Pit Slope Design in Weak Rocks: Experience from Sukinda Chromite Valley, India

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Abstract. Sukinda chromite valley is the largest chromite deposit in India with six chromitite bands mined by several open pit mines. Host rock ultramafic sequence is weathered and altered to a thick profile of limonite that forms majority of the pit walls. The limonitic rockmass is massive, silt and clay rich and exhibits very low strength (~1-5 MPa), leading to shallow pit slopes and sterilization of ore below the designed pits. Geotechnical audit of several open pits indicated the potential of steepening the pit slopes. Conventional material characterization programme was found inadequate as undisturbed sampling is difficult in weak limonites. Extensive site characterization programme was implemented to resolve the issue. Geotechnical models were developed in Rocscience Slide 2, including FE groundwater models. Range of overall slope angle scenarios were evaluated to arrive at stable and optimal slope angles. Study indicates near surface monsoon water table significantly reduces the stability of pit walls. Horizontal drains were found to improve the stability and helped achieving FoS required for design acceptance. Optimal slope designs were implemented successfully in many open pits in Sukinda that extended the life of the mine significantly.

Keywords: Weak rock · pit design · water management

1 Introduction

Open pit mining in weak rock is fundamentally different from mining in hard rock, requiring specialized approach during design, implementation, operation, and closure phases. “Weak rock” generally refers to materials with intact strength between “extremely weak” (R0) to “weak” (R2) classes, with equivalent UCS between 250 kPa and 25 MPa [1]. Instabilities in pit walls excavated in weak rock may show failures governed by intact strength of the material or partially governed by discrete or relic structures preserved within the weak rockmass. In addition, weak rock materials are sensitive to surface and groundwater issues, requiring specific attention while dealing with weak rock slopes. Collapse of weak rock slopes may have significant impact on safety and economics of an operation [2].

This paper deals with the challenges associated with pit slope design in weak rocks as a whole and of Sukinda chromite valley, Odisha, India, in particular. Sukinda valley

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is the largest chromite deposit in India with multiple, sub-vertical to steeply inclined chromite bands hosted by a thick sequence of weak limonitic rockmass. Approximately 193 million tons of total reserve is estimated in the Sukinda valley that comprises almost 98% of the country's chromite ore reserve. Presently around 12-14 open pit operations produce chromite [3]. Most of these open pits are operating for several decades and now have reached the pit limit due to shallow slope angles, sterilizing ore below the limits of designed open pits. Our study indicated that poor strength parameters obtained from geotechnical labs and inadequate water management practices resulted in conservative slope designs. It was identified that specialized site characterization programme may resolve the issue. We have recommended optimal pit slope designs with strategies for design implementation. Such evaluation has helped several mine operators in Sukinda valley to implement slope steepening programme safely and thereby extend the life of the mine.

2 Geo-Mining Conditions in Sukinda Valley

Regionally, Sukinda Valley comprises of a Precambrian ultramafic suite that was intruded into the older Iron Ore Supergroup of Singbhum Creton. The ultramafics consist of serpentinised dunite-peridotite, ortho-pyroxenite and chromitite. Six major chromitite bands are reported from the area, named band 1 to 6. The whole sequence is folded into a south-westerly plunging synform with chromitite bands extending approximately 25 km [4].

The sequence was subjected to intense weathering and alteration. Ultramafics (primarily peridotites) were serpentinised to varying degrees and affected by near surface chemical alteration, forming limonites. The limonitic rockmass is massive, silt and clay rich and exhibits poor strength (1-5 MPa). The weathering profile is deep along the sub-vertical orebodies and grades into slightly weathered rockmass through a transition zone. The orebodies show effects of near surface, in-situ weathering forming friable chromite, generally up to the depth of transition zone and grades into hard, lumpy chromite with increasing depth. Depending on the degree of weathering and alteration, final pit slopes are likely to develop either completely within limonites, or with exposure of peridotite in the lower benches, or completely within the peridotites (Fig. 1).

The area experiences average annual rainfall in the order of 1500-2000 mm, with majority of rainfall during the monsoon months. Groundwater primarily occurs in water table (WT) condition in the upper limonites and semi-confined to confined condition in the deeper fractured, peridotite rockmass.

3 Site Characterization

In order to achieve steeper slope designs, integrated geotechnical and hydrogeological data gathering programme were adopted with the following major components.

Surface investigations were undertaken by geological, structural, and drone mapping in the open pits, to assess distribution of various rock types, major structures, structural fabric and to evaluate discontinuity characteristics.

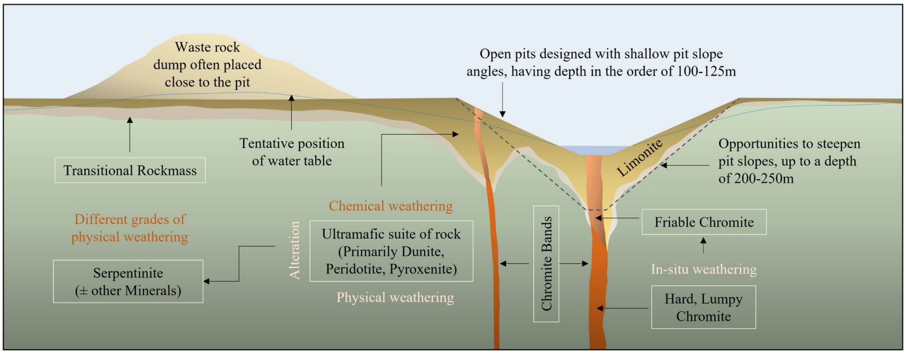

Fig. 1. General geological and geotechnical conditions of open pit mining in Sukinda valley. Dashed line indicates potential opportunities of pit slope steepening

Sub-surface geotechnical investigations were generally undertaken by triple tube, PQ and HQ, exploration and inclined geotechnical drilling with geotechnical logging and sampling. Significant precaution was required to collect undisturbed weak rock samples from the core drilling programme. Oriented core drilling and downhole ATV logging helped to establish a robust structural database for the lower, jointed rockmass.

Hydrogeological investigations were piggybacked to the drilling programme that primarily included downhole geophysics, aquifer pumping tests, packer, and spinner tests to assess hydraulic conductivity of the major lithologies and the discrete flowing features. Some of the boreholes were utilized to install standpipe and vibrating wire piezometers to help long term monitoring.

Weak rock materials were further characterized by civil engineering type site investigation, specifically to assess the strength of weak limonitic rockmass. Standard Penetration Tests were undertaken alongside collection of undisturbed tubed samples, disturbed samples, and geotechnical logging.

Laboratory strength testing was undertaken in multiple laboratories to assess physico-mechanical properties of the intact rock and the discontinuities. Weak to very weak rockmass was subjected to index tests, moisture content, porosity and void ratio, bulk and dry density, Atterberg's Limit, PSD (sieve and hydrometer), triaxial (CU, CD, UU), slake durability and direct shear tests. Hard rock samples were subjected to UCS, Young's modulus and Poisson's ratio, Brazilian, and natural joint shear strength tests.

4 Modelling and Analysis

Experience of mapping, geotechnical logging, and lab tests from multiple projects in Sukinda valley indicates that the open pit mining region may be divided into few major geotechnical domains.

- Weak rock (limonite) domain - includes completely to highly weathered/ altered materials, generally represented by Mohr-Coulomb strength parameters.
- Transitional domain - occurs between weathered/ altered and fresh to slightly weathered domains, represented by Generalized Hoek-Brown strength parameters.

- Fresh rock domain - primarily consists of fresh to slightly weathered peridotites, represented by Generalized Hoek-Brown strength parameters.
- Friable chromite domain - occurs close to the surface, generally represented by Mohr-Coulomb strength parameters.
- Hard-lumpy chromite domain - occurs at depth, below the friable chromite domain. Generalized Hoek-Brown strength parameters were considered for this domain.

Three-dimensional geotechnical domain models were developed in Leapfrog Geo software package [5]. Input geotechnical parameters for each domain were established from statistical analysis of the geotechnical database.

During pit slope redesign programme, range of overall, inter-ramp and bench scale models were evaluated with an objective to steepen the final overall slope angles. Internationally accepted factors of Safety (FoS) and Probability of Failure (PoF) values for open pit design were considered [6]. Geotechnical domain models developed in Leapfrog Geo were considered as input to the geotechnical modelling software Slide Version 9.020 [7]. Non-circular failure analyses were undertaken considering the geological, structural, and geotechnical heterogeneity of the rockmass. Morgenstern-Price and Spencer Method of Slices were used for Limit Equilibrium (LE) analysis. Probabilistic analysis using Monte-Carlo sampling techniques were performed with cohesion and friction angle as variable for the weak Mohr-Coulomb materials, and GSI and UCS as variables for the hard rock materials. Effects of waste rock dumps on the stability of pit slopes were also considered in case the dumps are placed close to the pit. Numerical groundwater models provided input data to the stability modelling. The pit slopes were generally evaluated with saturated monsoon WT that represents the worst-case scenario. The effect of horizontal drains on slope stability were evaluated by simulating the installation of ~50m long horizontal drainage holes.

Majority of the open pits operating in Sukinda valley are designed with overall slope angles in the order of 25° to 30°. Our study indicated that pit slopes may be steepened up to 10° or even more at certain pit walls, depending on the disposition of weak and strong rock behind the pit walls, material strength, groundwater setting and by considering the effects of horizontal drains. An increase in pit slope by around 10° significantly increases the open pit reserve and life of the mine with a reduction in stripping ratio and thereby lower stripping cost and land requirement for waste placement. However, the study indicates that slope steepening can only be achieved through extensive site investigation and slope modelling process with appropriate water and slope management during implementation and operation phases.

5 Slope Stability Scenario Analysis

Various slope stability scenarios were evaluated to arrive at design recommendations.

Stability of upper limonite slope: This was checked separately to assess potential of slope instability that may restrict only to the upper limonites. LE analysis considering only the upper, drained limonite were undertaken and scenarios with $\text{FoS} > 1.3$ were considered to arrive at overall slope angle recommendations. Thin strip of limonites exposed in the pit slope are susceptible to failure and should be removed.

Effect of horizontal drains: Probabilistic LE analysis indicated that the FoS of saturated pit slope (Fig. 2a) increases with drainage in the upper limonite (Fig. 2b) and further increases with drainage in lower jointed rockmass (Fig. 2c). As a result, horizontal drainage holes were recommended in the pit walls developed in upper limonite and lower jointed rockmass.

Possible effects of elevated water table within the waste dump: During monsoon, waste dumps close to open pit may have elevated WT that may increase pore water pressure (PWP) behind the pit walls. We evaluated scenarios with high WT in the dump that shows significant increase of PWP behind the pit walls (Fig. 3a, 3b), resulting in notable reduction in FoS (Fig. 3c). However, FoS increases with drainage in the pit slope (Fig. 3d), emphasizing the effectiveness of drainage in the pit slope, monitoring of PWP and water management for the waste dumps.

Shallow Failure Potential: During monsoon, limonite slopes generally experience shallow transient PWPs [6] which may destabilize the otherwise stable slopes. Such

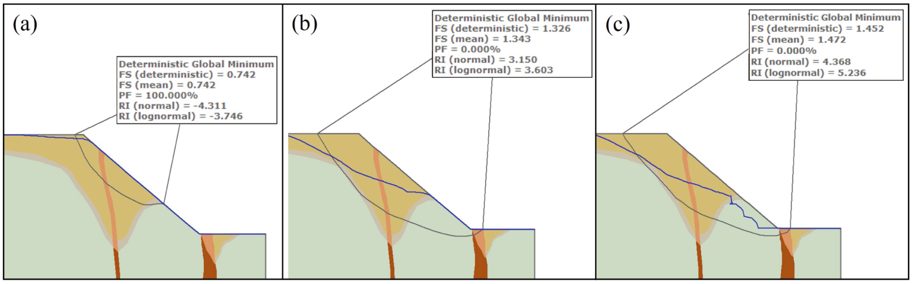

Fig. 2. Effect of horizontal drains on the stability of pit slopes (a) saturated pit slope without drainage, (b) saturated pit slope with drainage in the upper limonite, (c) saturated pit slope with drainage in the upper limonite and the lower peridotite

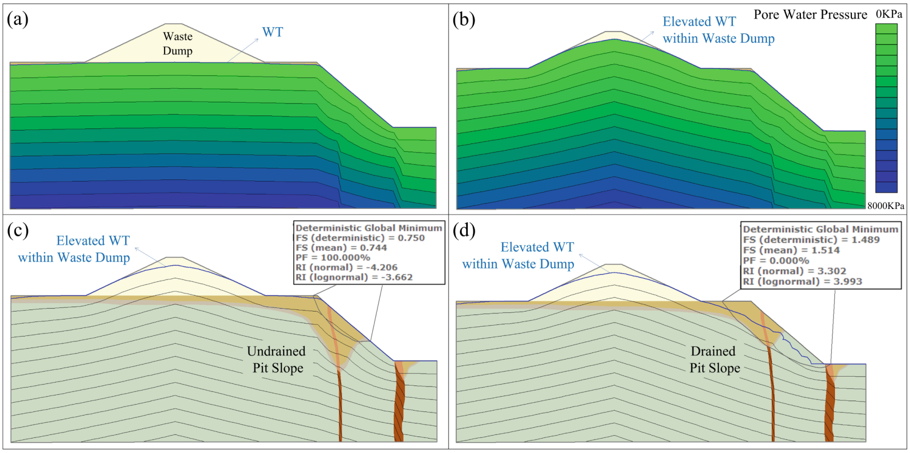

Fig. 3. Effect of elevated WT within the adjacent waste dump & its impact on the stability of pit slopes in undrained and drained conditions. PWP Contours are drawn at 500kPa interval

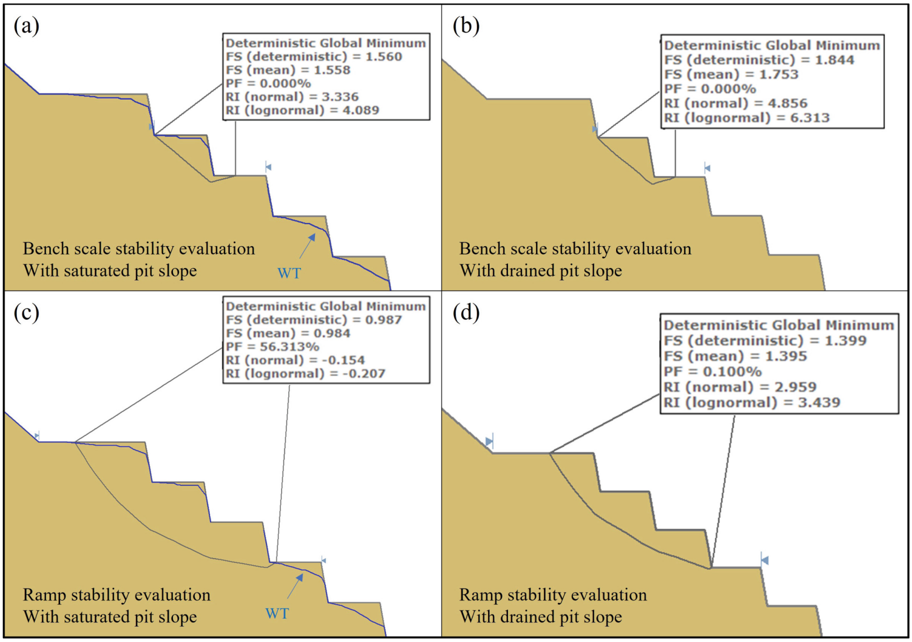

Fig. 4. Effect of PWP on the stability of bench and ramps developed in limonitic rockmass

failure may happen at single to multi-bench scale and may also affect part of a ramp that may adversely impact mine production. Limonite strength near surface is generally much reduced due to weathering, excavation damage and rainwater ingress. As a result, saturated cohesion and friction angles from CU test better represent the near surface conditions which was found significantly low. LE analysis at single (Fig. 4a, 4b) and multi-bench scale (Fig. 4c, 4d) under saturated (Fig. 4a, 4c) and drained (Fig. 4b, 4d) condition indicates reasonable improvement in FoS with drainage. This analysis further emphasizes the importance of drainage of the pit slopes from a slope stability point of view.

6 Recommendations for Design Implementation

A comprehensive slope management programme is essential to implement recommended pit slope designs. This includes implementation of Ground Control Management Plans with Trigger Action Response Programme and an integrated slope monitoring programme combining visual inspection, survey monitoring and radar-based monitoring. It is anticipated that weak rock slope instabilities will develop relatively slowly, reflecting onset of plastic deformation. As a result, any monitoring programme in place should be well suited to capture slope movement early. In addition, appropriate surface water control measures are required to prevent degradation of weak rock slopes. Groundwater management should include horizontal drains, pumping wells in weak rock settings, sump pumping and pumping out waterbodies close to the open pits. VWPs may help refining slope depressurization programme. Small pushbacks in weak rocks and appropriate stand-off distance between waste dump and pit crest should improve the stability of the slopes.

7 Conclusions

Weak rock mine settings, such as in Sukinda chromite valley, are constrained by shallow slope angles due to low intact strength of the slope materials and sensitivity to pore water pressures. As a result, steep orebodies are sterilized below designed pit, leading to economic loss and restricted mine life. Representative, undisturbed sampling and strength testing from weak rock remains a challenge which can be resolved by specialized geotechnical investigation with detailed hydrology and hydrogeology assessment. Robust slope design process with evaluation of likely mining scenarios may help in optimizing the pit slopes. Appropriate water management and ongoing slope monitoring should be an integral part of open pits and waste dumps. Our work helped achieving relatively steeper and stable pit slopes in multiple open pit operations in Sukinda valley. Such analytical procedures may be adopted globally in similar geo-mining conditions.

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