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ABSTRACT

The problem of open pit slope stability is a matter of concern when the mining operations go deeper followed by weak strata conditions. In Goa iron ore mines the problem of slope instability has been faced by several mines, after the on-set of monsoon. A review of case studies available on the subject demonstrates that the ground displacement, stress redistribution, effect of ground water, low strength characteristics of the slope forming materials played significant role for the cause of slope failures. Slope monitoring studies indicated that the mechanism of slope failures could be complex and dependent on failure pathways, where certain units fail first and it is followed by subsequent failures due to redistribution of stresses from the preceding zone. The results of several observations, laboratory testing of slope forming materials and monitoring of the slopes have lead to an awareness of various mechanisms of failure and the conditions under which they occur. In real world situations, the failure mechanisms are much more complex involving many other variables due to complexity within the geological materials. The paper addressed the design of practical pit slope angles in such type of weak strata conditions. The testing techniques for material properties enable weak zones to be identified and their relative strengths are accurately determined. Case study of a large Iron mine discussed in detail to demonstrate how deep mining can be carried out under difficult ground conditions.

INTRODUCTION

Slope Control in intensely weathered and fracture rock mass is a matter of concern for the design of safe slope angles to maintain safety and prolonging the operating life of the mine. The strength properties of soft rock/ soil type material and its classification in terms of stability classes is a difficult task due to complex geology of the slope forming materials. Many of the Goan Iron mines which produce around 30 million tons per year for export experience the slope stability problems after the on-set of monsoon. There is a need to design safe operating slopes to combat the problem of slope failure. Several slope failures were recorded in the Goan Iron ore mines. The mechanism of failure is not well understood. However, the details of slope failure that occurred in the past were carefully documented and summarised in Table No.1. Case study of Saniem Iron ore mine is discussed in detail.

Saniem (Sacorda) Mine is a well known iron ore deposit on the Conquirem-Melca range of Central Goa. This is one of the few mines, which produces +63% Fe ore. It was worked very smoothly till 1994, since then this mine developed tension cracks which are widened from time to time and later a part of the mine has collapsed and mechanized resulting in unstable pit slope. The paper describes the details of structural geology, lithology and method of working adopted at this mine, which is not quite different from other mines in Goa. However, there is a need to develop proper slope design guidelines to work out the deposit from its present depth to another 50 m depth. This is an attempt to appraise the unique problem faced by the mine management in order to find out ways and means to overcome the problem as around 4.0 Mt of proved reserve are left to be mined.

Saniem Mine having lease are of 50.3 Hectares is located in Sacorda village, South Goa. It is located at 6 km to the NE of NH-4 A and lies on the Conquirem-Poikul-Melca iron ore range of Central Goa extending about 20 km SE of Madei River. The geographical co-ordinates of the mines are Lat N 15º 74’ 35.2”, Long E 74º 09’ 09.5” (Toposheet No.48 I/3).

The mine is being operated since 1950’s. It was started manually in the fifties for manganese ore extraction and subsequently, it was mechanized during 1970’s. Till date around 3.5 Mt of iron ore has been extracted. Most of it lies above water table and more than 50% of which was hard lumpy ore. During 1998-1999, mining operations are suspended for want of a proper solution to slope stability problem.

Table 1. Summary of slope failures: Goan Iron Ore Mines

S.No.	Material In which Slope is excavated	Height of slope prior to failure (m)	Slope Angle (Deg)	Slope Condition
1	Phyllite	80	41	Above water table (drained)
2	Phyllite	80	35	Drained
3	Mn.Clay	50	35	Drained
4	Phyllite	90	30	Partly drained
5	Mn Clay topped by laterite	90	41	Drained
6	Phyllite	60	39	Water table 10m above toe
7	Weathered Dyke	46	42	-
8	Phyllite with laterite (on top)	98	32	-
9	Phyllite with laterite (on top	48	35	Water table 16m above toe
10	Phyllite with laterite (on top)	98	36	-
11	Phyllite and laterite	58	34	-
12	Phyllite and laterite	59	46	-
13	Mn clay(laterite on top)	70	45	Drained
14	Phyllite	70	32-35	Drained
15	Phyllite	75	32-35	Drained
16	Phyllite	70	31-33	Drained
17	Phyllite	70	32	Drained

MINE GEOLOGY

The Conquirem-Poikul-Melca range of which Sacorda is a part is no different from other ranges except perhaps in structure. The structure, consists of a series of isoclinal folds in synclinal troughs, is mainly controlled by the main Regada fault running in NW-SE direction.

It is evident from the local lineaments mapped by Geological Survey of India that iron ore range lies between two major NW-SE trending faults about 4 km apart, the western most of the two is as close as 400 m from lease boundary. The E-W trending fault, one of which lies in the eastern boundary of the lease has displaced the ore body.

The actual pit slope angle was 30º when the failure occurred with a pit slope height of about 100 m. the occurrence of failure possibly coincided with the extension of workings intersecting the seasonal water table, which is midway on the pit slope about 30 m above pit bottom. This failure raised doubts for the first time about the strength of the foot wall and hanging wall formations.

Mining Method.

Saniem mine is one of the highly mechanised opencast mines. Mining is carried out only during dry months from December to April every year. Various types of heave earth-moving machinery being deployed such as Ripper Dozer, Hydraulic Excavator and Wheel Loader. For handling of ore and waste, 10 Ton capacity tipper trucks are used. Bench width of 10 m and bench height of 7 m is maintained with an overall pit slope angle of 30º from the horizontal. The roads within the mine are maintained at gradient of 1:16.

Since mining operations at this mine are in low key, a modest production target of 1.50 million tons per year will be maintained throughout. This production being achieved by removal of about 6.50 million tons of waste/rejection per year, with an ore to waste ratio of 1:2.6. Rejection generated from the mine mainly comprise of laterite, phyllites and clays. At the proposed production rate of 2.50 million tons per year, the anticipated life of mine is about 12 years.

The nature of the strata, depth of working, structural behaviour of the ore body, mining conditions and type of machines used are generally the factors governing the pit slopes. A chronological sequence of slope failures occurred at Saniem mine is summarised below.

CHRONOLOGY OF SLOPE FAILURES

It has been observed from the pit slope failures, that sliding takes place two months after the onset of monsoon i.e. in the month of August, every year. The chronology of pit slope failures as observed in this mine is very peculiar and got no direct bearing in which material the slopes were excavated with the slope height and slope angle.

August 1994. Tension cracks widened in the month of August, 1994 reaching a maximum width of 1.5m – 2 m and 10m-12 m deep over a length of 200m. on 4th August, 1995: Area-II collapsed with subsidence in Area-I. Cracks extended in Area-II and Area-I, covering a length of about 500 m. DGMS inspected the site. Proposal for working 1995-96 prepared and approved by DGMS and worked.

1995 Monsoon. During 1995 the monsoon the rainfall recorded is 3.8 m. The area was closely under monitoring. Before monsoon, cracks were filled with soil material and water diversion was made. No appreciable change during monsoon observed. Meanwhile, during November, 1995, “Watch & Work” approach to mining has started.

1996 Monsoon. During 1996,around 3.5m of rain fall recorded. subsequently, a working plan was prepared and the pit worked from November 1996 to May 1997. Total excavation was 4.0 lakh tons. Monitoring continued during this period.

1997 Monsoon. During 1997, around 4.1m of rainfall recorded. Plan for 1997-98 was prepared in the month of November, 1997 and work started in December, 1997 in Area-I and Area-II from level 158 L to 94. Total handling of 800,000 tons done up to June, 1998. Subsequently, all the freshly developed tension cracks were filled with laterite muck and rain water was diverted from the flanks of the pit.

1998 Monsoon. During 1998, rainfall was 3.5 m. Small cracks was first noticed in Area-III. It was about 2-3 cm wide and extended over a length of about about 70-80 m. No work was carried out during 1998-99. Protective measures like permanent fencing around the collapsed area has been done. Monitoring of the pit slope walls carried out once in a week till May, 1998 and subsequently twice in a week till mid June 1998. No filling of the cracks was done prior to the monsoon.

1999 Monsoon. Around 4.9 m of rainfall has occurred during 1999. A maximum horizontal movement of about 9.0 m and vertical movement of 8.5m was observed in Area-III. Similarly horizontal movement of 3.2m and vertical movement of 2.2m movement is recorded in Area-II. No appreciable ground movement noticed prior to 19.07.1999, till which time 1.3 m rainfall has occurred. No movement is recorded since November 1999. Necessary protective measures were implemented. Since 1999 till date, the yearly rainfall ranged from 3.2 m to 4.2 m. As a result development of cracks followed by subsidence is an on-going activity, which need to be tackled every year. Every year after the on-set of monsoon a fresh working plan to be prepared and worked under the guidance and approval of Director of Mines Safety.

CAUSES FOR PIT SLOPE FAILURES

The pit slope which is 90 m in height is maintained by bench height of 5-6 m and 6-7 m bench width, maintaining an overall slope angle of 30º. Near the surface, 15-20 m comprise of hard laterite followed by 20 m of transitional zone of limonite/ferrugineous clays followed by 25-30 m thick blackish brown plastic shale material which is located in the immediate footwall portion. The clays are of porous in nature and after getting highly saturated, there will be increase in pore water pressure and consequent loss of internal friction reduces the load bearing capacity and material behaves like a mud like material resulting in plastic flow/mud flow type failure. This, in turn causes crumpling of benches in hard laterite in the surface.

Pit Slope failure: Gross instability of benches

The pit slope formations consists of soft blackish clays which forms the footwall of the ore body. However, the top 20 m of the formation comprise of laterite and lateritised ore body intersected by a number of fissure fillings and a large weathered dyke which has been altered into clay material. Seasonal water table intersects the pit slope and flows out through a number of springs at the contact plane of laterite and impervious clays.

Pit slope above the seasonal springs is usually unstable. The benches on this part of the pit slope slide down and break off into large boulders along the fault and fissure filling planes. The lower benches in soft clays below laterite formation get deformed and slide down the pit slope, horizontally and vertically and present an appearance of subsidence of the strata.

Tension cracks in slope stability analysis.
Slopes show signs of distress something before ultimate failure occurs and one such manifestation is the appearance of cracks along the slope crest. They are often the first visible indication that a slope may be unstable and their presence or absence is often adopted as a crude indicator of slope stability.

These faults and joint planes must be the cause of weaknesses in the strata resulting in slope instability. A close look at the walls of the cracks where the rock masses have separated from the main body seems to have smooth surface with limonitic coating all along. The old crevices or cracks seem to have been filled with small rounded laterite pebbles and rubble which proves that old cracks were filled with these material and now the same have separated due to stress developed due to mining.

The potential surface failure surfaces are combination of joint controlled planar surfaces and curved surfaces through weak rock zones. Where zones of low strength rock mass are encountered in pit walls, failure can develop which differ kinematically from the analysis of jointing patters.

Factors controlling the strength of weak rock mass

Weak rock masses may occur as a result of a number of independent factors. The sole reason for a weak rock mass strength is the low strength of the rock material, it is more properly classified as having soil like strength. An approximate classification for weak rock and soil can be defined from uniaxial compressive strength. Generally the UCS values range from 0.04 Mpa to 1.0 Mpa which falls into soil classification. Slope Rock Mass Rating or SRMR was applied to understand the failure mechanisms in weak rocks with back analysis of failed slopes.

Slope Rock Mass Rating (SRMR).

Robertson et al (1987) using back analysis of slopes at Island Copper Mine in Canada found that the RMR (Rock Mass Rating) and MS (Hoek-Brown correlation to RMR) were poor predictors of the strength of the rock masses for weak rock masses. Robertson (1988) proposed SRMR Geomechanics classification of rock masses. He defines weak rock masses as those with shear strength parameters less than c'=0.2 Mpa and φ =30º.

Where weak rock zones are anticipated, the slope angle can be reduced through the region of weak rock. Approximate slope angles can be determined using limiting equilibrium method of analysis which allow general failure surface bounded by joint surfaces through strong rock regions and arc failures through weak rock zones. If slope flattening is not done, failure may occur the subsequent control of which may require stepouts or widened catch berms, which result in even greater slope flattening. Unfortunately slope failure often initiates when the soft rock zones are still unexposed but before there is an opportunity to take corrective action.

Physico-mechanical properties.

Undisturbed and disturbed soil samples were collected from thirteen locations at Sancordem mines to find out their geotechnical properties for the stability analysis. These samples were sealed and preserved in air- tight containers to preserve the natural moisture content. In the geo-technical tests were carried out for determining natural moisture content, specific gravity, bulk density, dry density, un-drained shear strength, angle of internal friction and Atterberg limits. All the experiments were carried out as per the guidelines recommended by Indian Standards.

- Most of the soils are of medium plastic silty clay with natural moisture content varying from 15% to 74%.
- Specific gravity is more due to the presence of iron ores and the values lie between 2.65 and 4.46.
- Shear tests show that the soils have medium un-drained shear strength of 25 kN/m^2 to 36kN/m^2.
- Bulk density values of the soils lie between 1.3 g/cm^3 to 2.04 g/cm^3.
- The cohesion values varied from 3.58 to 6.21 kg/cm^2 with corresponding angle of internal friction 15.5 to 22.30.

GEO-TECHNICAL INVESTIGATIONS

There are several ways to reduce the chances of surface ground control failures:
(1) Safe geo-technical designs
(2) Secondary supports or rock fall catchments systems
(3) Monitoring devices for advance warning of impending failures.

While it is important to note that geo-technical designs can be improved to increase factors of safety, proper bench designs can be improved to minimise rock fall hazards and certain support systems may enhance overall rock mass strength, diligent monitoring and examination of slopes for failure warning signs is the most important means of protecting exposed mine workers. Even the most carefully designed slopes may experience failure from unknown geologic structures, unexpected weather patterns or seismic shock on the slope. It is extremely important to place the permanent control points for the survey stations on stable ground. The surveys can be done manually by a survey crew or can be automated.

The formation of cracks at the top of a slope is an obvious sign of instability. Measuring and monitoring the changes in crack width and direction of crack propagation is required to establish the extent of the unstable area. Existing cracks should be painted or flagged so that new cracks can be easily identified on subsequent inspections. Measurements of tension cracks may be as simple as driving two stakes on either side of the crack and using a survey tape or rod to measure the separations. Tension cracks were mapped and monitored.

Geo-technical investigations at Saniem mine comprise of Geo-technical mapping of the tension cracks, their attitude of propagation with the help of EDM total station (1 Sec least count) by indirect triangulation method. The procedure involves setting up the instrument at a fixed base station having fixed location with reference to local mine grid. Target points are fixed along the benches at different section at 60 m and 30 m intervals covering the entire length and width of the cracks along its direction of propagation. From the observation of the EDM surveys the areas affected due to crack propagation is 200 m in length and 140 m in width from 187 RL to 140 RL (47 m). The general direction of crack propagation is S 30º E.

The most important purpose of a slope monitoring program is to (1) Maintain safe operational practices; (2) Provide advance notice of instability and (3) Provide additional geo-technical information regarding slope behaviour.

Pit Wall Collapse: Saniem Iron Ore Mine

Slope Stability Analysis.

For modeling the slope stability, cross-sections 6 P to 10 P were considered for the initial study. "**GALENA**" Version 3.0 under Windows has been used to attempt such analysis. The input data include definition of axis limits, slope profile, material profiles, material properties, pheratic and peizometric surfaces and method of analysis. The program utilises limiting equilibrium method of analysis to assess local safety factor associated with slope with various configurations. The **GALENA** system considers slope stability problems as they are encountered in the field i.e. the overall geology always remains more or less same, it is only the slope profile itself that changes. The overall geology is input in the definition of the model including the material properties. The slope profile can then cut through this model, as a slope would be excavated in the real world. Material above the slope profile is ignored, since this has been removed or mined out. In this way, **GALENA** enables large number of analysis to be undertaken without redefining the model each time.

While generating several model output files from **GALENA** software, Bishops circular and multiple circular method of analysis has been carried out. The selection of material properties for each rock type is an important input parameter. Therefore, test results reported by earlier studies was consulted based on the results the values for different material properties were considered along with the IBM test work results using that engineering judgement. The following slope parameters were considered during modelling for different slope geometries with varying slope angles. Initially, the slope is modelled for 88 m slope height with the material properties as derived from laboratory testing. Preliminary analysis has indicated that a Factor of Safety of more than Unity can be achieved. Back analysis of failed slopes is in progress. Further, analysis will be carried out to work out the pit another 50 m below the water table. The ore body is persisting at depth.

The Factor of Safety is not constant, but it is subjected to cyclic changes due to variations in water pressure. Further, the Factor of Safety tends to decrease with time, because of swelling of slope forming materials, effect of weathering, creep strength and alteration in slope geometry. However, the Factor of Safety can be increased by adopting best practices during mining operations. These practices include improvement in proper and de-watering system to minimise the in-situ moisture content of the slope forming materials to enhance the shear strength properties.

Slope Stability Guidelines.

Considering the back analysis of slope failures the factors that influence the slope stability include

1. Attitude of formation of contacts, structural elements in relation to attitude of slope.
2. Nature of slope forming materials.
3. Pressure of major discontinuities dykes, faults, sills, folds etc.
4. Position of ground water table.
5. Irregularities in pit design (abrupt changes).
6. Condition of benches.

For a desired slope (Height and inclination), the relative influence of the above factors can become determinant "stability-wise". Based on the above guidelines and field experience in Goan Iron Ore Mines the failure diagnostic weight age has been evolved with the following parameters :

1. Change in slope angles : 40%
2. Laterite cover and structural conditions : 25%
3. Ground Water uplift pressure : 15%
4. Surface erosion : 10%
5. Irregular pit design : 5%
6. Unidentified reasons : 5%

Based on the geo-technical investigations conducted the following measures need to be ensured for maintaining safe workings:

1. Monitoring with EDM to measure slope movement and to take timely action if the movement crosses critical limit.
2. To ensure meticulous execution of approved mine layout – aspects like slope angle, bench height, width and maintaining excavation limits.
3. By constructing buttress walls by placing the waste material preferably laterite muck at the toe of the excavated clay benches to provide toe support of the benches and will minimise slope movement.
4. De-watering the slope face by lowering the water table by pumping the water around the pit boundaries or drilling drain-holes into the pit slope face.
5. Segmenting the overall slope faces with stepped out excavation.
6. Workings along strike direction to be restricted upto 100-150 m.
7. To maintain a general pit slope angle of 25º – 28º in soft clay formations.

CONCLUSIONS

The subsidence and instability problem at Saniem (Sacorda) can be attributed due to the influence of several factors such as local geo-technics, incompetent nature of the foot-wall rocks and the strata immediately adjacent to the foot-wall and hydro-geological problem arising due to raising of water table in the monsoon and impervious nature of the foot-wall strata. Necessary protective measures are suggested to minimise the risk of strata movement using ground monitoring. Further, numerical modelling and analysis is in progress to evaluate the relationship between slope height and slope angle with reference to Factor of Safety to develop slope design curves.

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