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Stability Evaluation of Highwall Slope in an Opencast Coal Mine-A Case Study

*I. Satyanarayana, **G. Budi, ***Phalguni Sen, ****A.K. Sinha

*Deputy Director of Mines Safety, DGMS, Dhanbad, 826001, India (isnindian@gmail.com)
**Asst. professor, Dept. of Mining Engineering, IIT-ISM, Dhanbad, 826004, India (anandbudi@gmail.com)
***Professor, Dept. of Mining Engineering, IIT-ISM, Dhanbad, 826004, India (phalgunisen@yahoo.co.in)
****Deputy Director General of Mines Safety DGMS, Dhanbad, 826001, India (ashimkrsinha@gmail.com)

Abstract

In India, fast increase in output of coal 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. Therefore, Safe, properly designed, and scientifically engineered slope is essential for economic, safe and successful operation of opencast mine. This paper presents the results of stability evaluation of the pit slope at Medapalli opencast project (MOCP) of M/s Singareni Collieries Company Ltd. (SCCL). In this mine, the highwall was monitored visually and using cyclops. The displacement trend obtained from slope monitoring is a representation of the deformation taking place within the pit slope. In this study, slope stability analysis has been performed by using computer program FLAC/SLOPE to assess the effect of groundwater on stress distribution pattern and safety factor of pit slope. The basic input shear strength parameters required for numerical models were determined in the laboratory. The pit slope considered in numerical modeling was 170 m high, inclined at an overall angle of 45°.Water pressure reduces the stability of the pit slope by diminishing the shear strength of potential failure surfaces. From slope monitoring, it was observed that the cracks got developed and widened by 90 cm just before failure of slope. From numerical analysis, it is found that failure of slope is occurred in undrained condition at a distance of around 10m from pit crest to 20m deep. The slope was then stabilized by providing proper drainage system and the workings of the mine were started after stabilization. The results of limiting failure surface and factor of safety of slope obtained by numerical models are validated with field data.

Key words

Shear strength, Slope failure, Failure analysis, Numerical modeling, Monitoring, Safety factor.

1. Introduction

In mining, opencast technology accounts for the major portion of the world's coal production. In India, the demand for coal for 2016-17, was estimated to be 884.87 MT, whereas the domestic availability was estimated at 724.71 MT. The gap of 160.16 MT was projected to be met through imports (https://coal.nic.in/). 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 coal can be largely attributed to rapid increase in opencast mining activities and intensified mechanization. The opencast mining accounts for about 95% of total coal production in India (DGMS Report, 2016). 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. The benefit of an opencast mine largely depends on the use of the steepest slopes possible, which should not fail during the life of the mine. So, the design engineer is faced with the two opposite requirements, stability and steepness, in designing the deep open pit slopes. Steepening the slopes, thereby reducing the amount of material to be excavated, can save a huge money. At the same time, excess steepening may result into slope failure leading to loss of production, extra stripping costs to remove failed material, reforming of benches, rerouting of haul roads and production delays. The Directorate General of Mines Safety (DGMS) may even close the mine, in case un-safe conditions are created. Therefore, it is necessary that a balance between economics and safety should be achieved. 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. Appreciable research on the aspects of slope stability in open pit mining has been carried out during 1960s and 1970s (Stacey TR, et al.,2003). Later, very little development is achieved in the evaluation of slope stability techniques during the next 30 years (Stacey TR, 1996). Till then, slope stability remains a concern even in the most conservative slopes, due to the unknown properties and conditions of rock mass (Islam MR, et al.,2012). 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).

Girard and McHugh (2000) suggested the following ways of reducing the occurrence of slope failures resulting from mining operations:

1) Good geotechnical design;

2) Slope dewatering;

3) Slope support and rock fall catchment systems;

4) Monitoring systems to identify mechanisms of rock mass and slope behaviour and for advance warning of impending failures; and

5) Cutting back of slopes to more stable angles.

Because of the unpredictability of slope behavior, slope monitoring can be of value in managing and preventing slope hazards, and they provide information that is useful for the design of remedial work. As illustrated in figure 1.1, a slope monitoring system can be divided into four sections namely, Visual monitoring, surface measurements, subsurface measurements and remote monitoring technologies. A very cogent factor in an effective slope monitoring system, as pointed out by Little (2006), is the creation of a comprehensive database system for the large volume of geotechnical information obtained from the mine. All data from exploration core logging, face mapping, rock testing, water and slope monitoring must be incorporated into the database system to ensure that no data is lost, and that the data is available for safe and productive slope design.

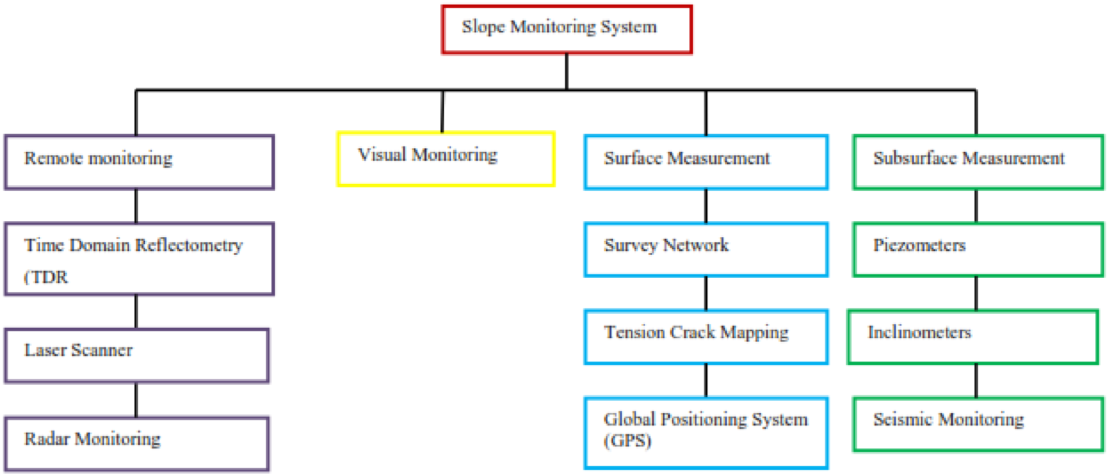

Figure 1.1 Slope Monitoring System (Little M.J., 2016)

1.1 Need for the Present Study

The Indian Coal Mining Industry has experienced the pit slope failures at Dorli OC-I of M/s SCCL, SRP OC-I of M/s SCCL, Medapalli OCP of M/s SCCL, KTK OC sector-I of M/s SCCL and Kawadi OCP of M/s WCL. The Indian Coal Mining Industry is moving towards deeper opencast mines upto a depth of around 500m like Manuguru OC-II Extension and RG OC-II extension. In India, Lot of accidents have been occurred due to highwall slope failure (table 1.1). These slope failure accidents in Indian mines have taken place due lack of sound design of slopes and lack of monitoring. So, the coal industry has identified slope design, monitoring and stabilization as one of the thrust areas.

Table 1.1 Accidents due to highwall 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

Because of increasing trend of slope failures in India, Stabilization of slopes is a big challenge in the opencast mining and needs to be addressed. In this mine, slope monitoring by cyclops was done to prevent failures, take remedial measures and to provide solutions against instability. The deformations are to be continuously detected and monitored, so that suitable preventive measures can be taken. Engineering of safe and stable slopes 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).

The main components of an open pit slope design as illustrated in figure 1.2 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 30◦ for those in very poor quality rock.

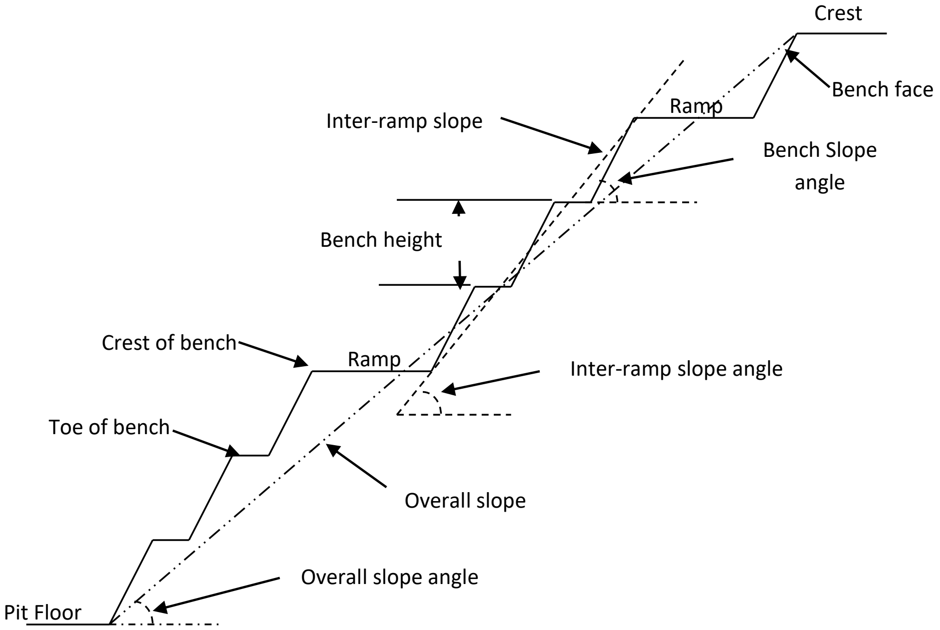

Figure 1.2. Various elements of an open pit slope

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 1.2.

Table 1.2. 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

Slopes need to be engineered considering the factors that influence slope design like depth of the pit, geology, rock strength, ground water 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 slopes is an integral part of the opencast and high wall 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 behavior, and applied loads.

2. Analysis of Highwall Slope Failure –Case Study

2.1 Location of the mine

The Medapalli 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.Kms 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. 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 location plan of the mine is shown in the figure 2.1.

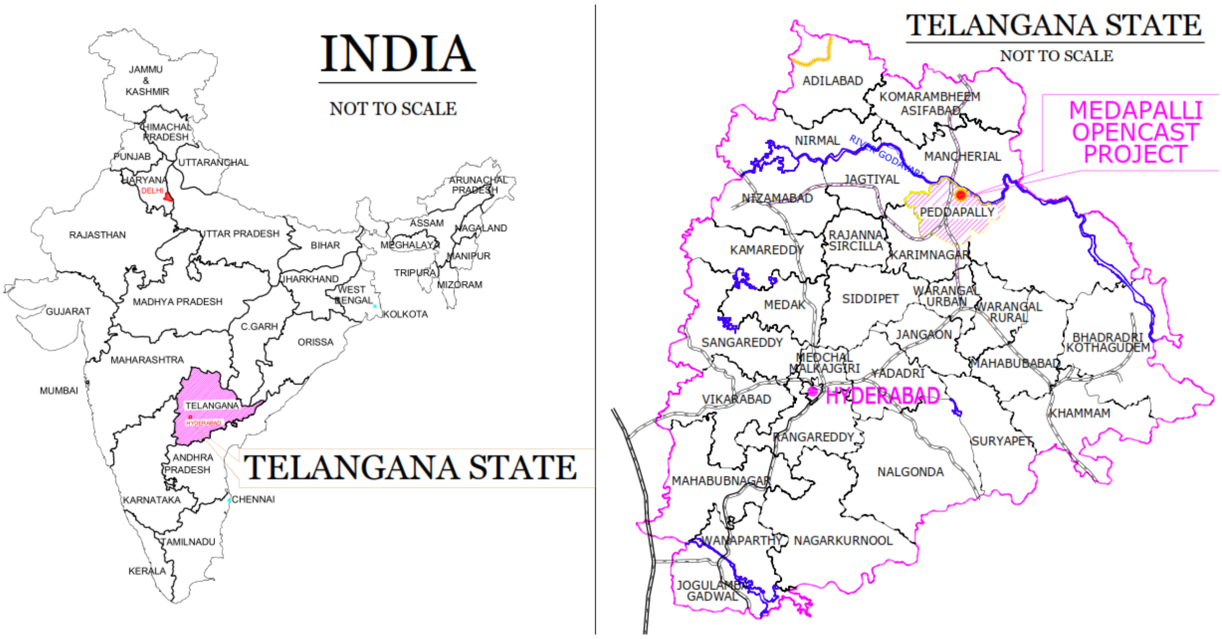

Figure 2.1 Local plan of Medapalli Opencast Project (MOCP Report, 2016).

2.2 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 bore holes is 32.95 per Sq. Km. The sub-surface data reveals that the Gondwana sediments rest un-conformably 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 are in conformity with regional trend. As the contact between the Talchir Formation and the overlying Barakar Formation is faulted, the basal coal seam abuts against the Talchir Formation (Hydrogeological report of MOCP, 2013). The general strike of the coal seams are NW-SE with gentle northeasterly dips (gradient varying from 1 in 6 to 1in 10). The borehole section in dipside of the quarry is given in figure 2.2.The Stratigraphic Sequence in Medapalli OCP is given in Table 2.1.

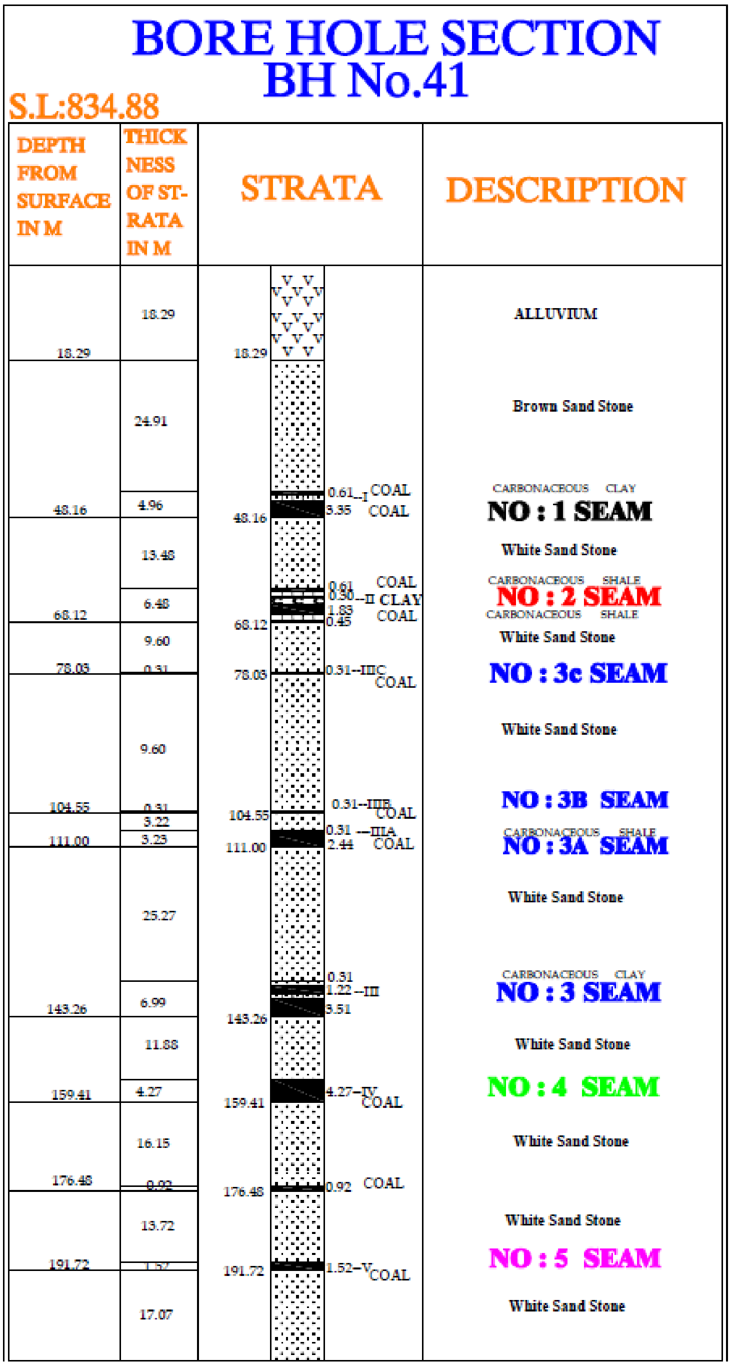

Figure 2.2. Borehole section in dipside of the quarry (MOCP Report, 2016)

Table 2.1. The Stratigraphic Sequence in Medapalli OCP (Hydrogeological report of MOCP 2013)

Age	**Group**	**Formation**	**General Lithology**	**Maximum thickness (m)**
Recent			Soil cover and Alluvium	18.29
P E R M I A N	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+
		Talchir	Fine to medium grained pale Greenish sandstone and green shales.	83.40+

2.3 Design parameters of Medapalli OCP

The physical parameters of the Medapalli OCP are given in table 2.2.

Table 2.2. Physical parameters of the Medapalli OCP (MOCP Report, 2016)

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 & Safe barrier around the quarry, embankment & dump) (Ha)	1171.55
j	Average Gradient of the seam	1 in 6.0 to 1 in 10

2.4 Hydrological conditions of the Highwall slope

The dip side area of Medapalli 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 study of river flow in bends plays an important role in many areas of hydraulic engineering and the research results have been widely applied (Lv S.J., et al. 2015). 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. Each year, lakes and reservoirs go through wet season, mean water season and dry season, due to the impact of rainfall and runoff, and the water-level of lakes and reservoirs appear the seasonal changes (Min Wanga, et al. 2016). The average annual rainfall is 1000 mm (Hydrogeological report of MOCP, 2013).

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 top soil. 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 effect of ground water 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 pressures is essential for designing and maintaining safe slopes (Girard, et al. 1998). The depths to water table from surface observed in different piezometric wells are given in table 2.3.

Table 2.3. Hydrogeological data of water table (Hydrogeological report of MOCP, 2013)

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

2.5 Final highwall bench configuration

The final highwall bench configuration on dipside of the Medapalli OCP is given in table 2.4.

Table 2.4. Final high wall bench configuration (MOCP Report, 2016)

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 150m)	10	8	80	

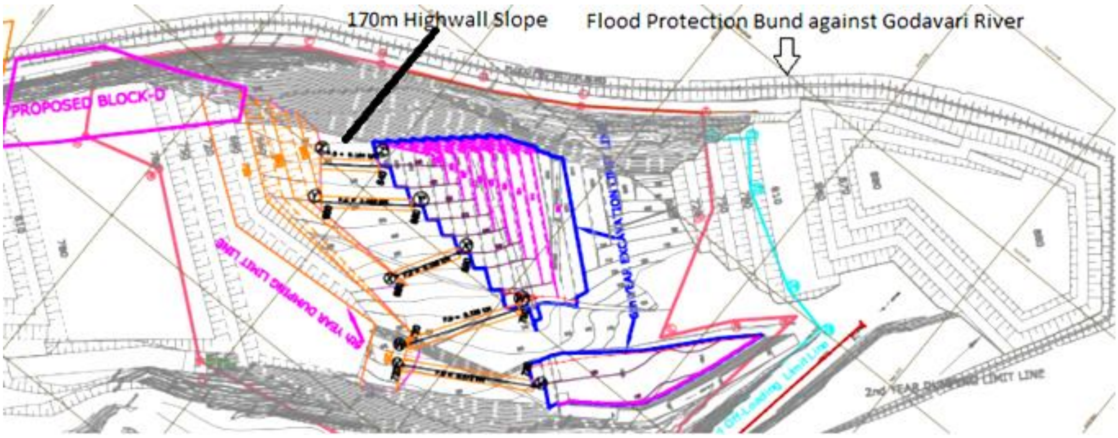

Figure 2.3. Mine Plan depicting slope of 170m highwall of Medapalli OCP

Figure 2.4. Photograph depicting the ultimate of 170m highwall of Medapalli OCP

The plan showing 170m highwall slope of Medapalli OCP towards dip side of the quarry along flood protection bund is shown in figure 2.3. The photograph of 170m pit slope on dip side of Medapalli OCP is shown in figure 2.4.

2.6 Stability Analysis of Highwall using FLAC/SLOPE

2.6.1 Selection of Suitable Method of Stability

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). Sainsbury et al. (2003) stated that the traditional definition of the Factor of Safety (FS) for slopes stability analysis was to calculate the factor of safety with respect to the soil/rock shear strength. The factor of safety of a slope can be computed with a finite element or finite difference code by reducing the rock shear strength in stages until the slope fails. The resulting factor of safety is the ratio of the actual shear strength to the reduced shear strength at failure. This method is called the shear strength reduction technique and is described by Dawson et al. (1999). Hoek (2009) pointed out that the shear strength reduction method is now widely used in open pit slope stability studies because it includes all the benefits of limit equilibrium analyses and it allows the user to study slope displacements that are critical in the evaluation of open pit stability. The shear-strength reduction technique was used first with finite elements by Zienkiewicz et al. (1975) to compute the safety factor of a slope composed of multiple materials.

As no significant joints were observed during formation of highwall on dipside of Medapalli 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 modeling. 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

20^0–30^0 of the dip of the slope or the distribution of geomechanical units varies along the dip 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 Medapalli OCP, the analysis of highwall slope is done by 2D modeling. In this study, numerical approach to slope stability analysis is preferred over traditional limit equilibrium methods due to the following advantages

(a) No assumption needs to be made in advance about the shape or location of the failure surface. Failure occurs `naturally' through the zones within the soil mass in which the soil shear strength is unable to sustain the applied shear stresses.

(b) Since there is no concept of slices in the numerical approach, there is no need for assumptions about slice side forces. Numerical method preserve global equilibrium until failure is reached.

(c) Numerical methods are able to monitor progressive failure including overall shear failure.

By considering all the factors, the stability analysis of pit slope is done by 2D numerical modeling finite difference software FLAC/SLOPE (Itasca Consulting Group, Inc., USA).

2.6.2 Basic input parameters for numerical models

Shear strength parameters are most important in numerical analysis of pit slope design. The core samples were tested in the laboratory to determine the density and shear strength parameters. The final test results of slope material in drained and undrained conditions are presented in tables 2.5 and 2.6 respectively which are considered for numerical analysis of slope stability.

Table 2.5 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 2.6. 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

2.6.3 Stability analysis of pit slope in dry condition

The mine is being worked shovel dumper combination with targeted production of around 4.0 Million Tonnes per Annum. In order to maximize profits with safety, the planned pit slope angle was 45^{o} with due consideration of geo-mechanical properties of strata, Indian statute and proper drainage system during the preparation of feasibility report of MOCP. In the feasibility report, it was mentioned that well-developed drainage system should be provided to divert rain water away from the pit. The design parameters of the mine are given in Table 2.2. When the mine was progressed upto 170m depth on dipside, the local slope failure was occurred in top benches. There was a need for scientific analysis to find out the reasons for failure of pit slope and avoid such situations in future mining. The core samples were collected separately during rainy and summer seasons and the test results of basic shear strength parameters are presented in table 2.5 and table 2.6.

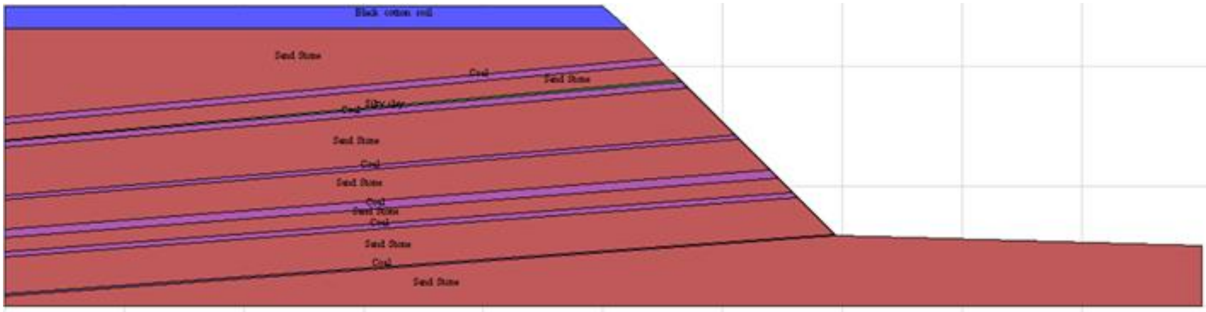

Figure 2.5. Details of numerical model of pit slope using FLAC/SLOPE in drained condition (height-170m, Overall Slope Angle-45^{o})

The stability analysis was done with a consideration of pre-split blasting, drained groundwater condition, and proper drainage for rainwater. As the slope failure was occurred at 170m depth on dipside of the mine, the depth of pit slope considered in modelling was 170m. At the time of failure of slope, the overall pit slope angle is 45° and is considered in numerical models under drained condition without considering groundwater table. All slope materials were simulated using Mohr-Coulomb constitutive model with the properties given in Table 2.5. The details of the numerical model geometry in drained condition are shown in figure 2.5. The thickness of different strata and inclination of the seams are also considered in numerical models. The cut-off safety factor of pit slope computed with the strength reduction technique is 1.24 in drained condition (figure 2.6). It is clearly evident from the guidelines given in the Table 1.2, that the overall pit slope in the drained condition is likely to be stable with available shear strength of pit slope material in this condition. It was also observed that the pit slope was stable in summer and winter seasons during field inspection.

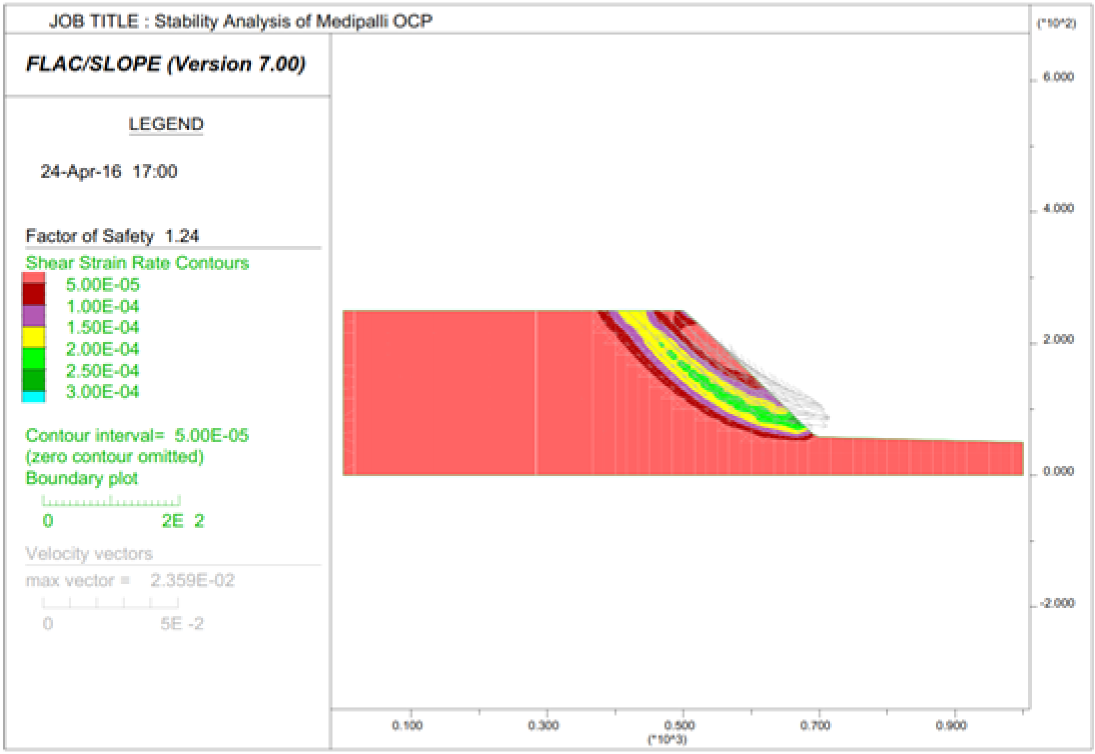

Figure 2.6. Limiting failure surface and factor of safety for FLAC/SLOPE analysis in drained condition (Overall slope angle-45°)

2.6.4 Stability analysis of pit slope in undrained condition

As the pit slope is stable in drained condition, it is necessary to analyze the pit slope stability in undrained condition. The presence of ground water in a rock slope can have a detrimental effect upon stability. The total average rainfall recorded was about 1000 mm. There was no drainage system and seepage holes in the pit slope to drain water during rainy season. As a result, gullies were formed along the benches due to flow of rain water and ultimately, water was accumulated at pit bottom as evident from the figure 2.4. As the area is very near to Godavari River and no seepage holes were drilled to drain-out water from the slope, the water table got charged near to surface. Due to increase in water table and flow of rain water over the benches, the soil and clay became soft with the passage of time and the strata were weathered. The core samples were collected and tested in the laboratory during rainy season. The test results are given in table 2.6. Numerical model is developed for the pit slope under undrained condition considering the overall pit slope angle is 45° (figure 2.7). The water table at the time of slope failure has also been considered 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).

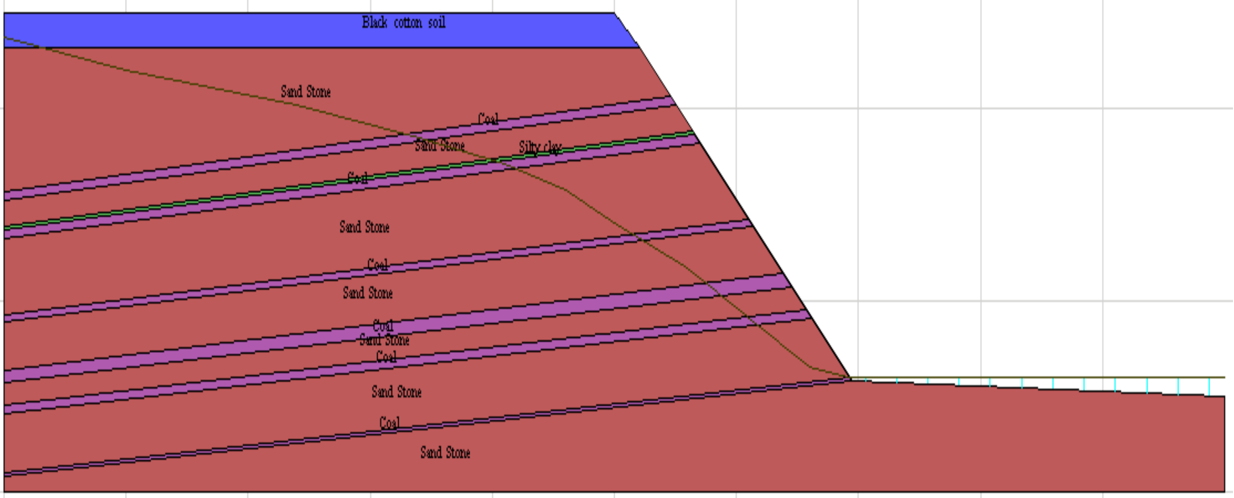

Figure 2.7. Details of numerical model of pit slope using FLAC/SLOPE in undrained condition (height-170m, Overall Slope Angle-45^o)

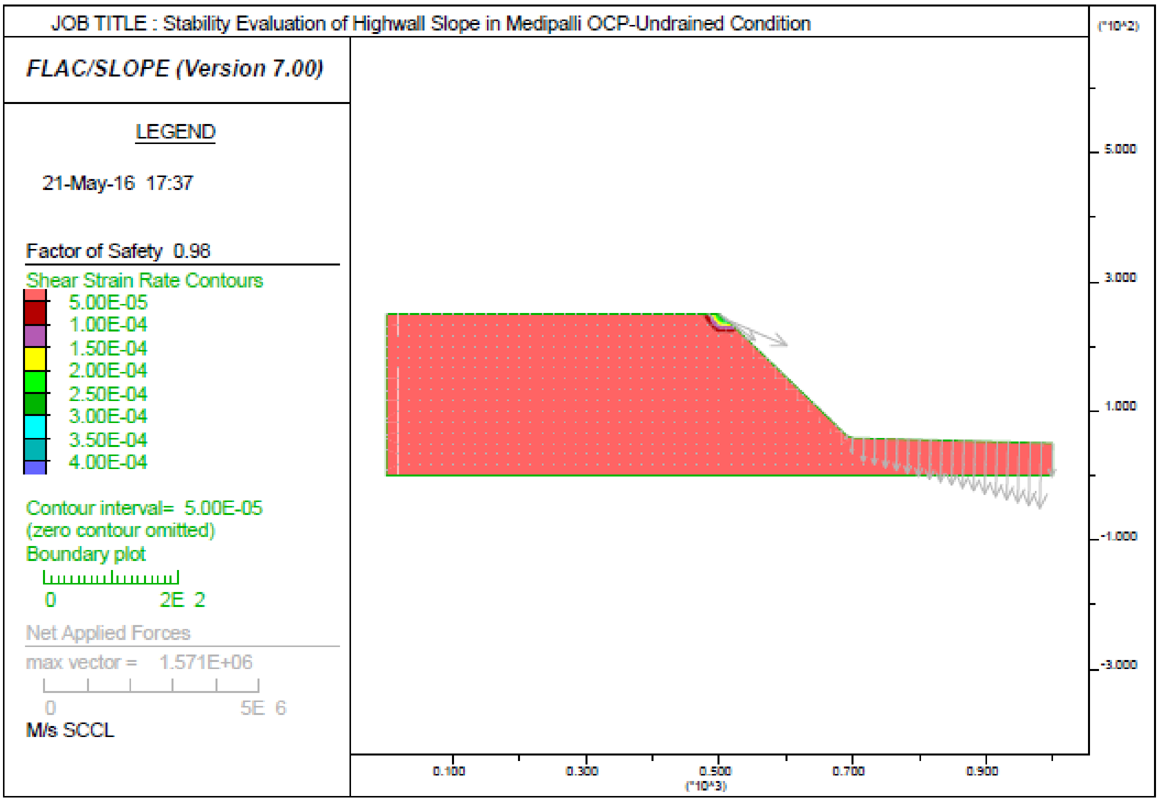

Figure 2.8. Limiting failure surface and factor of safety for FLAC/SLOPE analysis in undrained condition (Overall slope angle-45^o)

It is observed from the simulation that the influence of groundwater on factor of safety is remarkable. The results of numerical analysis in undrained condition indicated that the circular failure is observed in the pit slope at the crest and the factor of safety is 0.98 (figure 2.8). The photographs depicting failure surface, developed cracks and weak strata of pit slope on dipside of mine are shown in the figure 2.11. From numerical analysis, it is found that circular failure of slope is occurred in undrained condition at a distance of around 10m from pit crest to 20m deep which is also evident from field observations (figure 2.11). Circular failure is the basic mode of slope instability in weathered slope material, whereas plane, wedge and toppling failures occur in the hard rockmass.

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 No. of targets were fixed on the high wall slope of Medapalli 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 figure 2.9. The CYCLOPS will be connected to software GEOSCOPE. The system GEOSCOPE manages three levels of alarm for every prism in X, Y and Z directions. GEOSCOPE will set off alarms in case of movement. These alarms (Example. 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 Personal Computer will immediately render a state of the deformation or of the movement. The plan depicting the location of prisms is shown in figure 2.12.

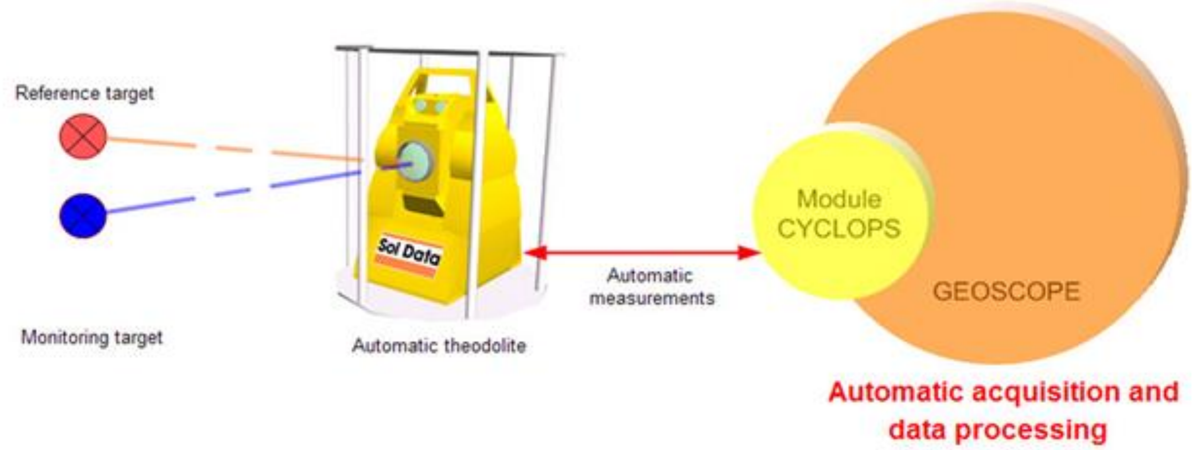

Figure 2.9. Principle of Operation of Slope Stability Real Time Monitoring by Cyclops (Source. www.soldatagroup.com)

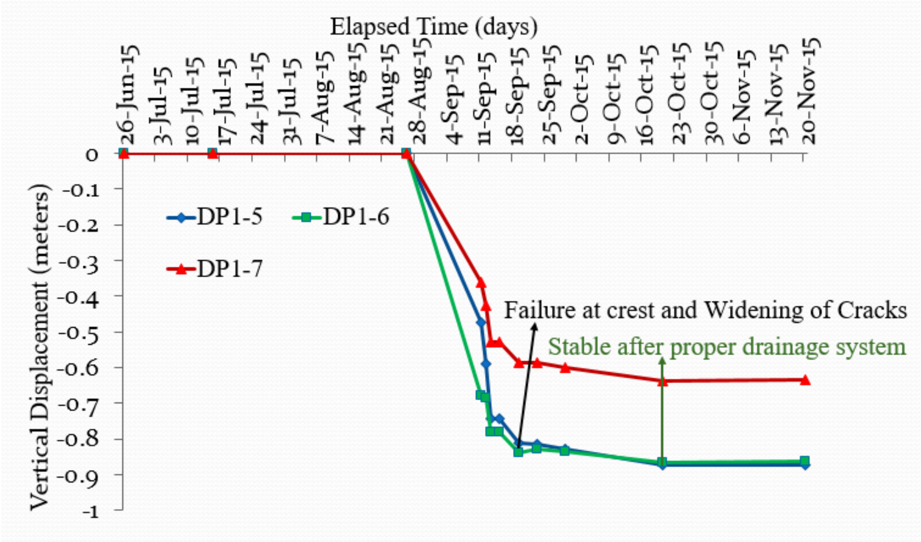

Figure 2.10. The displacement monitored by Cyclops

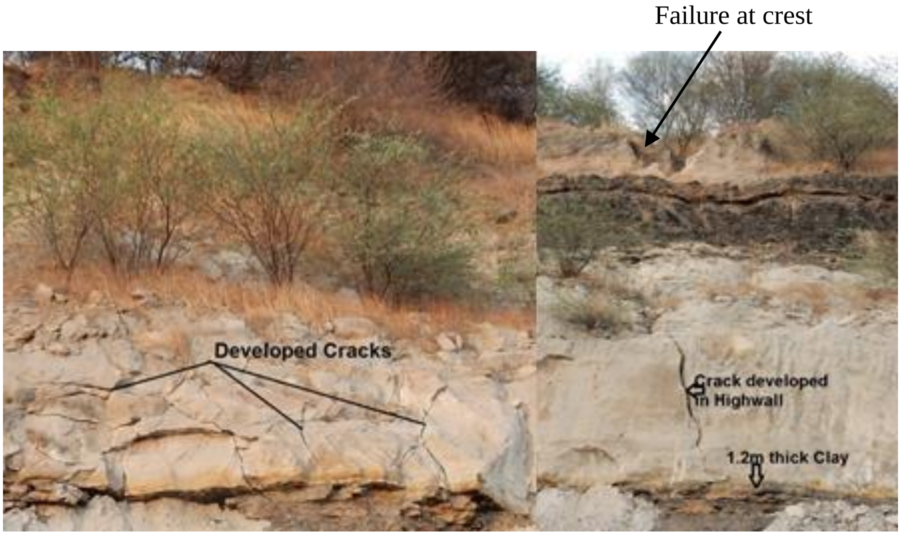

Figure 2.11. The cracks developed due to dipside highwall failure at Medapalli OCP

The automatic theodolite was positioned at a fixed point and measured readings of the all the 50 targets daily. It was observed that prior to development of cracks and failure at crest as shown in figure 2.11, there was no displacement as shown in the figure 2.10 before 26-Aug-15. 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 (figure 2.10). The slope gradually started displacing on the 26-Aug-15. The widening of cracks and slope failure at crest were occurred at about 90cm displacement (figure 2.10) on 19-Sep-15. The seepage of water along the slope was also observed due to improper drainage of water (figure 2.4). 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 adquate drainage system. The Mining resumed from 20-Nov-15 when the cyclops information indicated that the slope had stabilised (figure 2.10). 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.

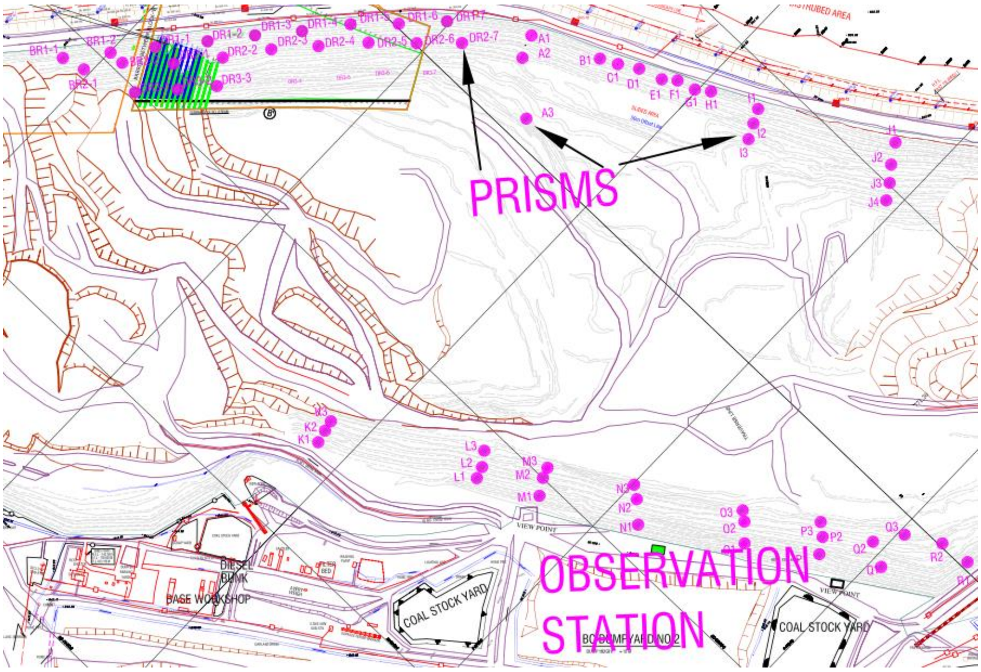

Figure 2.12. The plan showing the location of prisms at Medapalli OCP

3. Conclusion

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 Medapalli 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. The factor of safety computed with the strength reduction technique results to be 1.24 in drained condition 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 Medapalli 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.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 & monitoring) which are almost matching. Based on field observations and analysis results at Medapalli OCP, it is concluded that slope failures are likely to occur because of improper drainage system.

Therefore, it is recommended maintain well-developed drainage system in and around the mine to avoid entry of rain/surface water in the slope and continuous intensive slope monitoring to detect any instability well in advance. It is also recommended to provide perforated pipes in sub-horizontal holes to depressurize the ground water. 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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