# Slope Stability Analysis and Design of Open Pit Mine Slopes for Limestone Mine at Aruwakkalu, Puttalam, Sri Lanka

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**Abstract:** The largest open pit limestone mine in Sri Lanka which belongs to Holcim Lanka Limited is located at Aruwakkalu, Puttalam. The sub-surface of this site is comprised of an overburden of average thickness 24 m followed by a 9 m thick low grade limestone layer and a high grade limestone layer at the bottom which extends even below the seawater level.The overburden which is currently being excavated in five benches of near vertical cuts becomes unstable during the rainy season, which is a significant safety issue on this site. In this scientific investigation, the physical properties of each layer of material are determined by laboratory testing, in order to design optimum bench heights and slope angles for this open cast mine. Direct shear tests are carried out on undisturbed soil samples collected from the overburden, whereas rock-triaxial tests are carried out on the samples collected from low-grade and high-grade limestone layers, in order to determine design parameters: cohesion(c) and friction angle($\phi$) of these materials. The stability analysis is carried out by means of "SLOPE/W" software. The analysis of data for a three layer model reveals that the possible failures are confined to the overburden based on the outcome of this study. The overburden mine slopes could be optimized to three berms of each 8 m height, 6 m wide and of $70^0$ slopes, having a sufficient safety factor which will enhance the safety and productivity of the future mining operations on this site.

**Keywords:** Benching Optimisation, Limestone, Open Cast Mining, Slope Stability

## 1. Introduction

Slope stability analysis is a considering factor in various situations and fields. Slopes can be classified as natural and manmade slopes. Manmade slopes can be subdivided as cut slopes and fill slopes. Stability of the cut slopes is crucial for the safe and economical mining operations [1]. In open pit mines, usually cut slopes are produced for excavation purposes. It is important to maintain the slope stability of an open pit mining operation to keep an optimum bench height with an optimum slope angle to enhance the productivity.

Driving forces and resisting forces act on soil masses as illustrated in Figure 1 and if the driving forces are greater than the resisting forces, instabilities occur as shown in Figure 1 [2]. Gravity is the main driving force that acts on soil masses which increases due to presence of groundwater [3]. The main resisting force which acts on soil mass is the shear strength, which depends on the cohesion and friction angle of the soil mass.

It is important to keep the factor of safety (FOS) higher than one in order to ensure the stability of slopes. When FOS=1, the slope is in a state of impending failure [4].

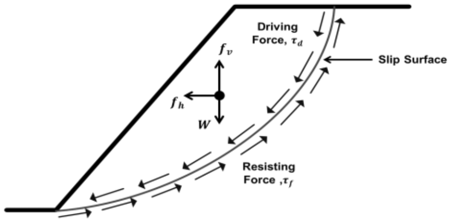

Figure 1: Forces acting on a slip surface (Not to scale)

For permanent slopes FOS>1.5 is acceptable. However, for the temporary made slopes such as mining benches, it is accepted to keep FOS in the range of 1.2 to 1.5 [5].

Before the computer age, the stability analysis was performed graphically or by using a hand-held calculator. For instance, limit equilibrium is the most commonly used and simple solution method, however it can become inadequate if the slope fails by complex mechanisms such as internal deformation and brittle fracture, progressive creep or liquefaction of weaker soil layers.

In limit analysis method, upper and lower bound plasticity limit theorems are used. In the finite element method, the soil mass is divided into number of small elements [6]. An appropriate stress-strain behavior is assumed for the soil material. Solutions obtained through the finite element methods are theoretically correct satisfying conditions of equilibrium, compatibility and failure criterion simultaneously [7].

Currently, 'Geo Slope' family softwares are widely used for stability analysis of earthen slopes [8]. This research aims to carry out a scientific investigation, in order to determine an optimum bench height and an optimum slope angle which can keep the excavations safe during all the seasons of the year on this mine site.

## 2. Methodology

Undisturbed samples were collected from top soil layer, intermediate low grade limestone layer and from high grade limestone layer in order to determine design parameters: cohesion(c), friction angle($\phi$) and bulk density($\gamma$) of these three types of material layers.

### 2.1. Test procedures

Direct Shear Test was performed for undisturbed soil samples collected from the top soil layer. Rock Triaxial Test was carried out for the samples collected from the intermediate low grade limestone layer and high grade limestone layer at the bottom of the deposit. Uniaxial Compressive Strength (UCS) Test was carried out for intermediate and bottom layers in order to draw the Mohr circles. Bulk density of all soil and rock samples were determined in order to conduct the analysis.

### 2.2 Test results

The results obtained from the Direct Shear Tests are summarized in Table 1. Cohesion determined from the sample F was deviated from the other cohesion values, hence it was not considered when calculating the average "C" and $\phi$ values.

Table 1: Direct shear test results for overburden soil layer

| Sample No. | Cohesion C (kPa) | Friction Angle ($\phi$) |
|---|---|---|
| C | 12.1 | $31.5^0$ |
| D | 12.9 | $28.9^0$ |
| E | 31.4 | $27.6^0$ |
| F | 74.0 | $26.0^0$ |
| Avg. | 19 | $29^0$ |

The results obtained from the Rock Triaxial Tests are summarized in Table 2 and Table 3.

Table 2: UCS and triaxial test results for low grade limestone layer

| Test No. | Cohesion C (MPa) | Friction Angle (ϕ) | Bulk density (ɣ) |
|---|---|---|---|
| 01 | 1.9 | $16^0$ | 1.86 |
| 02 | 2.1 | $13^0$ | 1.81 |
| Avg. | 2.0 | $15^0$ | 1.84 |

Table 3: UCS and triaxial test results for high grade limestone layer

| Test No. | Cohesion C (MPa) | Friction Angle (ϕ) | Bulk density (ɣ) |
|---|---|---|---|
| 01 | 2.2 | $43^0$ | 2.25 |
| 02 | 3.2 | $39^0$ | 2.18 |
| Avg. | 2.7 | $41^0$ | 2.22 |

## 3. Results

Slope stability analysis was initially tested for existing open pit dimensions under dry and wet conditions separately. The results of the analysis under dry condition for existing pit dimensions are illustrated in Figure 2 and summarized in Table 4.

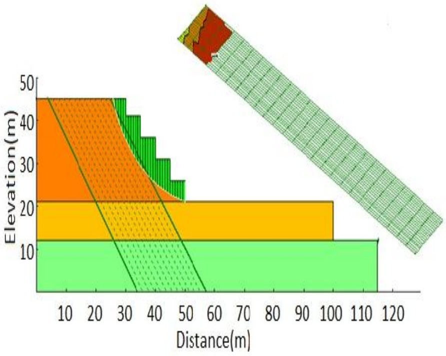

Figure 2: Critical slip surface for existing geometry (For dry conditions)

Table 4: Results of the slope stability analysis under dry conditins

| Condition | Dry | | |
|---|---|---|---|
| Layer | Overburden | Low Grade | High Grade |
| Bench Heights-Top to bottom(m) | 3-5-5-5-5 | 9 | 12 |
| Bench Width (m) | 5 | 50 | 15 |
| Bench Angles | $90^0$ | $90^0$ | $90^0$ |
| FOS | 1.13 | | |

The results of the analysis under wet conditions and for existing pit dimensions are presented by Figure 3 and Table 5.

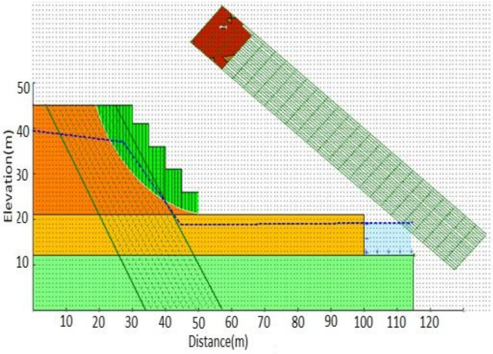

Figure 3: Critical slip surface for existing geometry (For wet conditions)

Table 5: Results of the slope stability analysis under wet conditions

| Condition | Wet | | |
|---|---|---|---|
| Layer | Overburden | Low Grade | High Grade |
| Bench Heights-Top to bottom(m) | 3-5-5-5-5 | 9 | 12 |
| Bench Width (m) | 5 | 50 | 15 |
| Bench Angles | $90^0$ | $90^0$ | $90^0$ |
| FOS | 1.08 | | |

The overburden was focused thoroughly by seeing the results of existing mine benches and a detailed analysis was carried out to model the overburden and to recommend an optimized pit operations for an efficient mining operations. The results of the detailed analysis are summarized in Table 8.

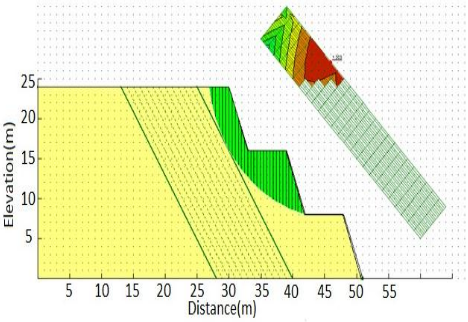

Figure 4: Critical slip surface for dry conditions

Table 6: Results of the slope stability analysis for proposed bench design (For dry conditions)

| Condition | Dry |
|---|---|
| Bench Heights-Top to bottom(m) | 8-8-8 |
| Bench Width (m) | 6 |
| Bench Angles | $70^0$ |
| FOS | 1.30 |

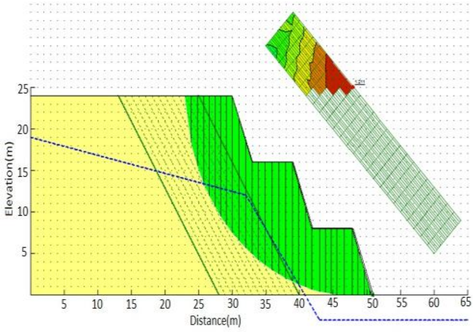

Figure 5: Critical slip surface for (wet conditions)

Table 7: Factor of safety of proposed bench design (wet conditions)

| Condition | Wet |
|---|---|
| Bench Heights-Top to bottom(m) | 8-8-8 |
| Bench Width (m) | 6 |
| Bench Angles | $70^0$ |
| FOS | 1.21 |

Table 8: The summary of the detailed slope stability analysis

| Case No. | Bench Heights-Top to bottom (m) | Bench Width (m) | Bench Angle | FOS | |
|---|---|---|---|---|---|
| | | | | Dry | Wet |
| 2 | 8-8-8 | 6 | $70^0$ | 1.30 | 1.21 |
| 3 | 8-8-8 | 6 | $60^0$ | 1.50 | 1.41 |
| 6 | 7.5-7.5-9 | 6 | $70^0$ | 1.33 | 1.18 |
| 7 | 7.5-7.5-9 | 6 | $60^0$ | 1.56 | 1.39 |
| 9 | 6-6-6-6 | 6 | $80^0$ | 1.39 | 1.21 |
| 10 | 6-6-6-6 | 6 | $70^0$ | 1.58 | 1.36 |
| 11 | 6-6-6-6 | 6 | $60^0$ | 1.81 | 1.62 |

## 4. Conclusions

As per the research findings of this study, following conclusions can be made:

- The three layered model analysis revealed that any failure takes place will be confined to the overburden. Hence, an in depth analysis to be focused on the stability of the overburden.
- The existing mine benches in the overburden have a factor of safety 1.28 in dry seasons whereas 1.12 in the wet seasons. Hence, it can be concluded that the existing benches in overburden are marginally safe during the wet seasons and are at a risk of failure.

- As the existing overburden mine slope is marginally safe under wet condition, it is important to redesign the overburden bench slopes to enhance the safety of mining operations.

## 5. Recommendations

As per the reaserch findings of this study, following recommendations can be made:

- A bench design of 8 m bench height and 6 m bench width for each of three benches and of $70^0$ bench angle for each of the three benches can be recommended to optimize the safety (FOS=1.21)(For wet condition) and the productivity of this mining operation.
- It is recommended to construct a surface cut-off drainage system to further enhance the stability and safety of the overburden.
- For wet conditions, this slope stability was done by altering assumed seepage water levels, due to lack of seepage water level data. However, a more precise analysis and interpretation could be made by constructing a few boreholes in overburden, installation of piezometers in them and by monitoring the change of water levels throughout the rainy seasons.

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