deeper opencast mines up to a depth of around 500m like Manuguru OC-II extension and RG OC-II extension. In India, a lot of accidents have occurred due to slope failure (Table 1). So, the Indian coal mining industry has identified slope design, monitoring and stabilization as one of the thrust areas.

The main components of an open pit slope design (Fig.1) are: (1) The over-all pit slope angle from crest to toe (floor), incorporating all ramps and benches, (2) The inter-ramp angle lying between each ramp that depends on the number of ramps and their widths. (3) The face angle of individual benches depends on vertical spacing between benches, or combined multiple benches, and the width of benches required to contain minor rock falls (Hoek, E.,et.al, 2004). The overall slope angles for these pits range from near vertical for shallow pits in good quality rock to flatter than 30º for those in very poor quality rock.

Slopes need to be engineered considering the factors that influence slope design like depth of the pit, geology, rock strength, groundwater pressures and blasting. An understanding of geology, hydrology, and soil properties is essential to apply slope stability principles properly. In Indian mining conditions, slope design guidelines are yet to be formulated for different types of mining practices and there is a growing need to develop such guidelines for maintaining safety and productivity. Till date, most of the design methods are purely based on field experience, thumb rules followed by sound engineering judgment.

The monitoring, analysis and stabilization of slope is an integral part of the opencast and highwall mining operations during the entire life cycle of the project. Analyses must be based upon a model that accurately represents site sub-surface conditions, ground behaviour, and applied loads.

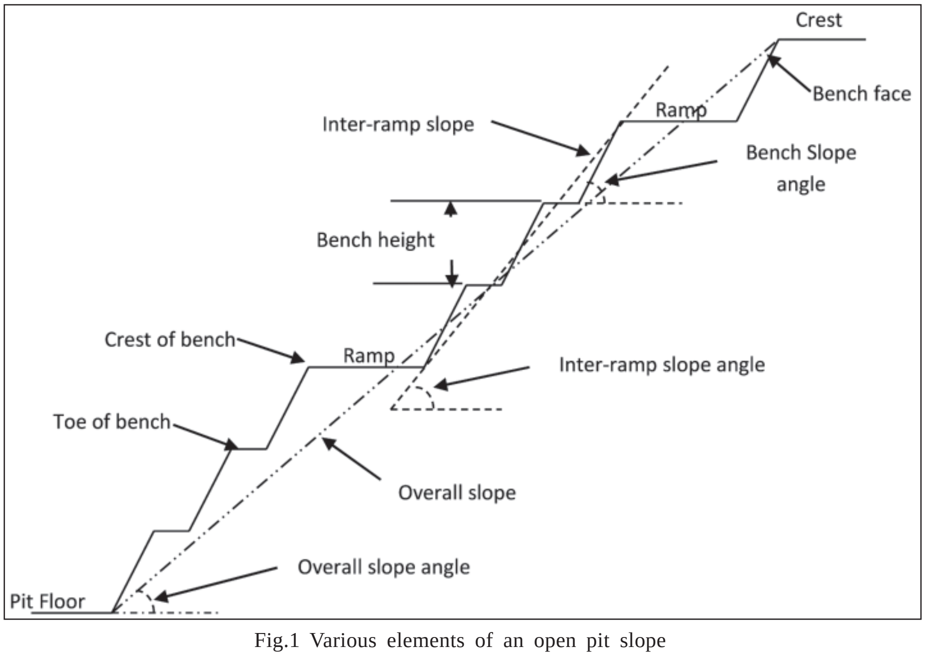

Fig.1 Various elements of an open pit slope

2. 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. This allows for steeper slope angles which provide an increased cost/benefit ratio by reducing the amount of waste stripping required and maximizing coal recovery. The benefits of steepening the slope angle are, however, counteracted by increased

Fig.2 Regional failure of benches at Umrer OCP, WCL

Fig.3 Local failure of bench at Dorli OCP-I, SCCL

operational risks arising due to the reduced slope stability. The Directorate General of Mines Safety may even close the quarry, in case unsafe conditions are created. Therefore, it is necessary that a balance between economics and safety should be achieved.

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

GROSS STABILITY PROBLEM

It refers 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.2). In India, regional failure of coal benches occurred at Jayanth opencast project of NCL and Umrer opencast project of WCL.

TABLE 2: MINE SLOPE DESIGN AND ACCEPTANCE CRITERIA (READ AND STACEY, 2009).

Slope scale	Consequences of failure	Acceptances criteria
		FOS (min) (static)
Bench	Low to high	1.1
Inter ramp	Low	1.15-1.2
	Medium	1.2
	High	1.2-1.3
Overall	Low	1.2-1.3
	Medium	1.3
	High	1.3-1.5

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, 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 of SCCL is given in Fig.3.

A general guidance to pit slope design acceptance criteria is summarized below (after Read and Stacey, 2009) and suggested FOS target for the case study presented in this paper is highlighted in Table 2.

3. Analysis of highwall slope failure – case study

3.1 LOCATION OF THE MINE

The Medipalli opencast project (MOCP) block is on the southern bank of river Godavari towards the north-west of the existing Godavarikhani group of mines. The block covers an area of about 3.86 sq.km lying between north latitudes 18°47'00" to 18°49'30" and east longitudes 79°28'00" to 79°30'00" in the Survey of Indian Toposheet Nos. 56-N/S and N/9 (Fig.1). The block boundaries are:

North and north-east	:	Godavari river
West	:	Boundary fault F2-F2
North-west	:	Boundary fault F2A-F2A
South-east	:	FCI reservoir.
North	:	Intake well of NTPC

The block is situated in the well-developed industrial area of Ramagundam. The nearest railhead is Ramagundam railway station, which is 6 km away. The subsurface data reveal that the Gondwana sediments rest unconformity over the basement rocks of Protozoic age namely the Sullavai group of sequence. The general trend of the coal measures is NW-SE with northeasterly dips which are in conformity with regional trend. The estimated geological reserves in Medipalli block is 68.05 Mt. The total mineable reserve including proposed highwall mining is 61.21Mt. From the start of the mine (1994 till March 2016) 20.75 Mt. of coal has been mined.142.26 M.Cum of overburden has been removed with average stripping ratio of 1: 5.50. The mine is being worked by shovel dumper combination with targeted production of 4.09 Mt. during financial year 2016-17.

3.2 GEOLOGY OF THE MINE

A total of 153 boreholes were drilled in the block with a cumulative meterage of 14472.03 m. The density of boreholes is 32.95 per sq. km which includes boreholes drilled for piezometric studies, evaluation of soil properties for bund construction and for assessment of quality. The sub surface data reveals that the Gondwana sediments rest unconformably over the basement rocks of Proterozoic age namely the sullavai group of sequence. The general trend of the coal measures is NW-SE with northeasterly dips which

TABLE 3: THE STRATIGRAPHIC SEQUENCE IN MEDIPALLI OCP

Age	Group	Formation	General lithology	Maximum thickness (m)
Recent			Soil cover and alluvium	18.29
Permian	Lower Gondwana	Barren measures	Coarse to pebbly felspathic sandstones with clays	25.91+
		Barakar	Upper member Dominantly sandstone with 8 no. relatable coal seams with clay layers	183.50+
			Lower member Predominantly coarse grained white sandstone	85.28+
		Talcher	Fine to medium grained pale greenish sandstone and green shales	83.40+

are in conformity with regional trend. As the contact between the Talcher formation and the overlying Barakar formation is faulted, the basal coal seam abuts against the Talcher formation. The general strike of the coal seams are NW-SE with gentle northeasterly dips (gradient varying from 1 in 6 to 1 in 10. The stratigraphic sequence in Medipalli OCP is given in Table 2. The borehole section in dipside of the quarry is given in Fig.4.

Design parameters of Medipalli OCP

The physical parameters of the opencast are as follows:

a	Maximum strike length along surface (m)	4290
b	Minimum strike length along surface (m)	3000
c	Maximum width of the quarry along surface (m)	1540
d	Minimum width of the quarry along surface (m)	500
e	Minimum depth of the quarry (m)	18
f	Maximum depth of the quarry (m)	220
g	Floor area of quarry (ha)	235.04
h	Area of excavation on surface (ha)	376.37
i	Total area of quarry (including external dump area and safe barrier around the quarry, embankment and dump) (ha)	1171.55
j	Average gradient of the seam	1 in 6.0 to 1 in 10

Back analysis of the highwall slope

Slope stability analysis is performed to assess the safe design of open pit mining slopes and the equilibrium conditions. The term slope stability may be defined as the

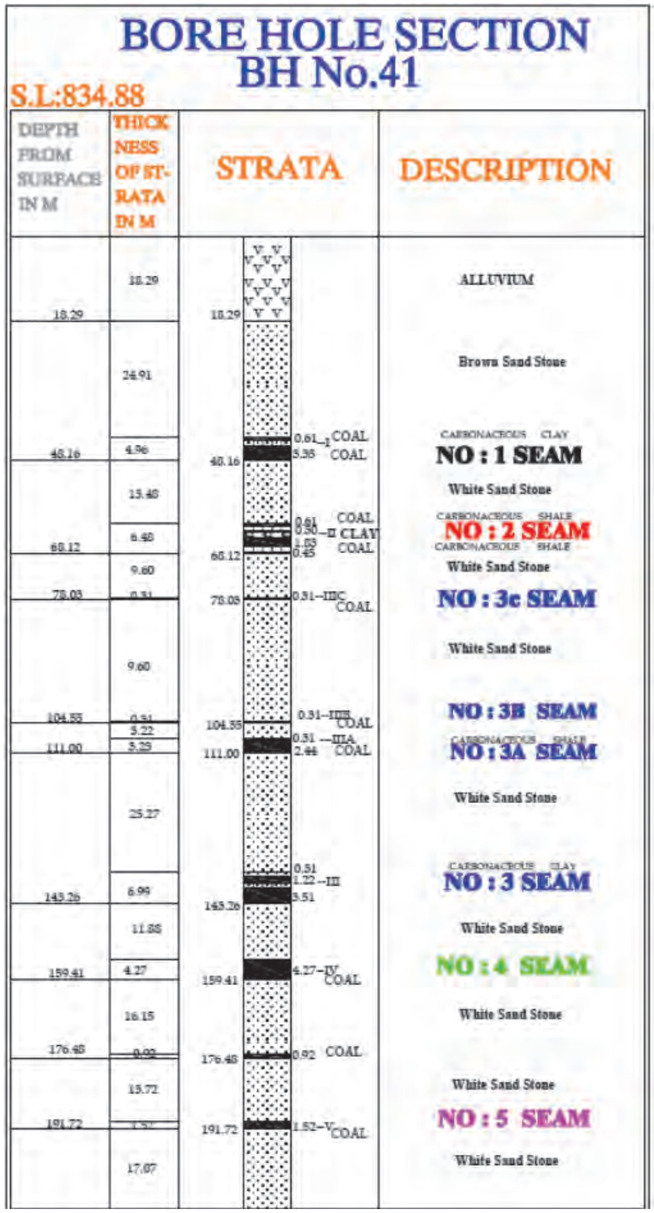

Fig.4 Borehole section in dipside of the quarry

resistance of inclined surface to failure by sliding or collapsing. Successful design of the slope requires geological information and site characteristics, e.g. properties of soil/rock mass, slope geometry, presence of water and groundwater conditions, alternation of materials by faulting, joint or discontinuity systems, movements and tension in joints, dynamic loading due to blasting, earthquake activity etc. The common used methods for slope stability analysis are:

- Limiting equilibrium methods
- Kinematic analysis
- Numerical modelling methods
- Physical modelling methods
- Probabilistic methods
- Back analysis
- Empirical methods
- Artificial neural network application

Choice of correct analysis technique depends on both site conditions and the potential mode of failure, with careful consideration being given to the varying strengths, weaknesses and limitations inherent in each methodology. A slope failure implies that the factor of safety of the slope at the moment of failure is unity. Based on this information, back analysis is often carried out to improve knowledge on slope stability parameters, such as soil/rock shear strength parameters and pore water pressure parameters at the moment of slope failure. Using back analysis, important factors that may not be well represented in laboratory testing, such as soil/rock heterogeneity and influence of fissures and structural fabric on soil/rock shear strength, can be incorporated.

These parameters are collected from the failed slopes and their history for estimating other slopes.

Hydrological conditions and geo-mechanical properties of the highwall slope

The dip side area of Medipalli OCP from bank of the Godavari River is characterized by flat to gently undulating terrain. The surface RL is about 740 mRL. River Godavari forming north-eastern boundary of the OCP. The highest flood level of Godavari river was recorded as to 746.60 mRL during the monsoon of 1983. The river sand bed level is at 735 mRL. The usual water level in rainy season is about 739 mRL. The opencast area is situated on the southern bank of Godavari river. The coal deposit has the in crop almost parallel to the river bank and on the dip side, it extends below the river bed. No fault is reported within the dip side ultimate slope. There is no major drainage course cutting across the area. The general drainage of the area is provided by two Vagus, which join the river Godavari. The drainage of the opencast area will be diverted to these Vagus by cutting drainage channels on the in crop side of the property. The average annual precipitation is 1000 mm.

As the slope mass is not provided with effective drainage system, i.e. in undrained condition, a phreatic surface will most likely develop in the sandstone below topsoil. Large portion of the block is covered under this HFL of the river. Therefore, flood protection bund is constructed around the opencast area to protect the opencast from inundation of floodwater.

The samples were tested to determine density and shear strength parameters. Direct shear tests were conducted on direct shear test machine. In general, the sand stones are white/light grey medium to coarse grained with low strength The final results of slope material in drained and undrained conditions are summarized in Tables 3(a) and 3(b).

The effect of groundwater present within the rock mass 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 pressure is essential for designing and maintaining safe slopes (Girard, et al. 1998). The depths to water table from surface observed in different piezometric wells (hydrogeological report of Medipalli OCP, 2013) are given in Table 4.

TABLE 4(a): GEO-MECHANICAL PROPERTIES OF SLOPE MATERIAL IN DRAINED CONDITION

Slope material	Density (kg/cu.m)	Cohesion (Pa)	Friction angle (degrees)
Black cotton soil	1783.9	28000	18
Silty clay	1732.9	25000	25
Sand	1712.5	5000	33
Sandstone	2222.2	190000	30
Coal	1457.7	272000	28

TABLE 4(b): GEO-MECHANICAL PROPERTIES OF SLOPE MATERIAL IN UNDRAINED CONDITION

Slope material	Density (kg/cu.m)	Cohesion (Pa)	Friction angle (degrees)
Black cotton soil	1896.0	22000	15
Silty clay	1855.2	21000	20
Sand	1967.4	4000	30
Sandstone	2364.9	165000	28
Coal	1529.1	260000	25

Final highwall bench configuration

The final highwall bench configuration on dip side of the Medipalli OCP is given in Table 5.

TABLE 5: HYDROGEOLOGICAL DATA OF WATER TABLE.

Piezometric well no.	Depth to water table from surface (m)
1	237.65
2	220
3	202
4	185
5	171
6	158
7	140
8	117
9	65
10	60

The ultimate slope of 170m highwall of Medipalli OCP towards dip side of the quarry along flood protection bund is given in Fig.5(a) and (b).

Stability analysis of highwall using FLAC/SLOPE

Due to the rapid development of computing efficiency, several numerical methods are gaining increasing popularity in slope stability engineering. The most popular method of slope stability estimation is shear strength reduction technique (SSR). The factor of safety (FS) for slope may be computed by reducing the shear strength of rock or soil in stages, until the slope fails.

As no significant joints were observed during formation of highwall on dip side of Medipalli OCP, the best suited numerical method of analysis for slope stability is continuum modelling. If rock mass of slope can be represented as an equivalent continuum, continuum models should be used to solve these types of problems. Therefore, many analyses begin with continuum models. If the slope under consideration is unstable without structure, there is no point in going to discontinuum models. In continuum models, the displacement field will always be continuous. The location of the failure surface can only be judged by the concentration of shear strain in the model.

The slope can be simulated in 2D or 3D by numerical modelling. It depends on many factors such as time required for simulation, critical parameter, requirement of simulation, field condition and computer configuration. Most design analyses for slopes assume a two-dimensional geometry comprising a unit slice through an infinitely long slope under plane strain conditions, i.e. the radius of both the toe and the crest are assumed to be infinite. However, three-dimensional analyses are required when the direction of major geological discontinuities do not strike within 200-300 of the strike of the slope or the distribution of geomechanical units varies along the strike of the slope. This also becomes necessary when the slope geometry in plan cannot be represented by two-dimensional analysis, which assumes axisymmetric or plain strain condition. As no major discontinuities were observed during formation of highwall in Medipalli OCP, the analysis of highwall slope is done by 2D modelling.

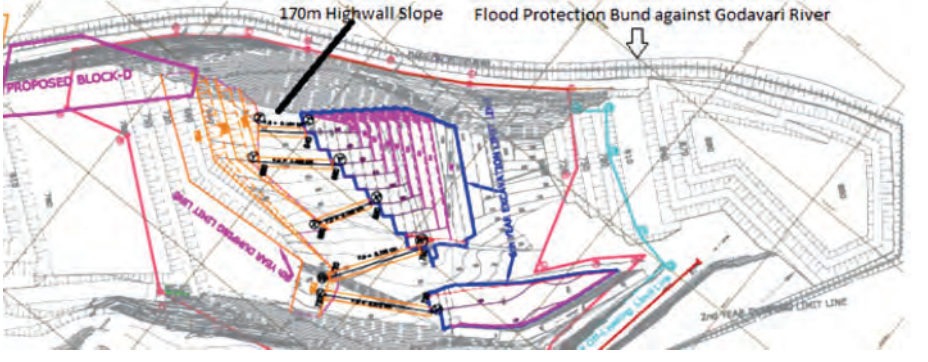

Fig.5(a) Mine plan depicting ultimate slope of 170m highwall of Medipalli OCP

Fig.5(b) Photograph depicting the ultimate slope of 170m highwall of Medipalli OCP

TABLE 6: FINAL HIGH WALL BENCH CONFIGURATION:

Geo mining condition of highwall	Bench parameters			Overall pit slope (degrees)
	Height (m)	Exposed width (m)	Individual bench angle (degrees)	
Black cotton soil, weathered sandstone (top 20 m)	5	5	70	45
Sand stone (remaining 150 m)	10	8	80	

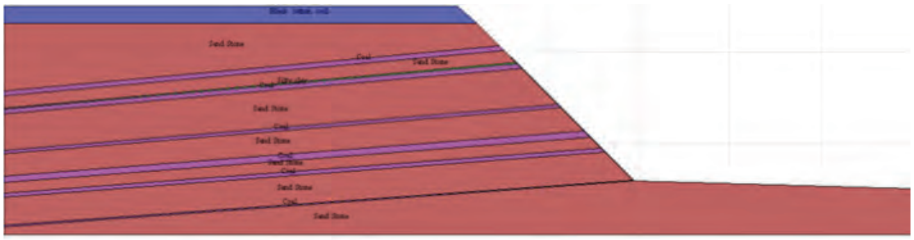

Fig.6(a) Details of modelled geometry in drained condition

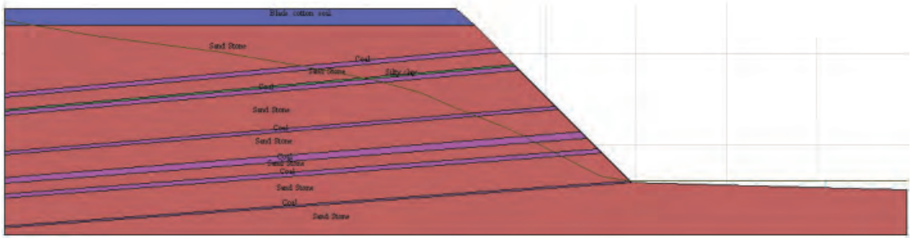

Fig.6(b) Details of modelled geometry in undrained condition

The highwall slope considered in modelling was 170 m high, inclined at an overall angle of 45°. All materials were modelled using conventional Mohr-Coulomb (elastic-ideally-plastic) constitutive model. The continuum elasto-plastic analysis has been carried out using the software FLAC (available from www.itasca.com). The details of the modelled geometry are shown in Fig.7(a) in drained condition and 7(b) in undrained condition. The different strata in highwall slope and their gradient were also modelled. The thickness of different strata and seams have been taken from borehole section given at Fig.6. In drained condition, the stability analyses were done with a consideration of drained groundwater condition, proper drainage for rainwater and slope monitoring.

In undrained condition, the water table data at the time of slope failure is given in Table 4 has been used in modelling. The water table or the phreatic surface will change constantly depending upon the development of the excavation (Morgenstern, 1971; Sharp et al., 1977). Tables 3(a) and 3(b) show the actual geo-mechanical properties of slope materials used in modelling during drained and undrained conditions respectively.

The factor of safety computed with the strength reduction technique results to be 1.24 in drained condition (Fig.8a) and 0.98 in undrained condition; according to the computation, the failure surface that grows from the crest of the pit and reaches toe of pit at the time of failure. When a slope fails it can provide a useful source of information on the conditions in the slope at the time of failure as well as an opportunity to validate stability analysis methods. Because the slope has failed, the factor of safety is considered to be unity or less than unity (1.0) at the time of failure (Duncan and Wright, 2005). It is clearly evident from the simulation that the highwall slope of medipalli OCP has failed due to improper drainage and sump water at the dipside of the highwall. The simulation analyses showed that the final slope is stable in drained condition and failed in undrained condition.

Validation of numerical simulation model

A comparison of numerical simulation results with the actual results obtained from the field is presented. Cyclops is a fully automated monitoring system comprising a motorized total station with video target acquisition under computer control. Total 50 targets were fixed on the highwall slope of Medipalli OCP for monitoring. The information of slope movement is visualized in real time. The principle of operation of slope stability real time monitoring by cyclops is shown in Fig.9. The cyclops will be connected to software GEOSCOPE. The system GEOSCOPE manages three levels of alarm for every prism in XY and Z directions. GEOSCOPE will set off alarms in case of movement. These alarms (EX: flashing light, beacon, SMS, e-mail, etc) will instantly alert the people in charge of the site. A visualization of the results in real time on a PC will immediately render a state of the deformation or of the movement, as well as a description of the deformations.

The automatic theodolite was positioned at a fixed point and measured readings of all the 50 targets daily. It was observed that prior to development of cracks and failure at crest as shown in Fig.11, there was no displacement as shown in the Fig.10 before 26.08.2015. The development of cracks and initiation of failure at crest was started when there was a displacement of about 40cm shown by cyclops indicating warning (Fig.10). The slope gradually started displacing on the 26.08.2015. The widening of cracks and slope failure at crest were occurred at about 90cm displacement (Fig.10) on 19.09.2015. The seepage of water along the slope was also

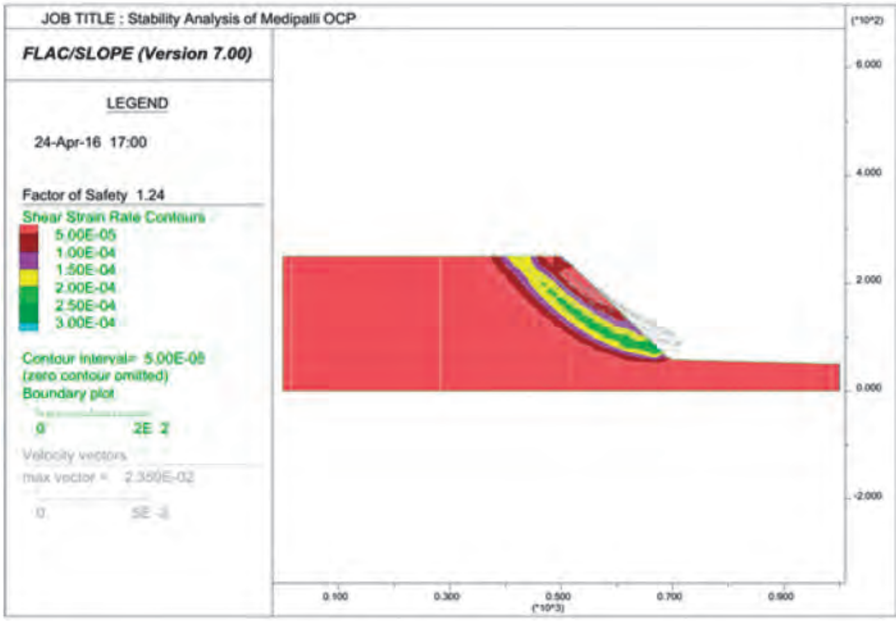

Fig.7(a) Computation of factor of safety, FOS, for the same model represented in Fig.6(a), using the strength reduction technique

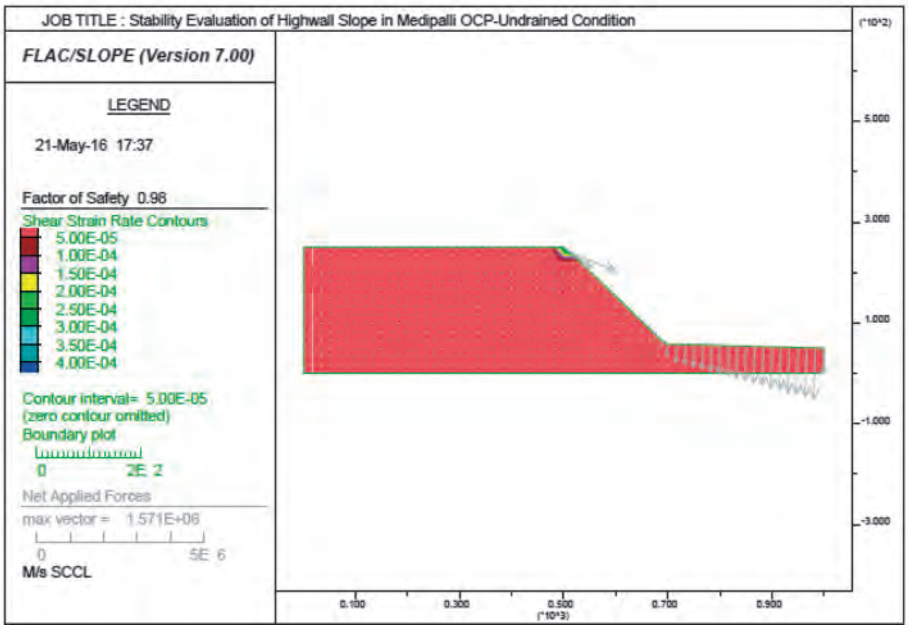

Fig.7(b) Computation of factor of safety, FOS, for the same model represented in Fig.6(b), using the strength reduction technique

observed due to improper drainage of water (Fig.5(b)). Erosion brought about by flowing water could also result in reduced strength (Morgenstern, 1971; Sage, 1976; Sharp et al., 1977; Hoek and Bray, 1981). Mining personnel were subsequently withdrawn from the area for safety reasons and provided proper drainage system. The mining resumed from 20.11.2015 when the cyclops information indicated that the slope had stabilised (Fig.10). Till date, there is no problem of slope failure. From simulation analysis, it is found that the simulation predictions are closer to the field data and show much better accordance with the field results.

Results and discussion

Many slope failure incidents in Indian coal mines have taken place due to uneconomic and lack of sound design of slopes. Diligent monitoring and safe design by qualified geotechnical engineers at mine sites is crucial. The analysis of stability of slopes for the ultimate pit slope at Medipalli OCP indicated the safety factor exceeding 1.2 for slope angle of 45 degrees with proper drainage system. However, the presence of water decreased the safety factor to around 0.98. There was displacement of about 90 cms recorded by real time monitoring system before slope failure. The results of simulation are validated and verified with field data (visual and monitoring) which are almost matching. Based on field observations and analysis results at Medipalli OCP, it is concluded that slope failures are likely to occur because of improper drainage system.

Therefore, it is recommended to maintain proper drainage system and continuous intensive slope monitoring. There should not be any flow of water or garland drains in and around the pit which reduces the cohesion and angle of internal friction of the friable strata leading to the slope failure. Additionally, dewatering of potentially unstable zones is also important to minimize hazards related to highwall failures. Conduct of slope stability assessment in Indian coal mines is mostly based on empirical and observational approach. Hence, efforts should be made by statutory bodies to have more application of analytical numerical modelling in this field to make slope analysis and design scientific.

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Fig.8 Principle of operation of slope stability real time monitoring by Cyclops (Source: www.soldatagroup.com)

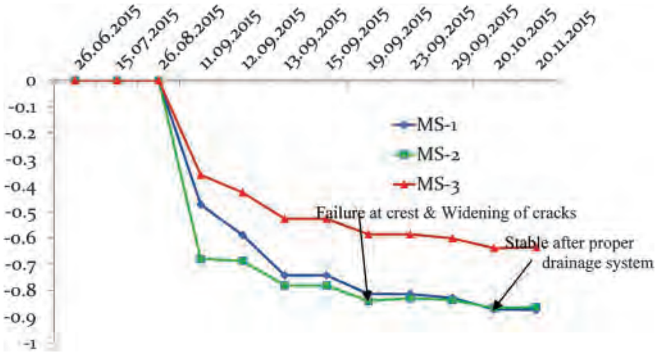

Fig.9 The displacement monitored by Cyclops

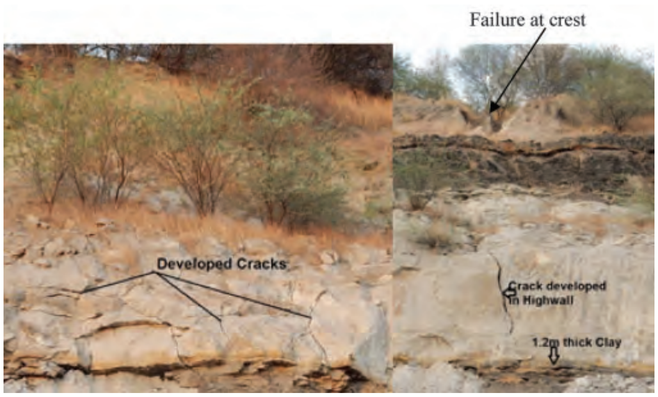

Fig.10 The cracks developed due to dipside highwall failure at Medipalli OCP

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