# DUMP SLOPE STABILITY ANALYSIS

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

**BACHELOR OF TECHNOLOGY**
**IN**
**MINING ENGINEERING**

BY
**B.PRITHIRAJ AMITESH KUMAR**
109MN0606

DEPARTMENT OF MINING ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA – 769 008
2013

# DUMP SLOPE STABILITY ANALYSIS

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

**BACHELOR OF TECHNOLOGY**
**IN**
**MINING ENGINEERING**

BY
**B.PRITHIRAJ AMITESH KUMAR**

UNDER THE GUIDANCE OF
**Dr. MANOJ KUMAR MISHRA**

DEPARTMENT OF MINING ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA – 769 008
2013

**National Institute of Technology**
**Rourkela**

---

## CERTIFICATE

This is to certify that the thesis entitled **"DUMP SLOPE STABILITY ANALYSIS"** submitted by **Sri B.prithiraj amitesh kumar** in partial fulfilment of the requirements for the award of Bachelor of Technology degree in Mining Engineering at National Institute of Technology, Rourkela is an authentic work carried out by them under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

**Prof. Manoj kumar mishra**
Dept. of Mining Engineering

# ACKNOWLEDGEMENT

I am indebted to **Dr Manoj Kumar Mishra**, Professor of Department of Mining Engineering for allowing me to carry on the project topic **“Dump slope stability analysis**”. I express my gratitude towards his inspiring direction, valuable suggestions and remarkable explanation throughout this project work. I thank him for his able guidance and painstaking effort in improving our understanding of this project.

I extend my veneration towards those whose details are mentioned in the reference section. I acknowledge my indebtedness to all of them.

I feel privileged to have very good batch mates and thank them for extending all sorts of help for successfully accomplishing this project.

**B.prithiraj amitesh kumar**
DATE :
Dept. of Mining
engineering
National Institute of Technology
Rourkela – 769008

# CONTENTS

# ABSTRACT

In this modern world mining has become an integral part of our life. Mining activities effect in generation of both economic and noneconomic materials. The noneconomic materials are stored at selected places known as waste dumps. The stability of the waste dump has been of a matter of great concern over the years. The problems increases with limiting availability of land. In this project work the slope stability analysis is carried out for the waste dump of a selected iron ore open cast mine. In this process samples are collected and tests are carried out on these samples to get different geotechnical parameters. The factor of safety of different sections of the existing design of the selected mine are calculated by the help of GALENA software. In the end new design of dump slope are proposed by optimising the bench dimensions and material properties by the help of back analysis of GALENA. Then conclusion and various recommendation are given on the basis of new design of the dump slope.

# LIST OF FIGURES

# LIST OF TABLES

# Chapter 1

# INTRODUCTION

# 1. INTRODUCTION

## 1.1 BACKGROUND

In these days opencast mining is the main focus in mining industry as they contribute maximum portion of the total production. Besides this due to maximum flexibility in working operation low gestation period and quick rate of invest open cast mining is getting popular. Open cast mining involves removal of overburden. The removed overburden need to be stored safely. As land available for mining activities has been a great problem to mining industry. So optimization of dump design is acutely needed to store maximum overburden within a limited space. As a result analysis of stability of operating slopes and ultimate pit slope design are becoming a major concern. Slope failures cause deprivation of production, additional stripping cost for recovery and excessive handling of failed material, loss of watering in the pits and may cause mine abandonment/premature closure. Besides this in recent years, there are numbers of landslide have taken place everywhere. They mostly happens on the cut slopes or embankment along roads, highway and sometimes within the vicinity of highly populated residential area especially those in the highly terrain. Thus to minimize the severity or casualty in any landslide a proper realization, supervising and management of slope stability are essential.

## 1.2 AIM OF THE STUDY

The aim of the research work was to evaluate the existing overburden slope practice as well as propose any change to the design of dump slope. Investigation of the safety status of a mine by the help of factor of safety and to propose various safe designs of dump slope. The goal was achieved by addressing the following specific objectives.

1) Complete literature review on the topic to understand the problems associated.
2) Visit to an open cast mine and collection of sample.
3) Lab experiments to be carried out to determine various geological parameters of the sample brought from the mine.
4) Determination of factor of safety from various geotechnical data of existing dump slope design.
5) Propose of various alternate safe design of dump slope

## 1.3 METHODOLOGY

The aim and specific objectives have been achieved by following the step by step process in figure 1.1.

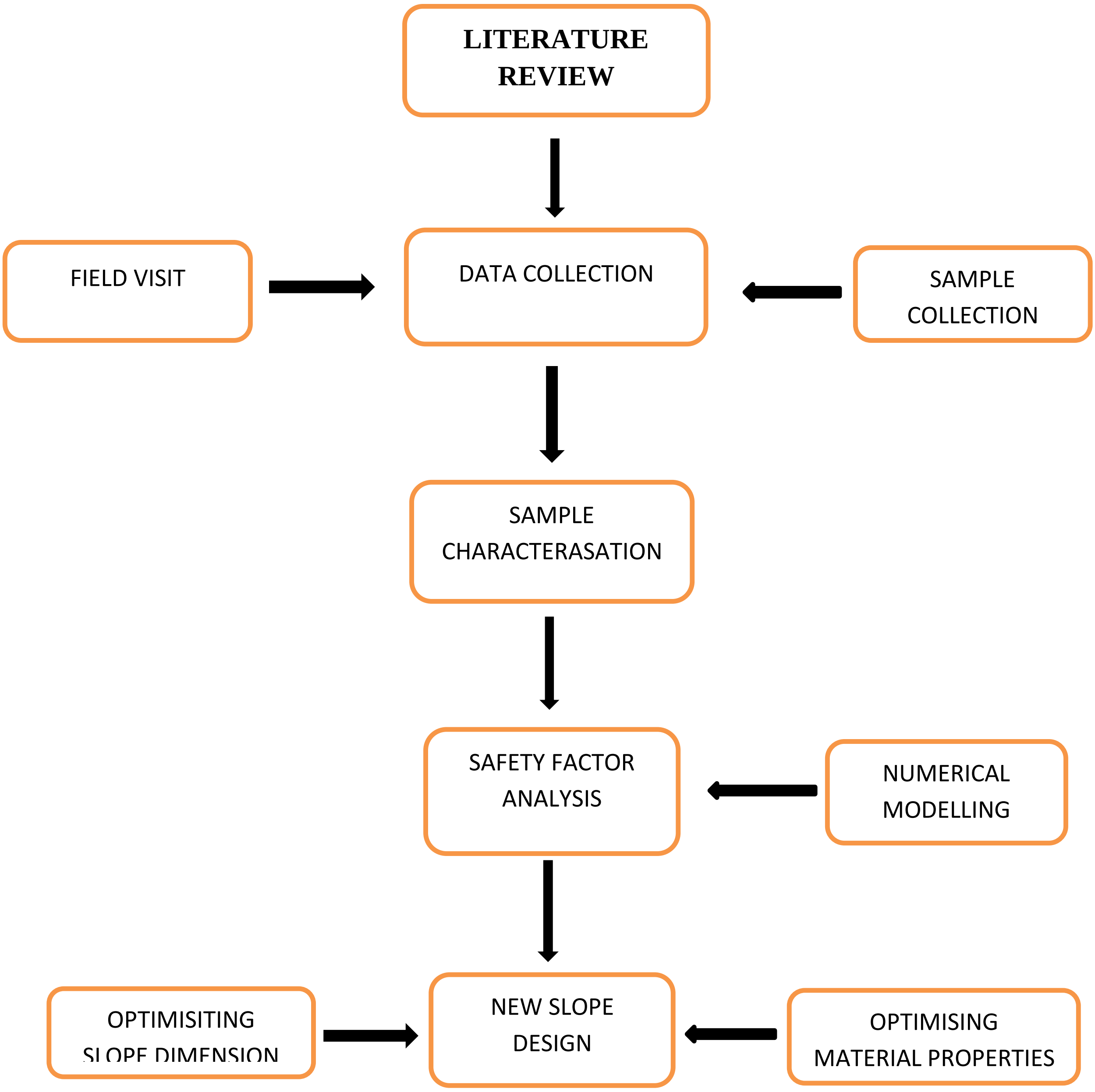


Fig no:-1.1: Flow chart of the Methodology Adopted

# Chapter 2

# LITERATURE REVIEW

# 2. LITERATURE REVIEW

The aim and objectives were achieved by the methodology discussed earlier. The available literatures on different aspects of the dump slope and its stability were critically reviewed and fundamental concept as well as different practices followed elsewhere are given below.

## 2.1 Stability Analysis – General Concepts *(McCarthy and David,* 2007*)*

The **slope stability analyses** are generally performed to measure the safe and economic design of human-made or natural slopes (e.g. water embankments, open-pit mining, mine excavations, landfills etc.) and the balancing conditions. The term "slope stability" can be defined as the ratio of the resistance offered by the inclined surface to failure by sliding or collapsing. The main aim of slope stability analysis are to locate danger areas, supervising potential failure mechanisms, finding of the slope susceptibility to different triggering mechanisms, designing of optimal slopes with respect to safety, reliability and economics, designing possible protective measures, e.g. barriers and stabilization.

Where the stability of a sloped earth mass is to be researched for the probability of failure by sliding along a circular surface, the principles of engineering statics can be applied to determine if a stable or unstable condition exists. When the total sliding mass is assumed to be a cylindrical shaped, a unit width along the face of the slope is taken for analysis, and the slip surface of the slope cross section is the segment of a circle. The forces affecting the equilibrium of the assumed failure mass are determined and the rotational moments of these forces with respect to a point representing the center of the circular arc are computed. In this procedure the weight of the soil in sliding mass is considered as an external load on the face and top of the slope contribute to moments which cause movement. The shear strength of the soil on the assumed failure surface provide resistance to the sliding.

A computational method is used to show if failure (sliding) occurs is to equate moments that would resist movement to those that tend to cause movement. The maximum shear strength owned by the soil is used in calculating the resisting moment. Failure is pointed out when moments causing motion exceed those resisting motion. The factor of safety against sliding or movement is expresses as:

$$F = \frac{\textbf{moments resisitng sliding}}{\textbf{moments causing sliding}}$$

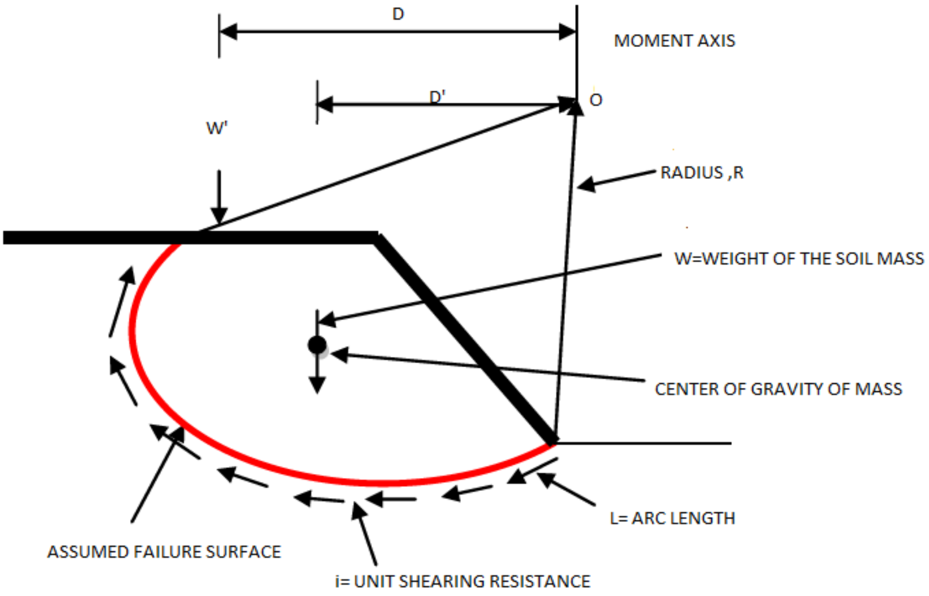


Fig:- 2.1: forces acting on an assumed slope failure mass

Here, W’=External loading on failure area.

D’= Distance between Moment axis and CG of mass.

D= Distance between Moment axis and failure surface.

Moment causing sliding = (W×D’) + (W’× D)

Moment resisting sliding = i × L × R

Hence, Factor of Safety (F)$= \frac{\textbf{Moment resisiting sliding}}{\textbf{Moment causing sliding}}$

$$F = \frac{i \times L \times R}{(W \times D') + (W' \times D)}$$

A factor of safety of unity means that the assumed failure mass is about to slide. A variation to this method for studying slope stability comprises calculating the shear strength required to provide sliding moments and resisting moments balance (equilibrium). The shearing resistance needed along the slip surface is compared to the shear strength that can be produced by the soil. If the soil shearing strength that can be produced by the soil is more than the shearing resistance required for equilibrium, failure happens with this method, the factor of safetycan be calculated is:

$$\mathrm{F} = \frac{\text{shearing strength given by soil}}{\text{shear strength required for equillibrium}}$$

## 2.2 Factors affecting slope stability *(McCurthy and David*, 2007*)***:**

Factors affecting the stability of any slope.

1. Gravitational Force.

2. Material properties of the dump slope.

3. Geology and hydrogeology of the dumping area.

4. Inclination of the dump slope.

5. Erosion of dump caused by flowing water.

6. Lowering of water adjacent to a slope.

7. Effects of earthquakes.

The result of all the movements is caused by the soil to move from high points to low points. The component of the gravitational force is very important to be considered that acts in the direction of probable motion.

The effects of flowing or seeping water are normally known as very important aspects in slope stability problems. But these problems have not been properly recognized. The main problem with seepage is it causes seepage forces which have major effect than normally realized.

As far as mass movement is concerned, erosion on the surface of the slope can increase the stability of the dump slope by removing certain weight of soil mass. On the other hand, it can decrease the stability by increasing the height of the slope or decreasing the length of failure. This happens by seepage at the toe portion**.**

Lowering of the ground-water surface can cause increase in weight which is caused by decrease in buoyancy of the soil. The increase in weight results in increase in the shearing stresses which ultimately causes decrease in safety factor. Practically no changes in volume will take place except at a constant slope rate, and in spite of the increase of load, increase in strength may be insignificant.

A decrease in the inter-granular pressure and increase in the neutral pressure supports shear force at a certain volume. For state of liquefaction of soil mass a different condition will be applicable. This type of condition is likely to be developed if the mass of the soil is subjected to vibration, which mostly happens due to earthquake.

### 2.3 Sliding Block Analysis (*McCurthy and David, 2007*) (Fig 2.2 and 2.3)

Slopes comprising of the stratified materials and embankment structures on the constructed or the stratified soil foundations can face failure due to the sliding along one or more of weaker layers. This type of failure often happens when different. Physical breakage and weakening of some earth materials takes place when the slope gets exposed to moisture. This happens because pore water pressure may cause reduction in stratum's shear strength.

Where the chances for the occurrence of a block slide is under the study with no pore pressure effect on the block, the factor of safety with respect to the shear strength of the soil on the assumed sliding plane is given by

$$F = \frac{cL+W(\cos\alpha+E\ sin\alpha)}{(\mathrm{W}\ \sin\alpha+\mathrm{E}\ \sin\alpha)}$$

Where the value of E is approximately 0.25. If the formation of a tension crack is along the top of the slope allows the growth of water pressure in the crack and the slippage zone, then safety factor can be given as :

Where Fw is the force caused by water pressures in the tension crack.

$$F = \frac{(cL + (W\cos\alpha - F_u + F_w\sin\alpha)\tan\Phi)}{W\sin\alpha + F_w\cos\alpha}$$

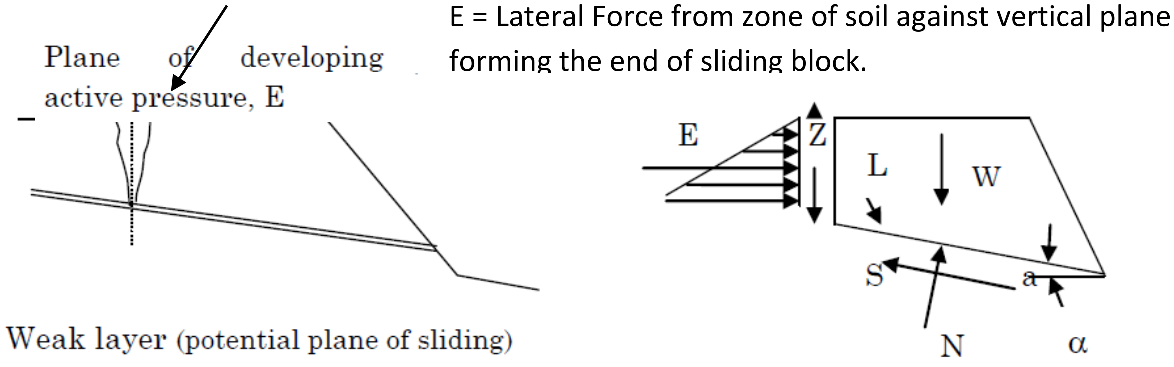


Fig:-2.2: Failure along weak plane by the help of active pressure zone at top sliding block

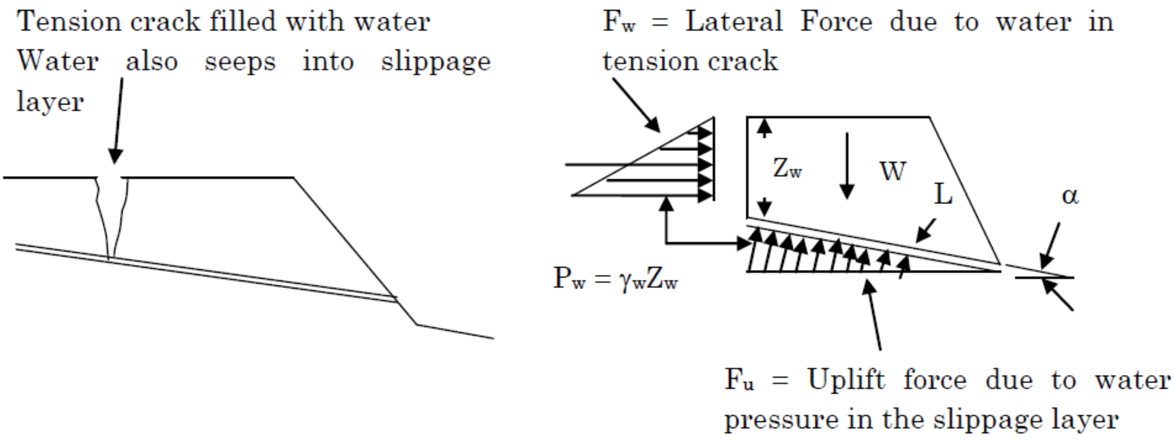


Fig:- 2.3: Failure along a weak plane where water pressure is being developed in the tension crack and slippage layer

Sections of different slopes have known to fail by translation along a weak foundation zone or layer, the force which is responsible for movement resulting from lateral soil pressure developed in case of the embankment. The zone of the slippage may develop only after the dam has impounded water for a period in dams, with seepage through the eventual slippage zone being responsible for weakening to the extent that a failure can occur.

The upstream as well as the downstream zones might be studied for stability. Despite the effect of water on the upstream embankment increases the weight „W“, the lateral pressure of the impounded water for a time period opposes block translation. The uplift force is appreciably greater for upstream zones. It determines the size and location of the section most susceptible to movement. It is typically a trial and error method, because the most critical zone is not always general.

### 2.4 Phreatic Surface

The term phreatic is used to specify the water table present below the ground. The phreatic surface is the surface where the pore water pressure meets the atmospheric pressure.

### 2.5 Effect of Tension Cracks

Development of Tension cracks along the face or crest of a slope can change the stability. A result of an analysis shows soil possessing zero shearing resistance which is subjected to the section of slippage plane can be affected by tension cracks. Another thing if water gets filled inside the tension crack it will produce some hydrostatic pressure which can alter stability of the slope and can cause slippage of weak planes. But generally safety factor gets less affected by tension cracks.

### 2.6 Limit equilibrium analysis

In this method of Limit equilibrium method it first defines a slip surface, then it analyses the slip surface to obtain the factor of safety, which is defined as the ratio between forces (moments or stresses) causing stability of the mass and those that resisting stability (disturbing forces).

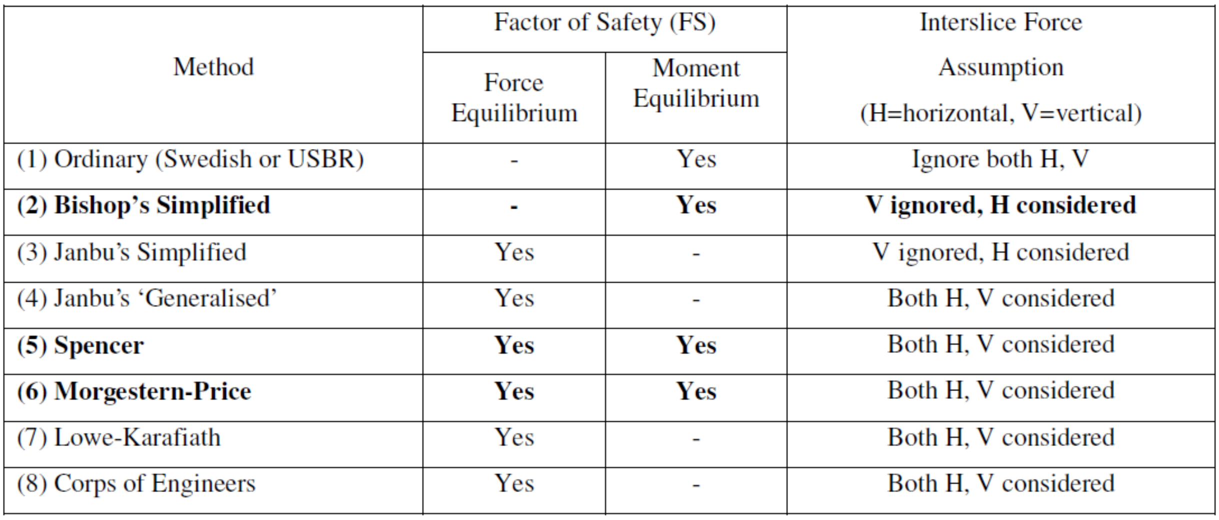
Two-dimensional sections are normally analyzed assuming plain strain conditions. The assumption for these methods is that the linear (*Mohr-Coulomb*) or non-linear relationships between shear strength and the normal stress on the failure surface regulate the shear strengths of the materials in the direction of the potential failure surface.

Functional slope design determines the critical slip surface where the factor of safety is found to be of last value. Computer programs can also help locate failure surface using optimization techniques. The program analyzes the stability of different layered slopes, different embankments, and structures. Fast optimization of different slip surfaces (circular & non-circular surfaces) gives the lowest factor of safety. External forces (Earthquake effects, external effects by loading, groundwater conditions, and stabilization forces) can be included. The software uses method of slices to decide the factor of safety.

### 2.7 Methods of Slice

The unstable soil mass is divided into a series of vertical slices and the slip surface can be circular or it can be polygonal surface. Methods of analysis which employ circular slip surfaces include: Fellenius (1936); Taylor (1949); and Bishop (1955). Methods of analysis which employ non-circular slip surfaces include: Janbu (1973); Morgenstern and Price (1965); Spencer (1967); and Sarma (1973). Table 1 shows equilibrium of force or moment achieved in the various 'assume failure surface' methods using method of slices in calculation of the factor of safety (FS).

Table no-: 2.1 Different Methods of slope stability analyses (from reference no-3)



| Method | Factor of Safety (FS) | | Interslice Force Assumption (H=horizontal, V=vertical) |
|---|---|---|---|
| | Force Equilibrium | Moment Equilibrium | |
| (1) Ordinary (Swedish or USBR) | - | Yes | Ignore both H, V |
| **(2) Bishop's Simplified** | **-** | **Yes** | **V ignored, H considered** |
| (3) Janbu's Simplified | Yes | - | V ignored, H considered |
| (4) Janbu's 'Generalised' | Yes | - | Both H, V considered |
| **(5) Spencer** | **Yes** | **Yes** | Both H, V considered |
| **(6) Morgestern-Price** | **Yes** | **Yes** | Both H, V considered |
| (7) Lowe-Karafiath | Yes | - | Both H, V considered |
| (8) Corps of Engineers | Yes | - | Both H, V considered |

The main differences in the different methods are the supposition on the inter slice forces. For example, the Ordinary Method doesn't include inter slice forces (V=H=0), Simplified Bishop Method presumes inter slice forces are horizontal (V=0, H>0), Spencer's Method considers all inter slice forces are parallel (V>0, H>0) with an unknown inclination which is calculated through iterations, Morgenstern and Price method uses the shear force, V to the normal force, H where V=l *f*(x) H.

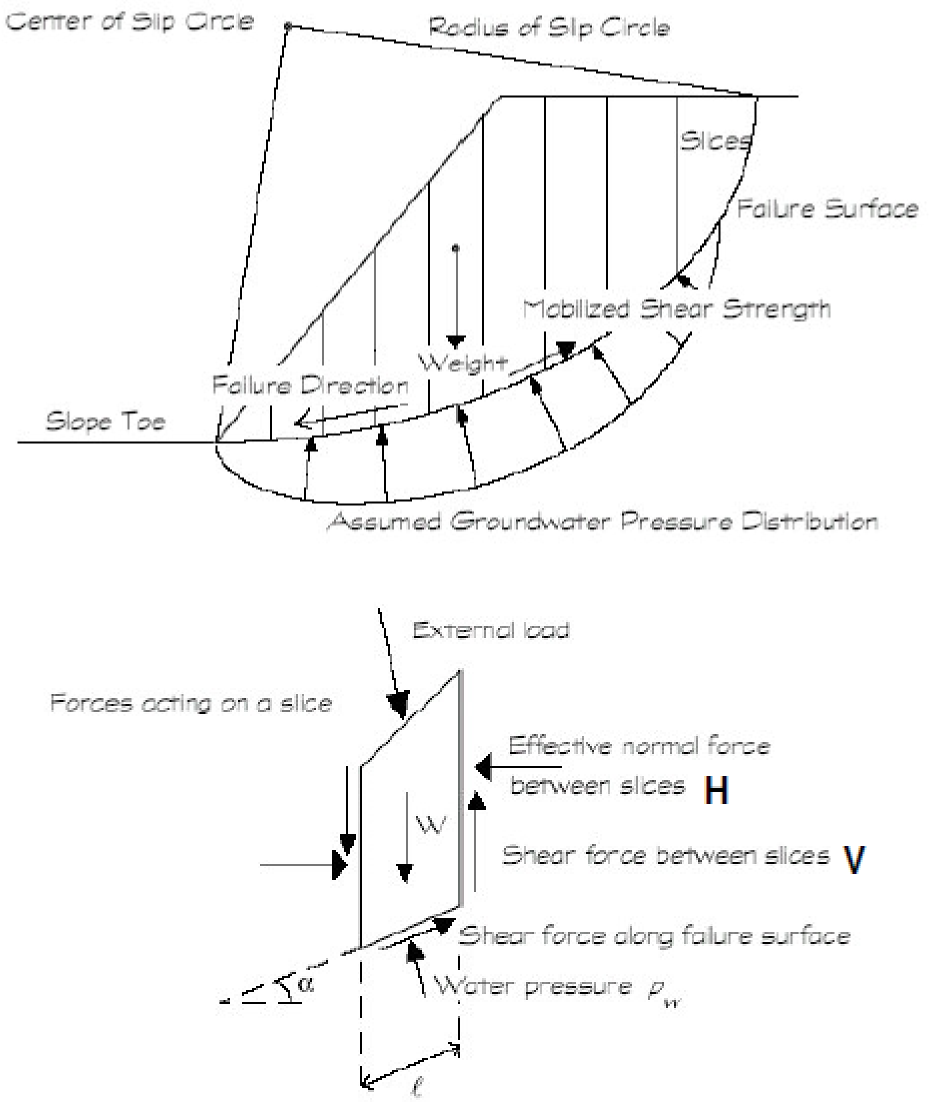


Fig 2.4: Depiction of forces acting on a typical slice (from-reference no-3**)**

### 2.7.1 Ordinary Method of Slices

The ordinary method of slices is the easiest method of slices. The factor of safety is directly calculated by resolving the forces in this method. The basic consideration for this method is that the inter-slice forces are parallel to the base of each slice, thus they can be left.

The factor of safety is:

$$F = \frac{\sum_{i=1}^{n}[c`b\sec\alpha + \;[W\cos\alpha + Q\;\cos(\mu-\alpha) + W_w\cos(\beta-\alpha) + K_h W\sin n\alpha - U.b]\tan\Phi`]}{\sum_{i=1}^{n}(W + W_w\cos\beta + Q\cos\mu)\sin\mu - \sum_{i=1}^{n}(W_w\sin\beta + Q\sin\mu)\left(\cos\alpha - \frac{h}{R}\right) + \sum_{i=1}^{n}K_h W\left(\cos\alpha - \frac{h_a}{R}\right)}$$

### 2.7.2 Bishop’s simplified method

This method doesn’t include the inter-slice forces, so only normal forces are used to determine the inter-slice forces. That’s why Bishops method is also called as trial and error method. In this method, the factor of safety appears on both sides of the equation to calculate the stability of a trial failure mass. The procedure for solution comprises *assuming* value for the factor of safety term on the right side of the equation. When the proper factor of safety has been applied for the trial, the value for right side of the equation will be equal to that of left side**.** Practically, exact agreement is not required to get a factor of safety value considered valid for the assumed slip surface. The result is for a unique trial failure mass, however and, as shown previously, a series of trials is usually required to decide the slope section and failure plane tending to actual failure or having the lowest factor of safety. The Factor safety appears both sides of the equation. The Factor of safety is as follows:

$$F = \frac{\sum_{i=1}^{n}\left[c`b\sec\alpha + \left[\frac{1}{\cos\alpha+\frac{\sin\alpha\tan\Phi}{F}}\left[W-\frac{c`b\tan\alpha}{F}-U.b+W_w\cos\beta+Q\cos\mu\right]\right]\tan\Phi`\right]}{\sum_{i=1}^{n}(W+W_w\cos\beta+Q\cos\mu)\sin\mu-\sum_{i=1}^{n}(W_w\sin\beta+Q\sin\mu)\left(\cos\alpha-\frac{h}{R}\right)}$$

$$+\sum_{i=1}^{n}K_hW\left(\cos\alpha-\frac{h_a}{R}\right)$$

### 2.7.3 Janbu’s Method

In places where there is variation in ground dimensions (the slope is not uniform or well defined) or where the subsurface is layered or otherwise non-isotropic, the soil zone most vulnerable to a sliding failure may not be accurately represented by a circular arc.

Similar to Bishop’s method of analysis, Janbu’s method calculates the factor of safety through an iteration. The process comprises the changes of normal stress on failure surface. The normal forces are generally derived from the addition of vertical forces and the inter-slice forces are neglected. The Factor of safety is:

$$F = \frac{\sum_{i=1}^{n}\left[c`b\sec\alpha + \left[\frac{1}{\cos\alpha+\frac{\sin\alpha\tan\Phi}{F}}\left[W-\frac{c`b\tan\alpha}{F}-U.b+W_w\cos\beta+Q\cos\mu\right]\right]\tan\Phi`\right]}{\sum_{i=1}^{n}(U_b\sin\alpha+WK_h+W_w\sin\beta-Q\sin\mu)}$$

$$+\sum_{i=1}^{n}\left[\frac{1}{\cos\alpha+\frac{\sin\alpha\tan\Phi}{F}}\left[W-\frac{c`b\sin\alpha}{F}-U.b\cos\alpha+W_w\cos\beta+Q\cos\mu\right]\sin\mu\right]$$

### 2.7.4 Spencer’s Method

The Spencer’s method is known as the best method for finding the factor of safety. Both force and moment equilibrium are taken into account. The factor of safety is determined through number of iteration, slice by slice, by varying „F‟ and „δ‟ until force and moment equilibrium equated . The force equilibrium equation is:

$$Z_R = Z_L + \frac{FW\sin\alpha - c`b\sec\alpha - W\cos\alpha\tan\Phi`}{\sin(\delta-\alpha)\tan\Phi` - F\cos(\delta-\alpha)} + \frac{U.b\sec\alpha\tan\Phi` + WK_h(F-\tan\Phi`\tan\alpha)\cos\alpha}{\sin(\delta-\alpha)\tan\Phi` - F\cos(\delta-\alpha)} + \frac{Q[F\sin(\alpha-\mu)-\cos(\alpha-\mu)\tan\Phi`]}{\sin(\delta-\mu)\tan\Phi` - F\cos(\delta-\alpha)} + \frac{W_w[F\sin(\alpha-\mu)-\cos(\alpha-\mu)\tan\Phi`]}{\sin(\delta-\mu)\tan\Phi` - F\cos(\delta-\alpha)}$$

The Moment equilibrium equation is:

$$h_R = \frac{Z_L}{Z_R}h_L - \frac{Z_L}{Z_R}\frac{b}{2}\tan\alpha + \frac{Z_L}{Z_R}\frac{b}{2}\tan\delta + \frac{hW_w\sin\beta}{Z_R\cos\delta} + \frac{hQ\sin\mu}{Z_R\cos\delta} - \frac{h_a k_h W}{Z_R\cos\delta}$$

### 2.8 Slope Stability Analysis System – GALENA

*GALENA* is constructed to be a simple, user-favorable yet very efficient slope stability software system. It was initially developed to satisfy the need of BHP (now known as BHP Billiton) geotechnical engineers who eventually see that there were many problems with other slope stability analysis software systems available. Geotechnical engineering seldom gives one unique answer and extensive parametric studies are often required before realistic results are calculated. *GALENA* enables such parametric studies to be undertaken firstly and easily.

The *GALENA* system comprises slope stability problems as they are largely encountered in the field. That is, the total geology normally remains the same; it is the slope surface that needs change in many situations. In *GALENA***,** the total geology is specified for the model, including the material properties. Material above the slope surface is ignored since this has been removed or mined out. In this way, *GALENA* enables a large number of analyses to be undertaken without the need to redefine the model each time.

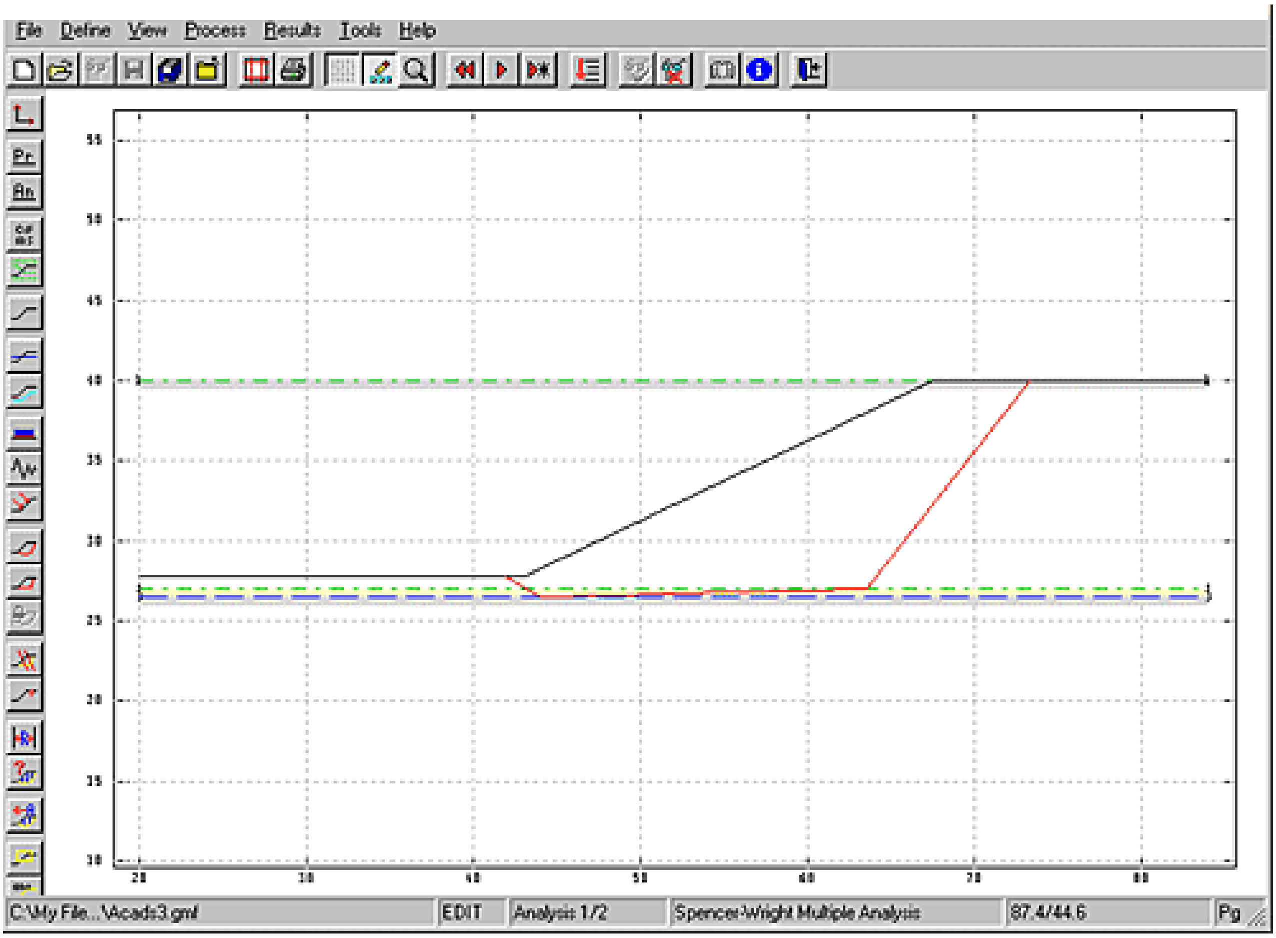


Figure no 2.5: A typical slope analysis in GALENA

*GALENA* involves the Bishop Simplified, the Spencer-Wright and the Sarma methods of analysis to calculate the stability of slopes. The Bishop method determines the stability of circular failure surfaces, the Spencer-Wright method is applicable for circular and non-circular failure surfaces, and the Sarma method is used for problems where non-vertical slices are required, or is used for more complex stability problems. It is possible to analyze more than one layered slopes with tension cracks, earthquake forces, externally distributed loads and forces, and pore pressures from within or above the slope (e.g. dams and river banks) including phreatic surfaces and piezometric pressures. *GALENA* incorporates various techniques for locating the critical failure surface with user-supplied restraints. There is alos facility to do back analysis to decide material properties according to desired safety factor.

Either effective or total stresses may be used on any material layer. For the total stress case, the increase in undrained shear strength with depth can be simulated using Skempton's relationship by simply entering the value of the plasticity index for that material.

Probabilistic analysis can be readily undertaken using either defined material properties, or defined mean values, and standard deviation for the production of density and distribution plots. *GALENA* allows shear strength to be defined using traditional c and phi values, the Hoek-Brown (1983) failure criterion (m, s and UCS), or with shear/normal data from curves of any shape.

### 2.9.1 Methods of Analysis

*GALENA* comprises three different methods of slope stability analysis:

i. BISHOP SIMPLIFIED METHOD - suitable for circular failure surfaces.
ii. SPENCER-WRIGHT METHOD - suitable for circular and non-circular failure surfaces.
iii. SARMA METHOD - suitable for more complex problems particularly where non-vertical slice boundaries (such as faults or discontinuities) are significant.

In most instances, slope stability problems can be analyzed with one of the above methods. However, for complex slope stability problems where in-situ stresses are significant, it may be more appropriate to use a stress analysis method such as finite element or finite difference etc. Nevertheless, ***GALENA*** will provide fast and accurate answers for most slope stability problems and it has some features that are designed a particularly for the practicing geotechnical engineer, which are detailed within this User's manual.

# Chapter 3

# MINE DESCRIPTION AND FIELD DATA COLLECTION

# 3. MINE DESCRIPTION AND FIELD DATA COLLECTION

## 3.1 M**ine description and layout of dump slope**

The aim of this research work is to analysis the safety status of a dump slope of a nearby iron mine. So several samples are collected from different places of bench. The mine is in the state of Kiriburu area, Jharkhand, about 200 km from Rourkela. The parent rocks of the deposits is Banded Iron Formation (BIF) with iron bands present in the form of magnetite, goethite, maghemite, etc (SGAT, 2006). In addition the BIF along with volcano sedimentary rock pile constitute the iron ore group. The typical ores which are found in this region are Haematite, Magnetite, Goethite and Siderite. The major chemical composition of the iron ore produced here are Haematite ($Fe_2O_3$), Magnetite (Fe3O4). The cut-off grade of Iron in the ore in this region is 55%. So material having cut-off grade less than 55 % is selected to be dumped. The mine is mainly operated by open cast method. The main mechanization involved in mining operations are drilling, blasting, shovel and dumper combinations. The dumper size is of 30 TE. The waste generated during the mining operation are dumped in a selected area called dump. The area available for dumping is 172m×249m. the waste are dumped by 30 te trucks and compacted by dozers . At present the present height of the dump is around 41-45 m. samples are mainly collected from two sections they are xx and yy .

### 3.1.1 Section xx

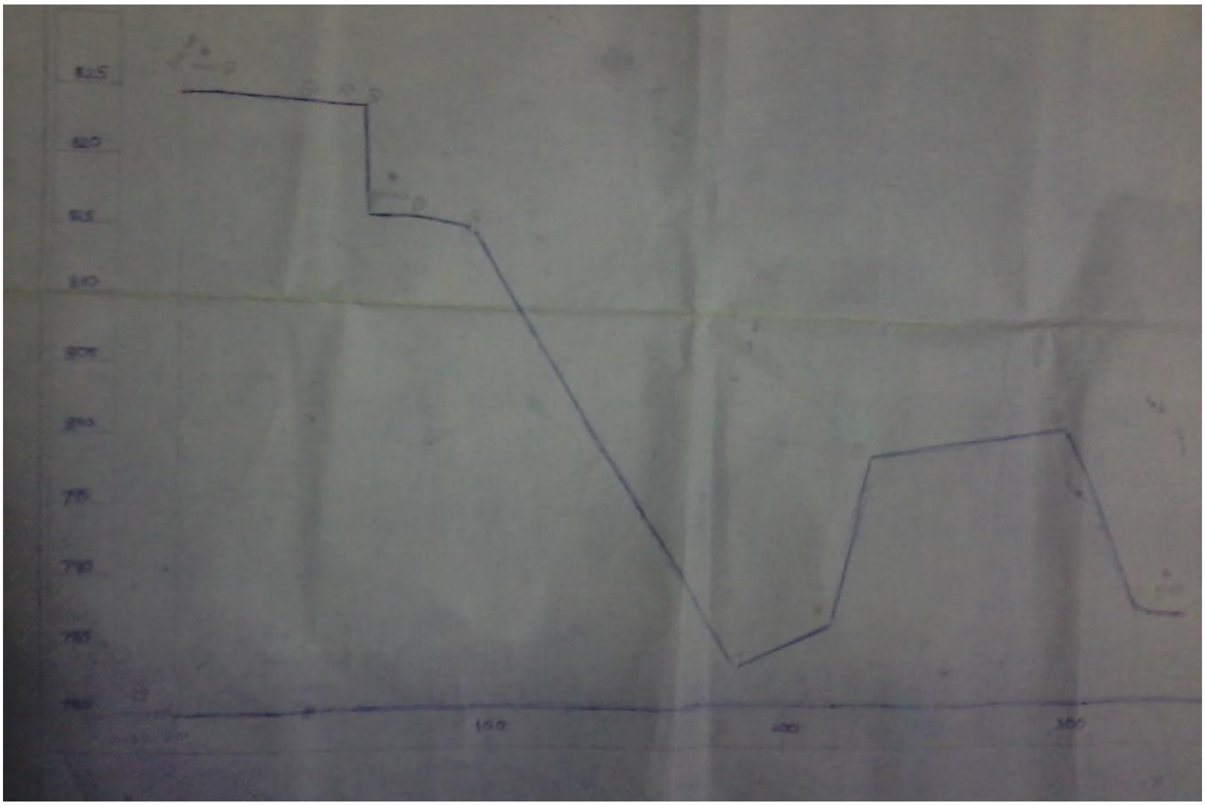


Fig no 3.1

### 3.1.2 Section yy

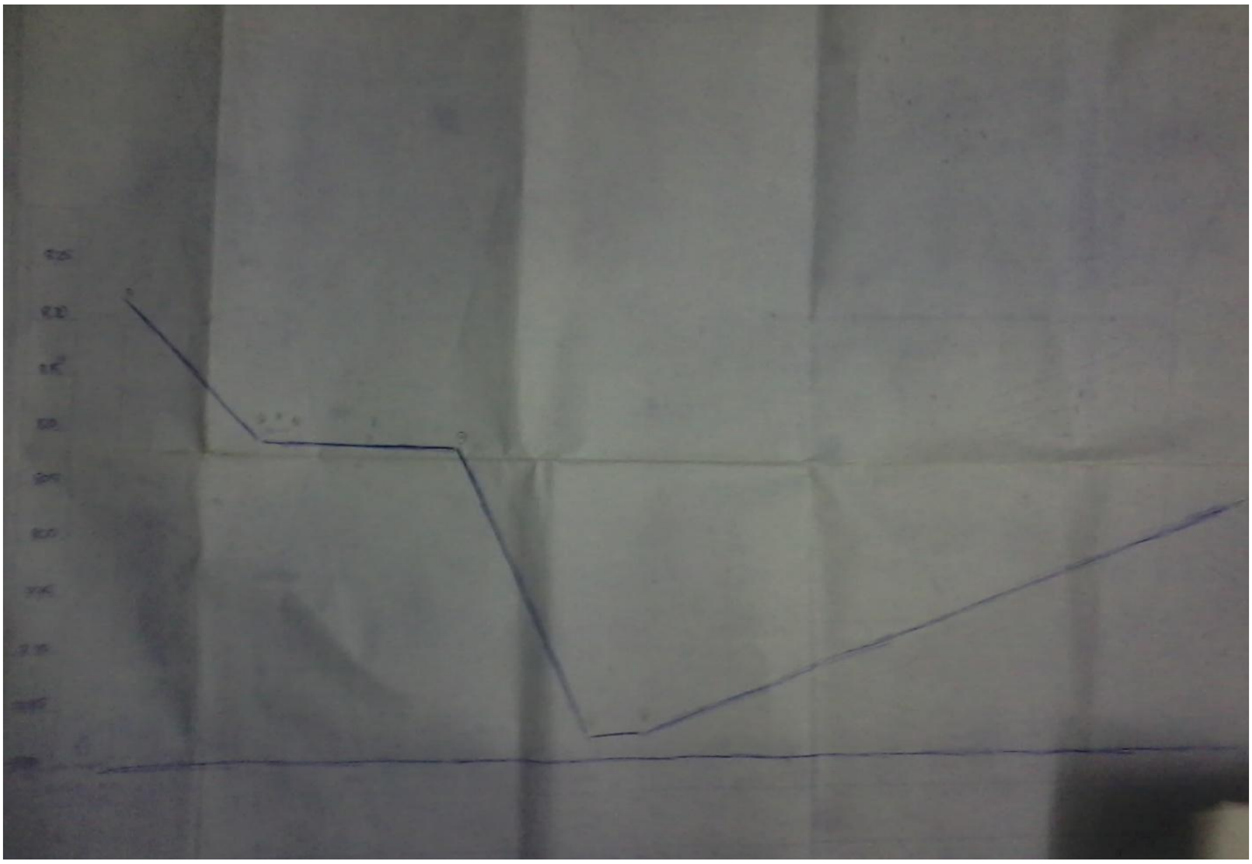


Fig no :-3.2

### 3.2 Sample Preparation and collection:

The samples were obtained from six different places of the dump during the autumn season. Initially the ground was dug up to half meter to take samples of proper moisture content representing the total dump. The locations from where the samples sourced were selected after careful consideration to represent the whole area. The location was first cleared of soft soil cover, then a trench of about 2 to 3 m deep was dug. Then a hollow cylindrical mould of 6 inch dia and 10 inch long was put into the ground by continuous and careful hammering. Then the cylindrical mould along with the soil inside of it was taken carefully out of the ground which was then properly packed to prevent the passage of air. The packing was done by the help of plastic gunny bags to ensure air tight packing as shown in figure 3.5 and 3.6. Proper care was taken to ensure that the parameters of the sample doesn't change during bringing it to the lab. The preparation process is shown in the following figure 3.3-3.6.

Fig 3.3: Preparation of location of sample collection    Fig 3.4: mould with sample

Fig 3.5: Sealing of the mould

Fig 3.6: Collected sample

# Chapter 4

# TESTS, PROCEDURES AND RESULTS

# 4. LAB TESTS, PROCEDURES AND RESULTS

For estimating the slope stability of the studied mine the following geological parameters are determined.

1. Unit weight ‘γ’

2. Cohesion ‘c’

3. Friction angle ‘ø’ (UU test)

4. Angle of repose ‘ß’

5. Pore water pressure.

The tests as proctor compaction test and triaxial test are depicted below.

## 4.1 Proctor Compaction Test (ASTM D698):

**Aim:** To determine the Maximum dry density and optimum moisture content.

**Equipment used**

1-Proctor Mould with a detachable collar assembly and a base plate.

2-Manual rammer weighing 2.5 kg which can provide a height of 30 cm free fall.

3-A sensitive balance and sample extruder.

4-a Straight edge.

5-Squeeze bottle

6-Mixing tools such as mixing pan, spoon, trowel, spatula etc.

7-Moisture cans.

8-Drying Oven

**Test procedure**

1. 10 lb (4.5 kg) of air-dried soil was obtained in the mixing pan. All the lumps are broken so that it passes No. 4 sieve.

2. Approximate amount of water was added to increase the moisture content by about **5**% .

3. The weight of empty proctor mould without the base plate and the collar was determined.

4. Collar and base plate was fixed.

5. The first portion of the soil in the Proctor mould was placed and compacted the layer applying 25 blows.

6. The layer was scratched with a spatula forming a grid to ensure uniformity in distribution of compaction energy to the subsequent layer. Again the second layer was placed and 25 blow applied same procedure carried out for the last portion..

7. It is ensured that the compacted soil was just above the rim of the mould.

8. The collar was detached carefully without disturbing the compacted soil.

9. The weight of the mould with the moist soil was determined. The sample was extruded and broken into pieces collect the sample for water content determination preferably from the middle of the specimen.

10. Empty moisture cans are weighed. Keep this can in the oven for water content determination.

11. The rest of the compacted soil were broken with hand (visually ensure that it passes US Sieve No.4). More water were added to increase the moisture content by 2%.

12. Steps 4 to 11 were repeated. During this process the weight increased for some time with the increase in moisture and dropped suddenly. Two moisture increments were taken after the weights starts reducing. At least 4 points were obtained to plot the dry unit weight, moisture content variation.

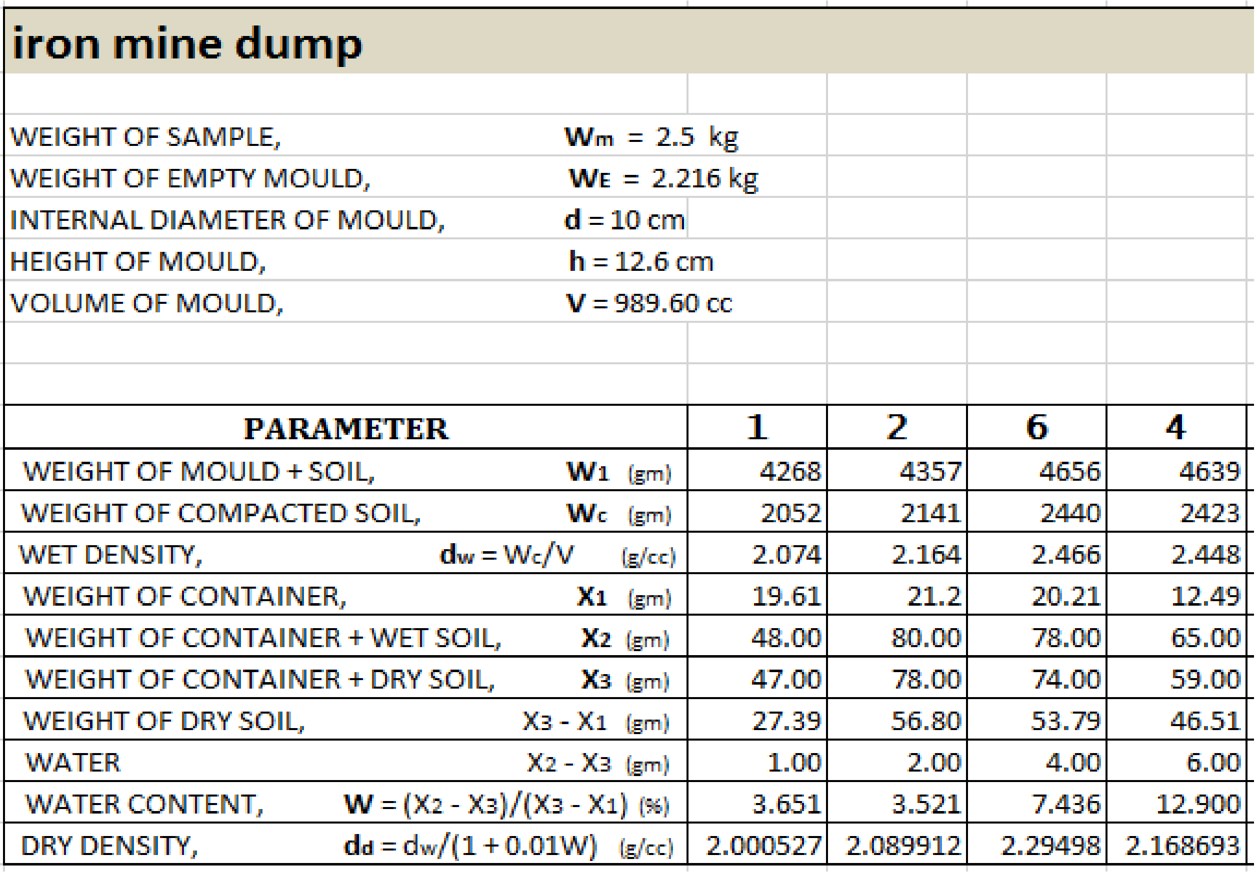
13. After 24 hrs of the sample in the oven was recovered and the weight was determined.

14. Then the complete tabulation done

Fig:- 4.1: Proctor Compaction Apparatus

Fig:- 4.2: Application of blows

Table no:-4.1 Results of proctor compaction test



**iron mine dump**

WEIGHT OF SAMPLE, $W_m$ = 2.5 kg
WEIGHT OF EMPTY MOULD, $W_E$ = 2.216 kg
INTERNAL DIAMETER OF MOULD, **d** = 10 cm
HEIGHT OF MOULD, **h** = 12.6 cm
VOLUME OF MOULD, **V** = 989.60 cc

| PARAMETER | | | 1 | 2 | 6 | 4 |
|---|---|---|---|---|---|---|
| WEIGHT OF MOULD + SOIL, | $W_1$ | (gm) | 4268 | 4357 | 4656 | 4639 |
| WEIGHT OF COMPACTED SOIL, | $W_c$ | (gm) | 2052 | 2141 | 2440 | 2423 |
| WET DENSITY, | $d_w = W_c/V$ | (g/cc) | 2.074 | 2.164 | 2.466 | 2.448 |
| WEIGHT OF CONTAINER, | $X_1$ | (gm) | 19.61 | 21.2 | 20.21 | 12.49 |
| WEIGHT OF CONTAINER + WET SOIL, | $X_2$ | (gm) | 48.00 | 80.00 | 78.00 | 65.00 |
| WEIGHT OF CONTAINER + DRY SOIL, | $X_3$ | (gm) | 47.00 | 78.00 | 74.00 | 59.00 |
| WEIGHT OF DRY SOIL, | $X_3 - X_1$ | (gm) | 27.39 | 56.80 | 53.79 | 46.51 |
| WATER | $X_2 - X_3$ | (gm) | 1.00 | 2.00 | 4.00 | 6.00 |
| WATER CONTENT, | $W = (X_2 - X_3)/(X_3 - X_1)$ | (%) | 3.651 | 3.521 | 7.436 | 12.900 |
| DRY DENSITY, | $d_d = d_w/(1 + 0.01W)$ | (g/cc) | 2.000527 | 2.089912 | 2.29498 | 2.168693 |

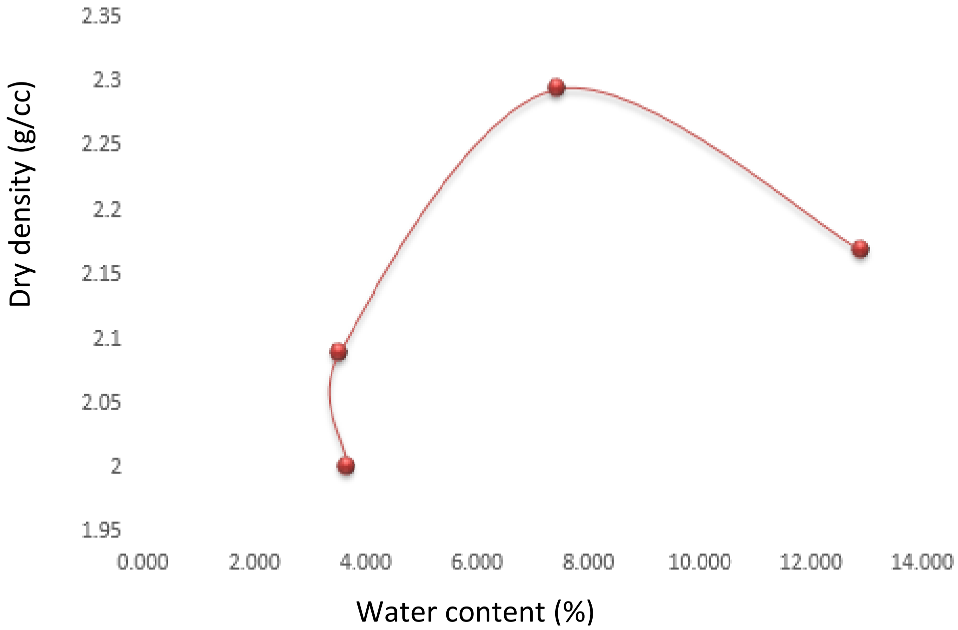


Fig no-: 4.3 Graph between dry density and moisture content

Thus the maximum dry density and the optimum water content of the samples determined were 2.2949 g/cc and 7.436 % respectively (figure-4.3).

### 4.2 Tri-Axial Test (ASTM D2850):

This test method determine the strength and stress-strain relationships of a cylindrical specimen of undisturbed or remolded cohesive soil. Specimens are subjected to a confining fluid pressure in a tri-axial chamber. No drainage of the specimen was permitted during the test. The specimen is sheared in compression without drainage at a constant rate of axial deformation (strain controlled).This test method provides data for calculating un-drained strength properties and stress-strain relations for soils. This test method provides for the measurement of the total stresses applied to the specimen, that is, the stresses are not corrected for pore-water pressure.

Apparatus For conducting the test, the testing system consists of the following five major functional components:

a) System to house the sample, that is, a tri-axial cell;

b) System to apply cell pressure and maintain it at a constant magnitude;

c) System to apply additional axial stress;

d) System to measure pore water pressure; and

e) System to measure changes of volume of the soil sample.

### 4.1.1Elements Used within the Triaxial Cell (figure no- 4.4)

The Tri-axial Test may be programmed so as to allow or exclude the hydraulic connection between the inside of the sample with the ambient outside the tri-axial cell or with special measuring instruments. Such connections may require the use of special and perfect drainage mediums around the sample, in particular: Porous Discs are required on the top and bottom of the sample and Filter Drains around its sides. However, when the sample is isolated, the bottom porous disc has to be replaced by an impermeable Base Disc whilst the upper porous disc has to be removed. In each case the sample was placed on a Pedestal and a Top Cap was placed on top of the sample. These elements will have the equal diameter as the sample. To make the sample isolated from the water within the tri-axial cell, it is covered with a very thin Membrane made of natural rubber (of appropriate diameter) which is placed over the sample using a Suction Membrane Stretcher and a water-tight fit is guaranteed at the junction with the pedestal and top cap by using Sealing Rings of appropriate diameter.

### 4.1.2 Sample Preparation for Tri-axial Testing

The samples are prepared with the use of a cylindrical mold . It has the following specifications as shown in table no :- 4.2

| Length (cm) | Diameter (cm) | L/D ratio | Volume (cm$^3$) |
|---|---|---|---|
| 10 | 5 | 2 | 196.4 |

As calculated from proctor compaction Test,

Maximum Dry Density =2.294 g/cc

Optimum moisture content =7.436%

Hence, Mass of the sample needed 2.294×196.4=450.54 gm

Water required =33.5 ml

The cylindrical shaped samples were tested using Tri-axial apparatus. A stress vs. strain curve was plotted. The maximum value of the stress is considered as the deviatory stress, from which the corresponding major and minor principal stresses are found out.

Minor Principal Stress = Cell confining Pressure.

Major Principal Stress = Deviatory Stress (Calculated from the stress-strain curve of the triaxial test) + Minor Principal Stress.

Fig no:- 4.4 triaxial testing apparatus

Fig no:-4.5 sample under test

Fig no :-4.6 sample before testing

fig no :-4.7 sample after failure

Table no-4.3 Result of Tri-axial Test

| **SAMPLE NO** | **Minor Principal Stress kPa** | **Load (N)** | **Major Principal Stress KPA (Load/area)** |
|---|---|---|---|
| 1 | 100 | 550 | 280.254 |
|  | 200 | 875 | 445.86 |
|  | 300 | 1150 | 585.987 |
| 2 | 100 | 575 | 292.993 |
|  | 200 | 900 | 458.993 |
|  | 300 | 1100 | 560.509 |
| 3 | 100 | 500 | 254.7 |
|  | 200 | 700 | 356.687 |
|  | 300 | 1000 | 509.554 |
| 4 | 100 | 380 | 193.630 |
|  | 200 | 575 | 292.993 |
|  | 300 | 775 | 394.904 |
| 5 | 100 | 475 | 242.038 |
|  | 200 | 650 | 331.210 |
|  | 300 | 900 | 458.598 |
| 6 | 100 | 525 | 267.575 |
|  | 200 | 775 | 394.904 |
|  | 300 | 1050 | 535.031 |

From the values of the Major and Minor principal stress, the cohesion(c) and friction angle (ø) values are calculated using Mohr-Coulomb criterion with the help of Roc-Data (ver 4.0, make: Roc-science Inc, Canada) software.

# Chapter 5

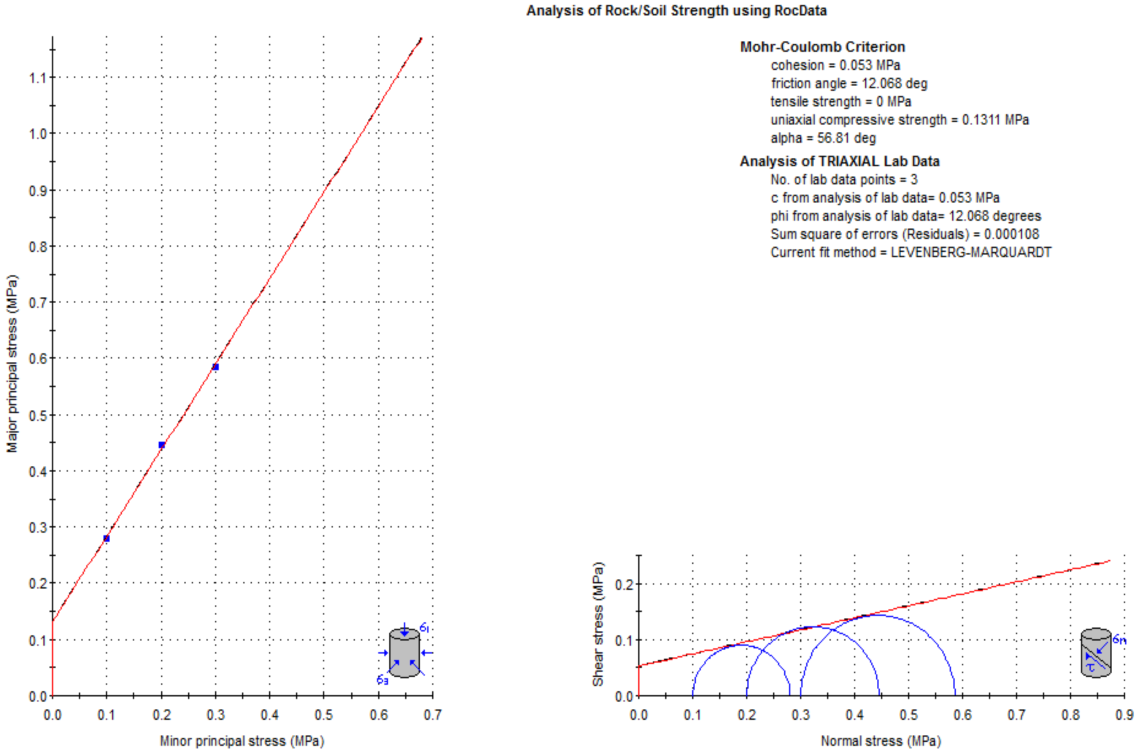
# ANALYSIS OF DATA

# 5. ANALYSIS OF RESULTS

Here analysis of the results from the lab tests are done by the help of two software and they are ROCLAB (ver 4.0)and GALENA (ver 6.0).

## 5.1 Mohr Coulomb Analyses (roc-lab software)

Mohr –Coulomb analysis was carried out by using the program "Roc-Data‟. Here, the Major Principal Stress and Minor principal stress are given as inputs. The different Mohr's circles for different samples are shown below.

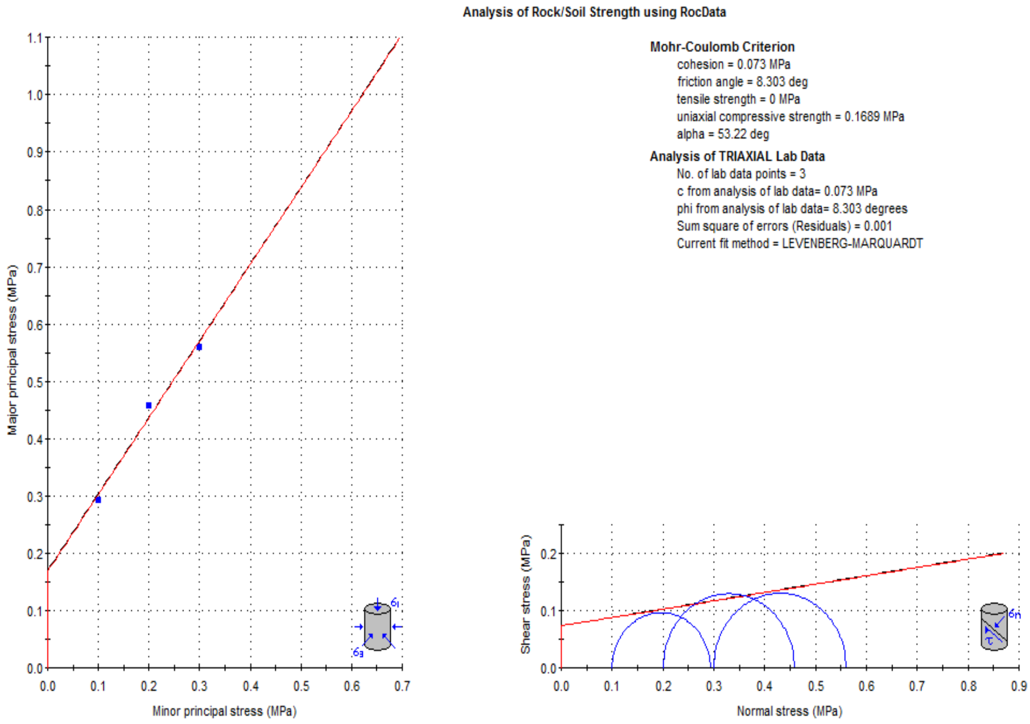


**Analysis of Rock/Soil Strength using RocData**

**Mohr-Coulomb Criterion**
cohesion = 0.053 MPa
friction angle = 12.068 deg
tensile strength = 0 MPa
uniaxial compressive strength = 0.1311 MPa
alpha = 56.81 deg

**Analysis of TRIAXIAL Lab Data**
No. of lab data points = 3
c from analysis of lab data= 0.053 MPa
phi from analysis of lab data= 12.068 degrees
Sum square of errors (Residuals) = 0.000108
Current fit method = LEVENBERG-MARQUARDT

Fig no :-5.1 Mohr's circle for sample 1

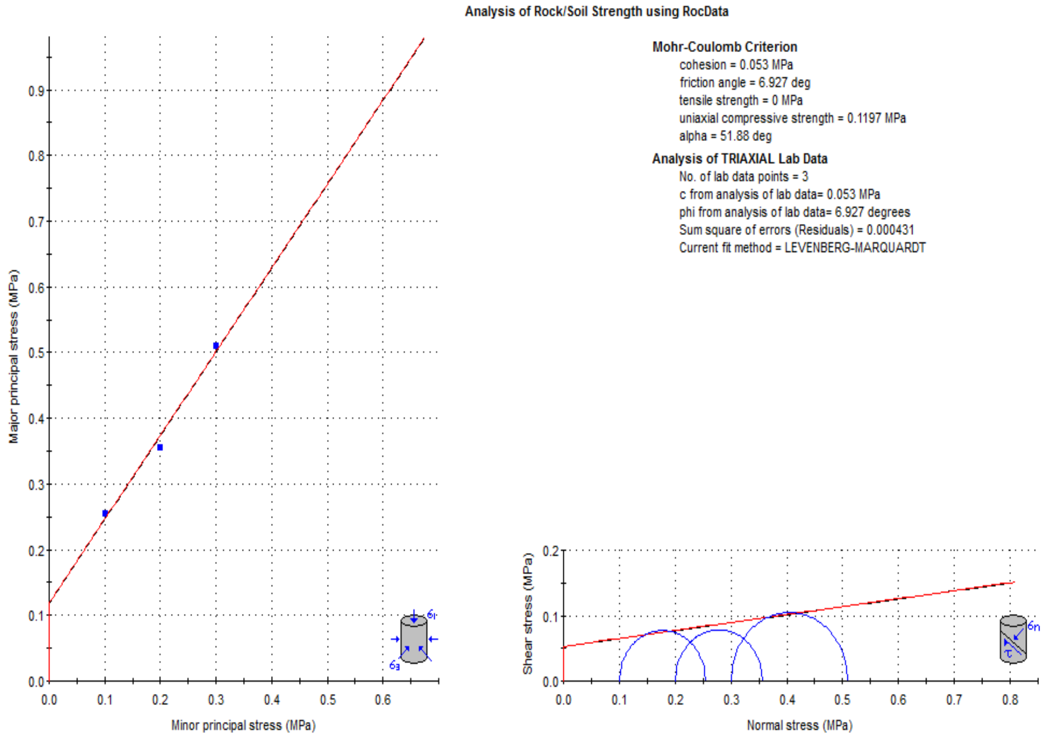


Analysis of Rock/Soil Strength using RocData

**Mohr-Coulomb Criterion**
cohesion = 0.073 MPa
friction angle = 8.303 deg
tensile strength = 0 MPa
uniaxial compressive strength = 0.1689 MPa
alpha = 53.22 deg

**Analysis of TRIAXIAL Lab Data**
No. of lab data points = 3
c from analysis of lab data= 0.073 MPa
phi from analysis of lab data= 8.303 degrees
Sum square of errors (Residuals) = 0.001
Current fit method = LEVENBERG-MARQUARDT

Fig no :- 5.2 Mohr’s circle for sample 2

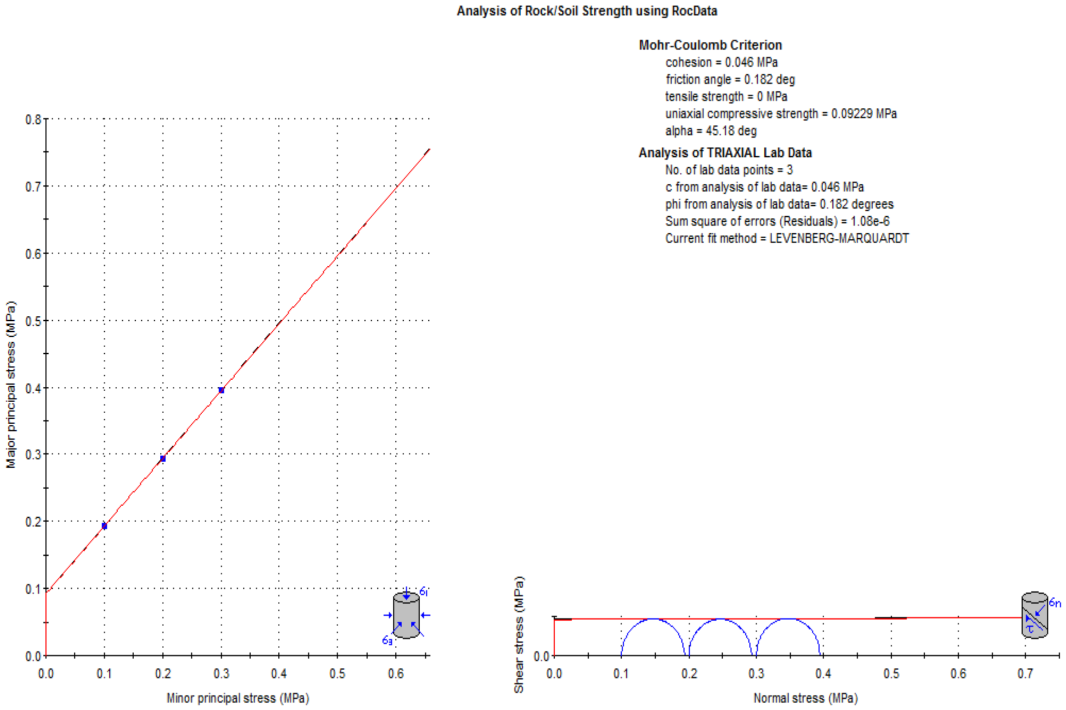


Analysis of Rock/Soil Strength using RocData

**Mohr-Coulomb Criterion**
cohesion = 0.053 MPa
friction angle = 6.927 deg
tensile strength = 0 MPa
uniaxial compressive strength = 0.1197 MPa
alpha = 51.88 deg

**Analysis of TRIAXIAL Lab Data**
No. of lab data points = 3
c from analysis of lab data= 0.053 MPa
phi from analysis of lab data= 6.927 degrees
Sum square of errors (Residuals) = 0.000431
Current fit method = LEVENBERG-MARQUARDT

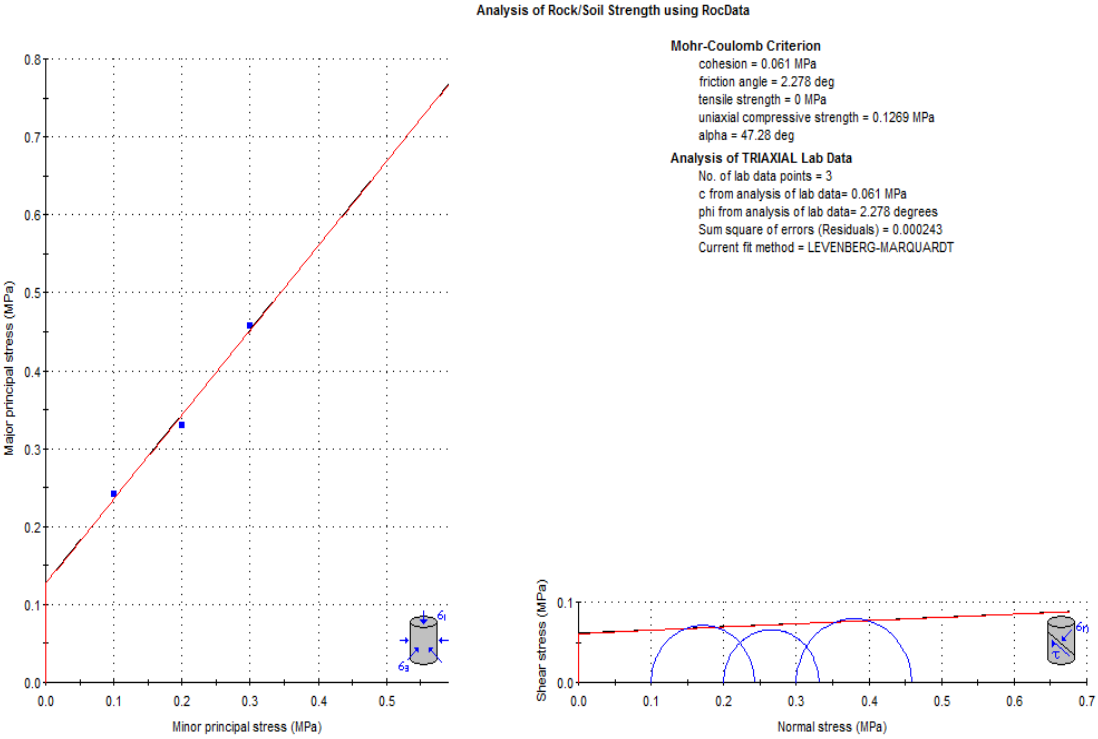
Fig no :- 5.3 Mohr’s circle for sample 3


Analysis of Rock/Soil Strength using RocData

**Mohr-Coulomb Criterion**
cohesion = 0.046 MPa
friction angle = 0.182 deg
tensile strength = 0 MPa
uniaxial compressive strength = 0.09229 MPa
alpha = 45.18 deg

**Analysis of TRIAXIAL Lab Data**
No. of lab data points = 3
c from analysis of lab data= 0.046 MPa
phi from analysis of lab data= 0.182 degrees
Sum square of errors (Residuals) = 1.08e-6
Current fit method = LEVENBERG-MARQUARDT

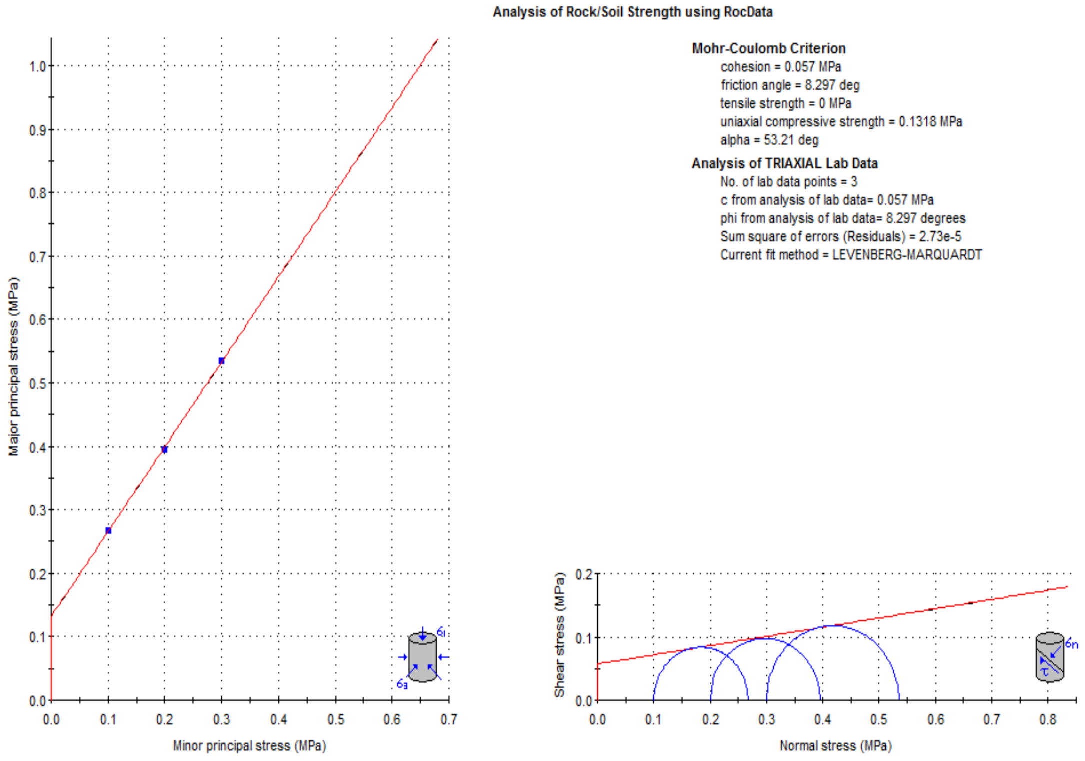
Fig no :- 5.4 Mohr’s circle for sample 4


Analysis of Rock/Soil Strength using RocData

**Mohr-Coulomb Criterion**
cohesion = 0.061 MPa
friction angle = 2.278 deg
tensile strength = 0 MPa
uniaxial compressive strength = 0.1269 MPa
alpha = 47.28 deg

**Analysis of TRIAXIAL Lab Data**
No. of lab data points = 3
c from analysis of lab data= 0.061 MPa
phi from analysis of lab data= 2.278 degrees
Sum square of errors (Residuals) = 0.000243
Current fit method = LEVENBERG-MARQUARDT

Fig no :-5.5  Mohr’s circle for sample 5



```
Analysis of Rock/Soil Strength using RocData

Mohr-Coulomb Criterion
    cohesion = 0.057 MPa
    friction angle = 8.297 deg
    tensile strength = 0 MPa
    uniaxial compressive strength = 0.1318 MPa
    alpha = 53.21 deg
Analysis of TRIAXIAL Lab Data
    No. of lab data points = 3
    c from analysis of lab data= 0.057 MPa
    phi from analysis of lab data= 8.297 degrees
    Sum square of errors (Residuals) = 2.73e-5
    Current fit method = LEVENBERG-MARQUARDT
```

Fig no :- 5.6 Mohr's circle for sample 6

Table no 5.1 Results from the Mohr's circle Analysis

| Sample no | Cohesion(c) ( kpa) | Friction angle (ø) ( degree) |
|---|---|---|
| 1 | 53.233 | 12.068 |
| 2 | 73.488 | 8.303 |
| 3 | 52.617 | 6.927 |
| 4 | 46.137 | 0.187 |
| 5 | 61.211 | 2.278 |
| 6 | 56.950 | 8.297 |

From the six sample we can consider three sample as hard, medium and soft according to the cohesion and friction angle .so they are

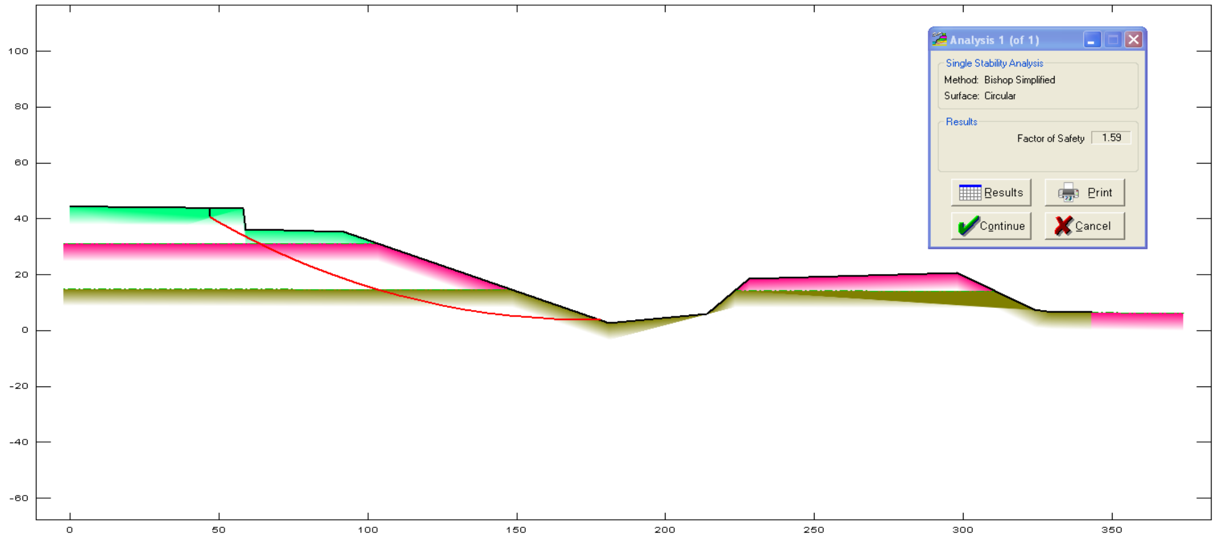
- Hard-: C-53.233kpa ø-12.068
- Mid-: C-65.219kpa ø-8.3
- Soft-: C-52.617kpa ø-6.927

As we have two section plan (ie-xx and yy) we can have 6 profiles by arranging three type of material to different section ie-top, med and bottom.

Table no 5.2 The profiles are

| **section** | **Profile 1(xx)** | **Profile 2(xx)** | **Profile 3(xx)** | **Profile 4(yy)** | **Profile 5(yy)** | **Profile 6(yy)** |
|---|---|---|---|---|---|---|
| Top | Soft | Medium | Hard | Soft | Medium | Hard |
| Med | Medium | Hard | Soft | Medium | Hard | Soft |
| bottom | hard | soft | medium | hard | soft | Medium |

5.2 Analysis of safety factor by using “GALENA” Section xx



Analysis 1 (of 1)

Single Stability Analysis

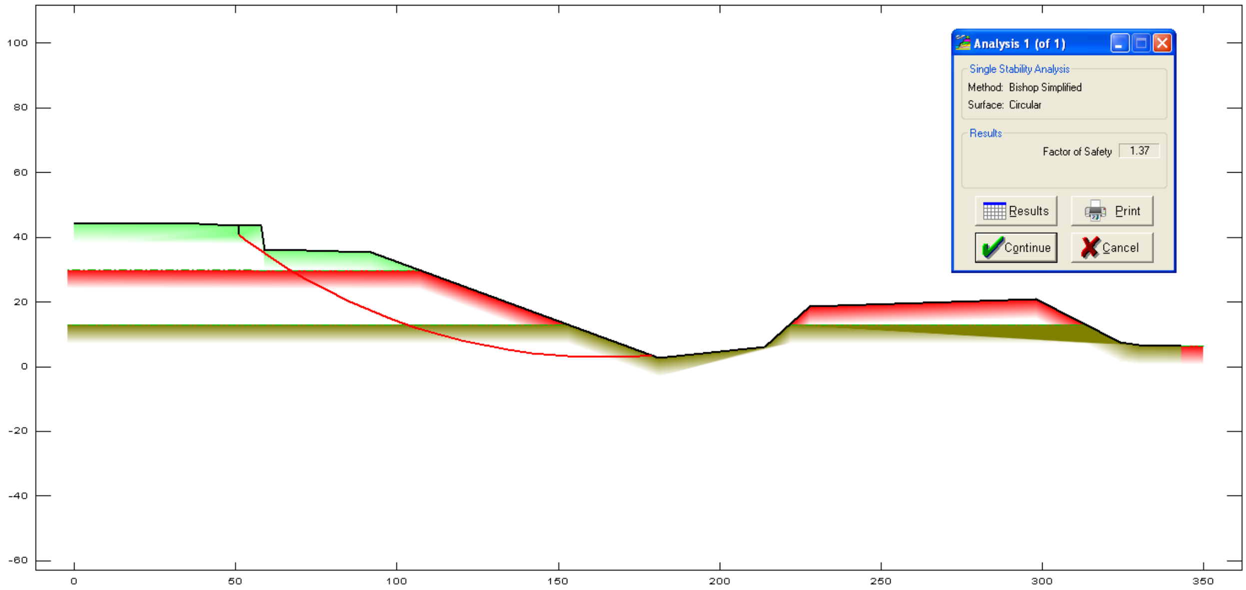
Method: Bishop Simplified

Surface: Circular

Results

Factor of Safety 1.59

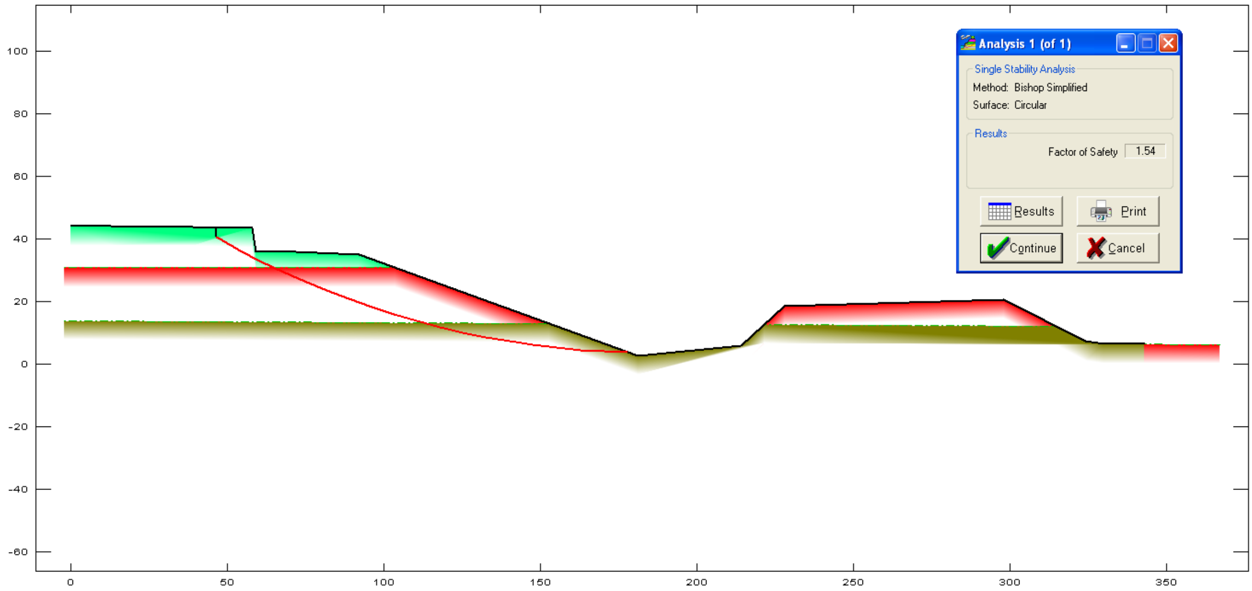
Fig no-: 5.7 Profile 1



Single Stability Analysis
Method: Bishop Simplified
Surface: Circular

Results
Factor of Safety 1.37

Fig no-: 5.8 Profile 2

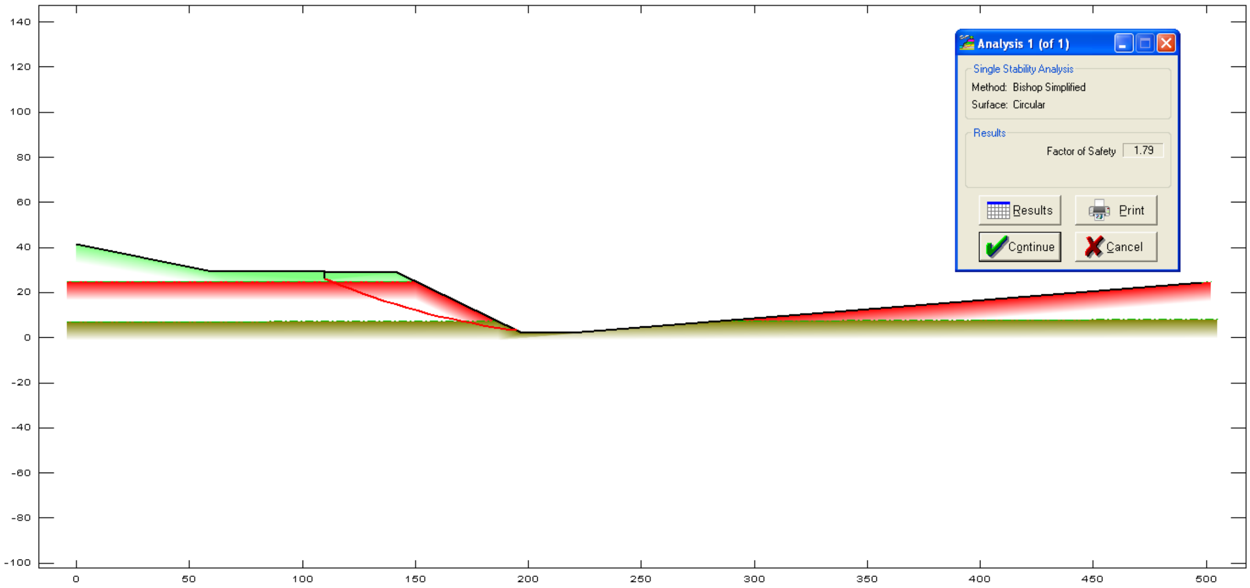


Single Stability Analysis
Method: Bishop Simplified
Surface: Circular

Results
Factor of Safety 1.54

Fig no-: 5.9 profile 3

## Section yy



Analysis 1 (of 1)

Single Stability Analysis

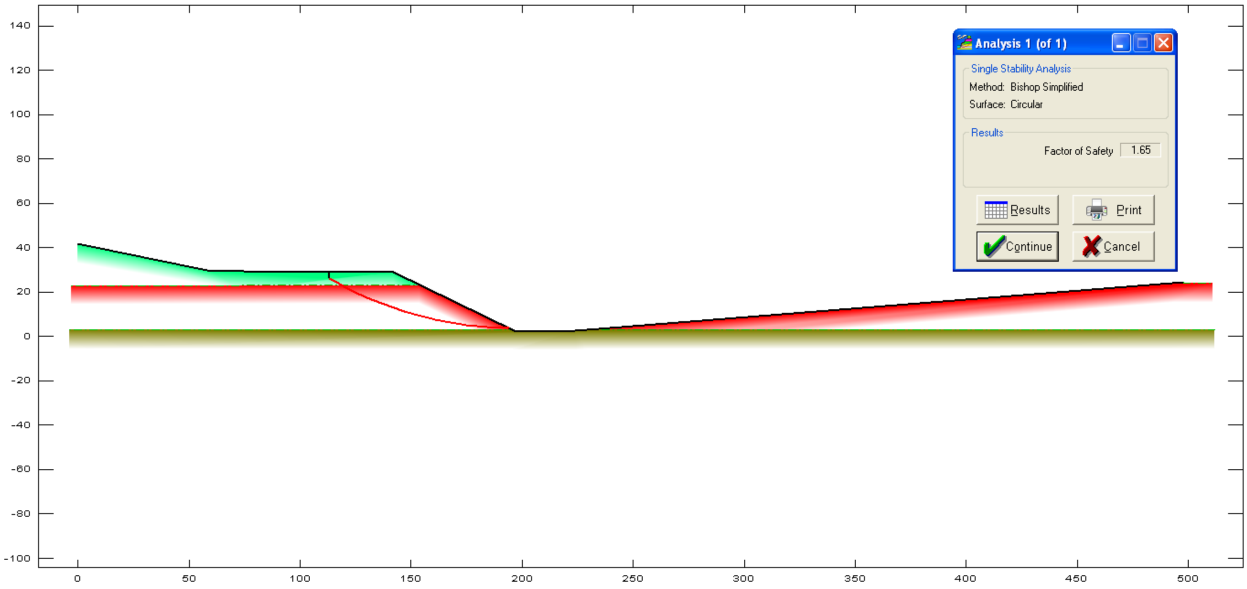
Method: Bishop Simplified

Surface: Circular

Results

Factor of Safety 1.79

Fig no-:5.10 profile 4



Analysis 1 (of 1)

Single Stability Analysis

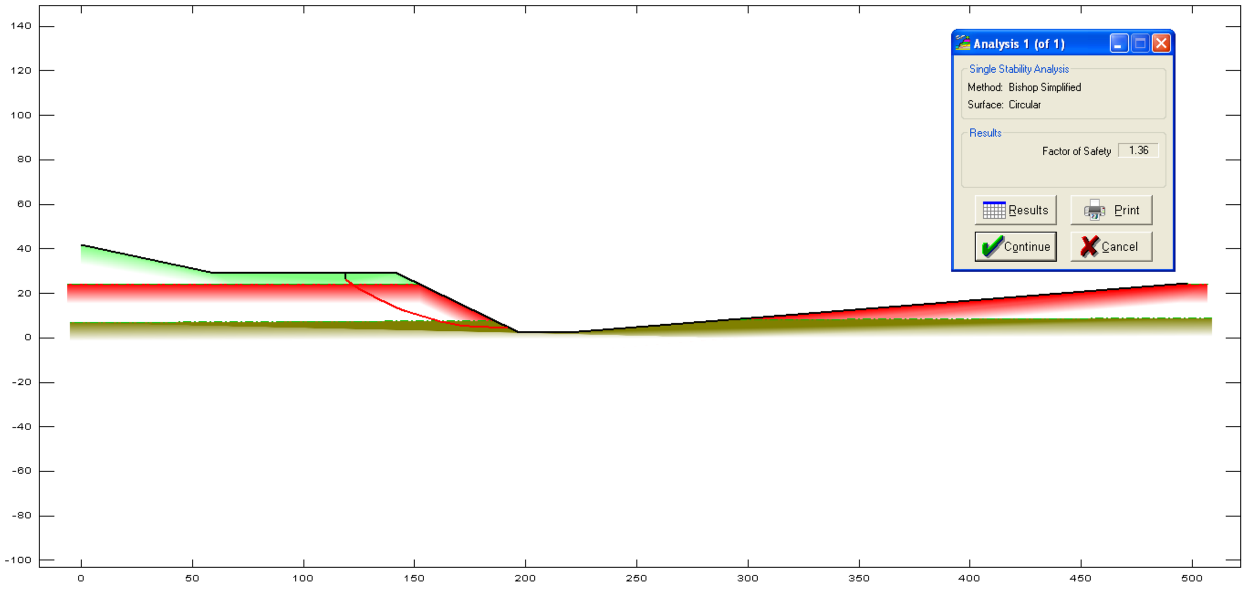
Method: Bishop Simplified

Surface: Circular

Results

Factor of Safety 1.65

Fig no-: 5.11 profile 5



Method: Bishop Simplified
Surface: Circular
Factor of Safety 1.36

Fig no-: 5.12 profile 6

Table no-: 5.3 Factor of safety of different sections are

| profile no | Factor of safety |
|---|---|
| 1 | 1.53 |
| 2 | 1.37 |
| 3 | 1.54 |
| 4 | 1.79 |
| 5 | 1.65 |
| 6 | 1.36 |

From the above slope stability analysis it is clear that all the six profiles of the two sections (ie-xx and yy) are safe as they all have safety factor more than 1.3.

# Chapter 6

## DESIGN OF AN OPTMUM DUMP SLOPE

# 6. DESIGN OF AN OPTIMUM DUMP SLOPE

From the existing slope analysis it is clear that the slopes of the mine under study are safe, but with flatter slope angle of about $11^0$. Hence improvement of the slope bench was considered. There are two types of approach for optimizing the dump slope design they are

## 6.1 optimizing dump slope by changing bench dimension

### 6.1.1 Design for a single bench

According to DGMS the maximum angle upto which a bench can be build is 37.5 degree. So taking bench angle 37.5 degree the chart of probable design are given for different heights and their safety factors are also mentioned.

Table no-: 6.1 single bench design

| Serial no | height | Slope angle (in degree) | Safety factor |
|---|---|---|---|
| 1 | 90 | 37.5 | 0.51 |
| 2 | 85 | 37.5 | 0.52 |
| 3 | 80 | 37.5 | 0.55 |
| 4 | 70 | 37.5 | 0.58 |
| 5 | 60 | 37.5 | 0.63 |
| 6 | 30 | 37.5 | 1.08 |
| 7 | 25 | 37.5 | 1.20 |

The above analyses show that with the existing overburden material, the benches beyond 30m high are unsafe as the safety factors are less than 1.00. At 30 m high, the safety factor is marginally more than 1.0 i.e. 1.08. But at 25 m the bench is safe with safety factor 1.2 (Figures 6.1 and 6.2 ).

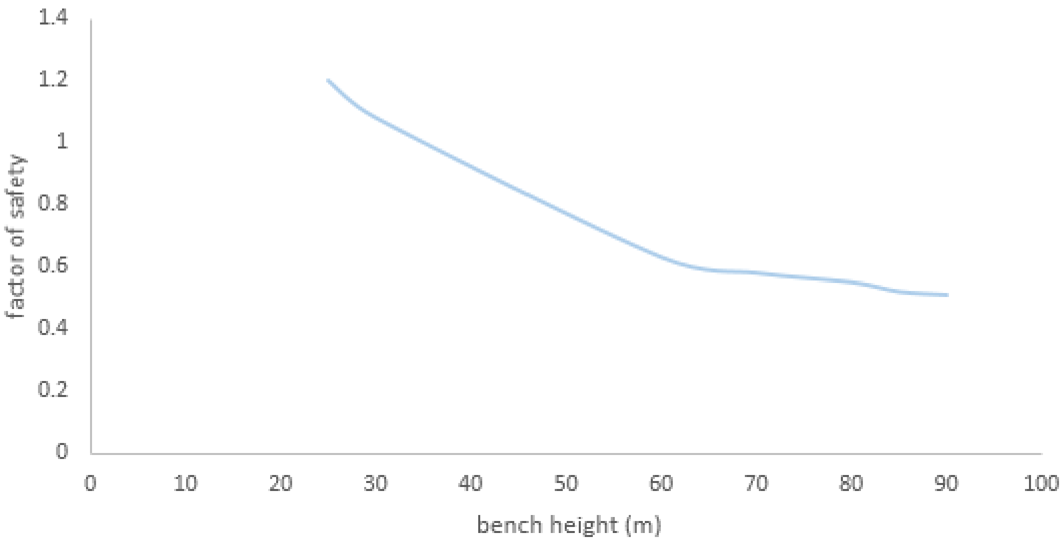
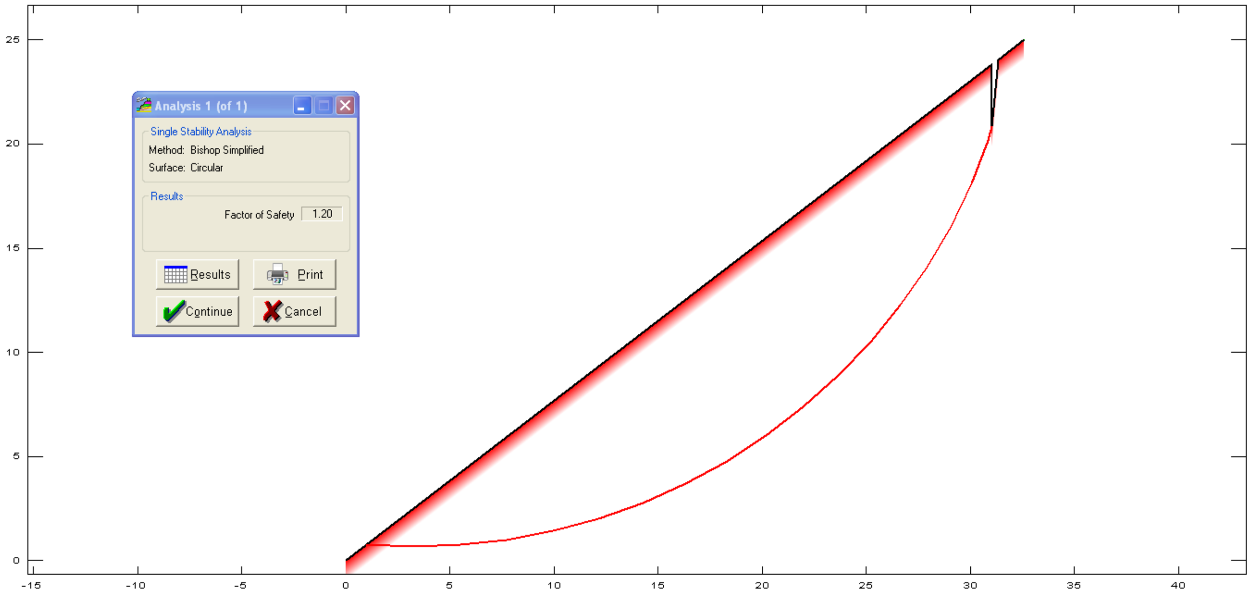


fig no-: 6.1 Graphical relation  of safety factor and the single bench height is given as below


Analysis 1 (of 1)

Single Stability Analysis

Method: Bishop Simplified

Surface: Circular

Results

Factor of Safety 1.20

Fig no-: 6.2 The bench design for 25 m height is given below

### 6.1.2 Design of dump according to overall slope angle

Previously the slope angle of the existing dump at 11° which is very less, so further designing is done here for maximum storage of waste with optimized overall slope angle. The usual constraints in designing the dump slope is the horizontal distance available for dumping. The horizontal distance available for dumping is 343 m for section xx and for the section yy it is 497 m. A chart of different bench parameters and there factor of safety is given below(figure 6.2 and 6.3)

**Analysis of section xx**

Table no-: 6.2 Chart for section xx (available distance=343 m)

| Serial no | Height | Slope angle | Safety factor |
|---|---|---|---|
| 1 | 60 | 18.92 | 1.04 |
| 2 | 55 | 17.44 | 1.14 |
| 3 | 53 | 16.84 | 1.18 |
| 4 | 52 | 16.54 | 1.20 |
| 5 | 50 | 15.94 | 1.25 |

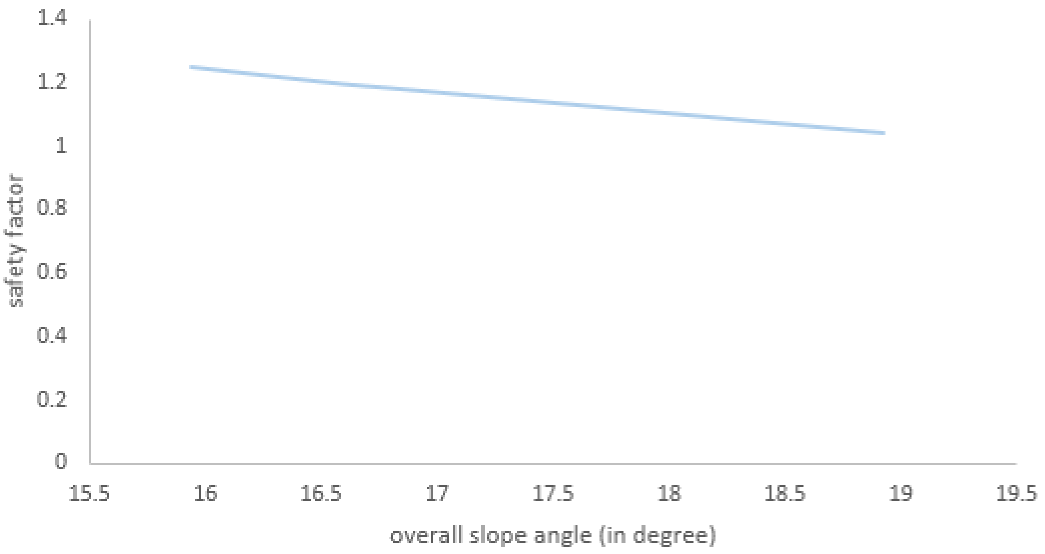
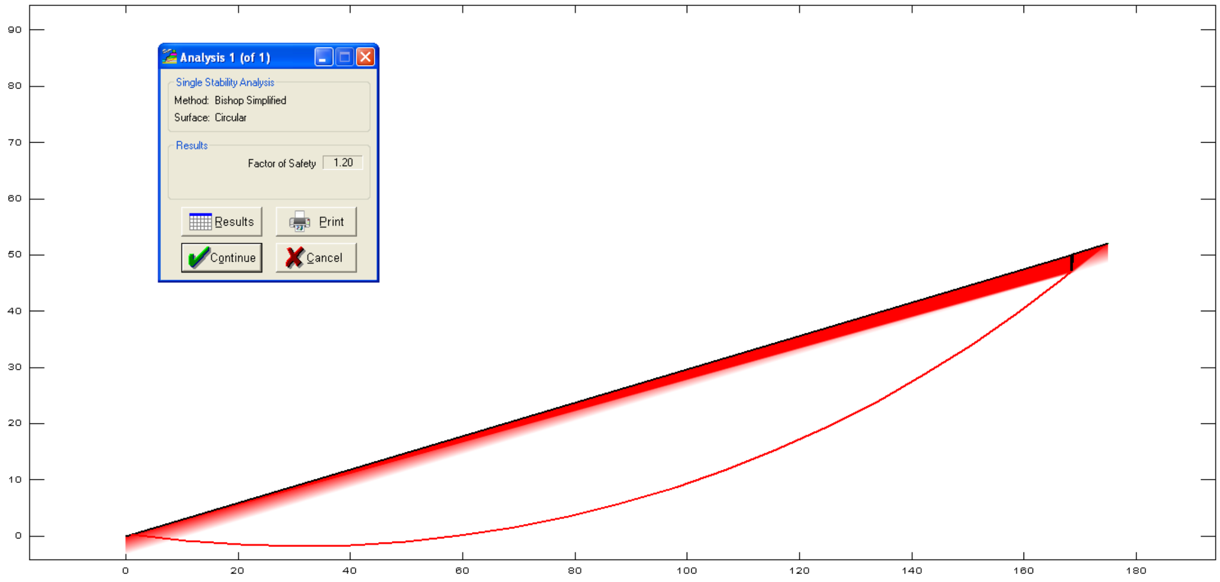


Fig no -: 6.3 Graphical relation between different overall slope angle and there respective safety of factor

So it can be inferred that as we go on lowering overall slope angle the safety factor increases. For this mine the optimum slope angle is 16.54° which is safe and all the dump having slope angle less than this will be safe.


Analysis 1 (of 1)

Single Stability Analysis

Method: Bishop Simplified

Surface: Circular

Results

Factor of Safety 1.20

Fig no :-6.4 design for 16.54° slope angle

**Analysis of section yy**

Table no-: 6.3 Chart for section yy (available distance=497 m)

| Serial no | Height | Slope angle | Safety factor |
|---|---|---|---|
| 1 | 70 | 15.70 | 1.13 |
| 2 | 67 | 15.06 | 1.18 |
| 3 | 66 | 14.84 | 1.20 |
| 4 | 65 | 14.63 | 1.22 |
| 5 | 60 | 13.54 | 1.32 |

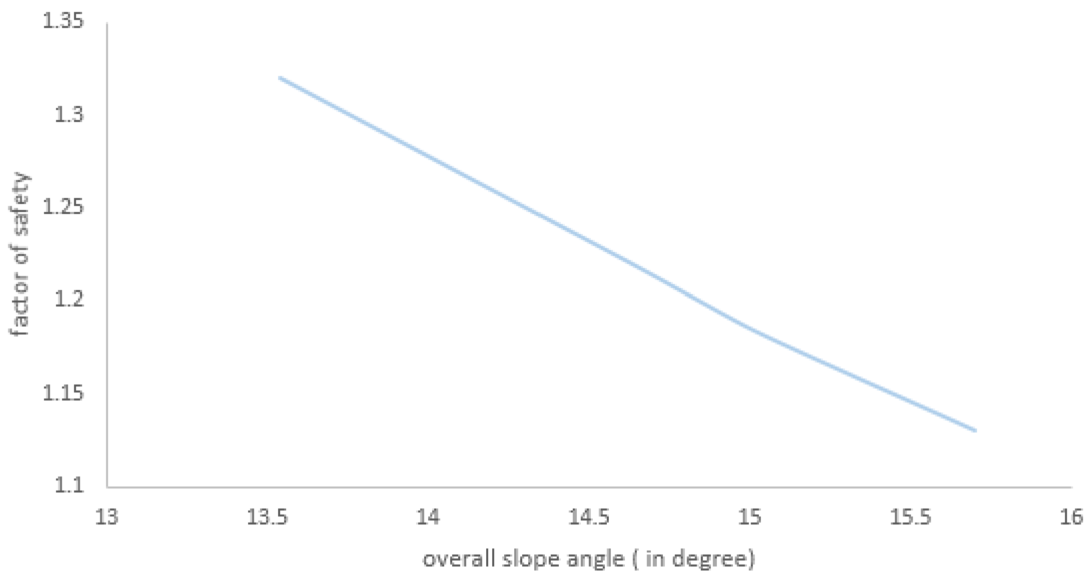
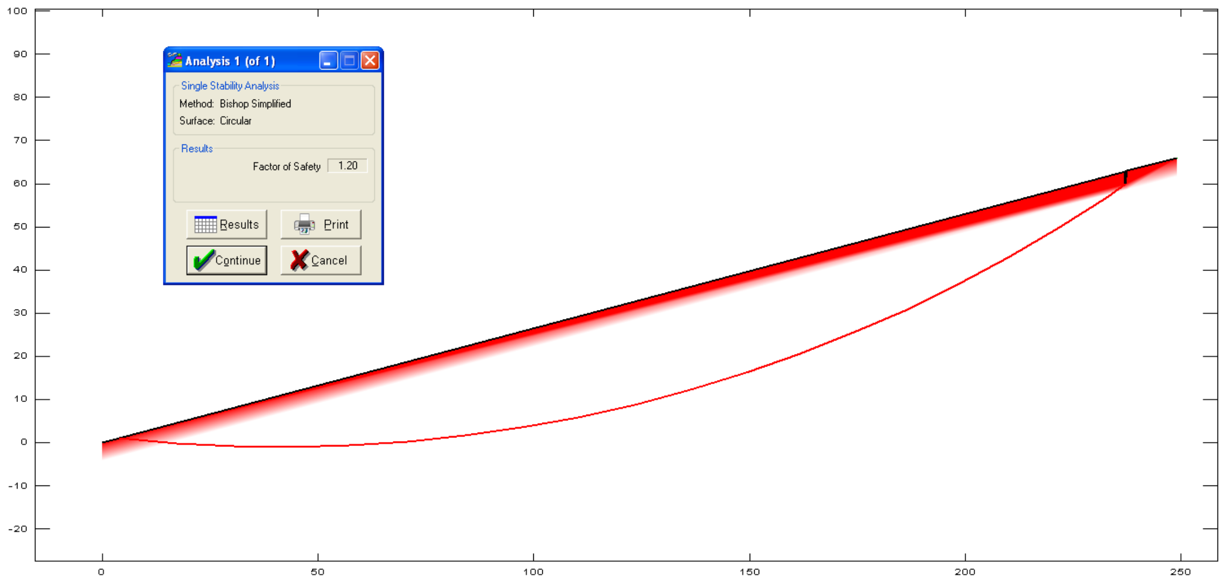


Fig no-: 6.5 Graphical relation between overall slope angle and the respective safety factor

The analyses show that as the slope angle increase the safety factor decreases. For this mine the optimized overall slope angle is 14.84° which is a threshold slope angle. The design of dump of overall slope angle 14,84$^0$ is given below.



Method: Bishop Simplified

Surface: Circular

Factor of Safety 1.20

Fig no:-6.6 So the design for 14.84° slope angle

## 6.2 Optimizing material properties

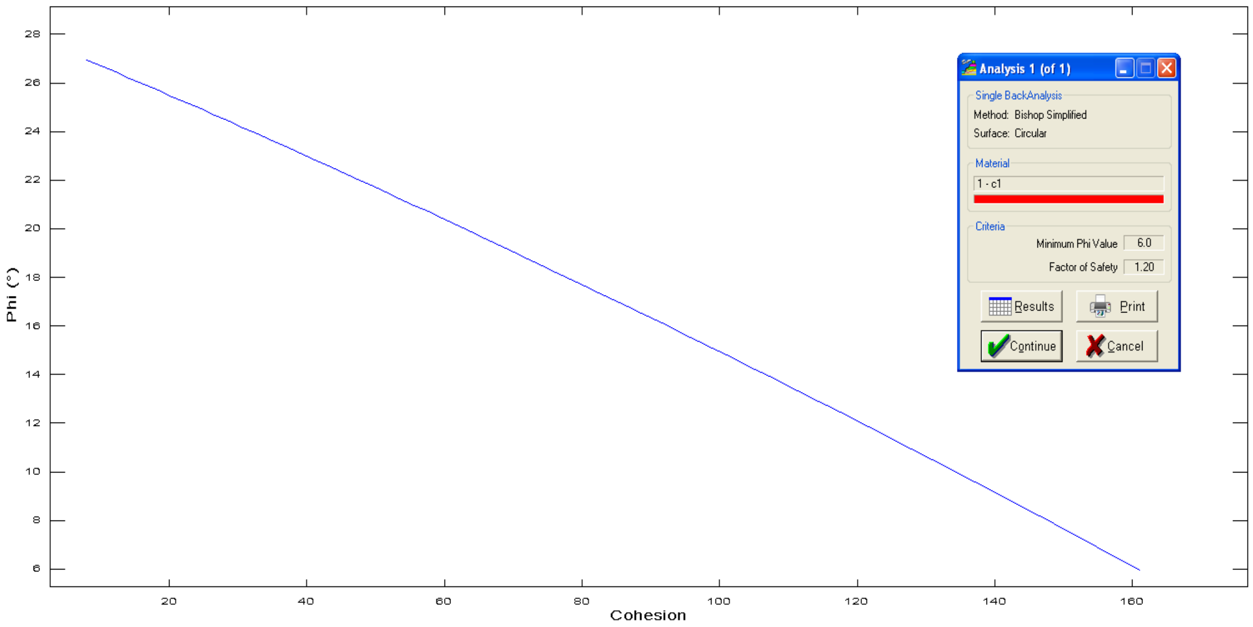
The material characteristics play a major role in slope stability. Its cohesion and friction angle are two most important parameters in the stability. Hence a back analyses was carried out to deermine the different combinatins of these two parameters with minimum safety factor of 1.20. The results are reported as below.

### 6.2.1 For section xx

Constants :- Available distance for dumping-343

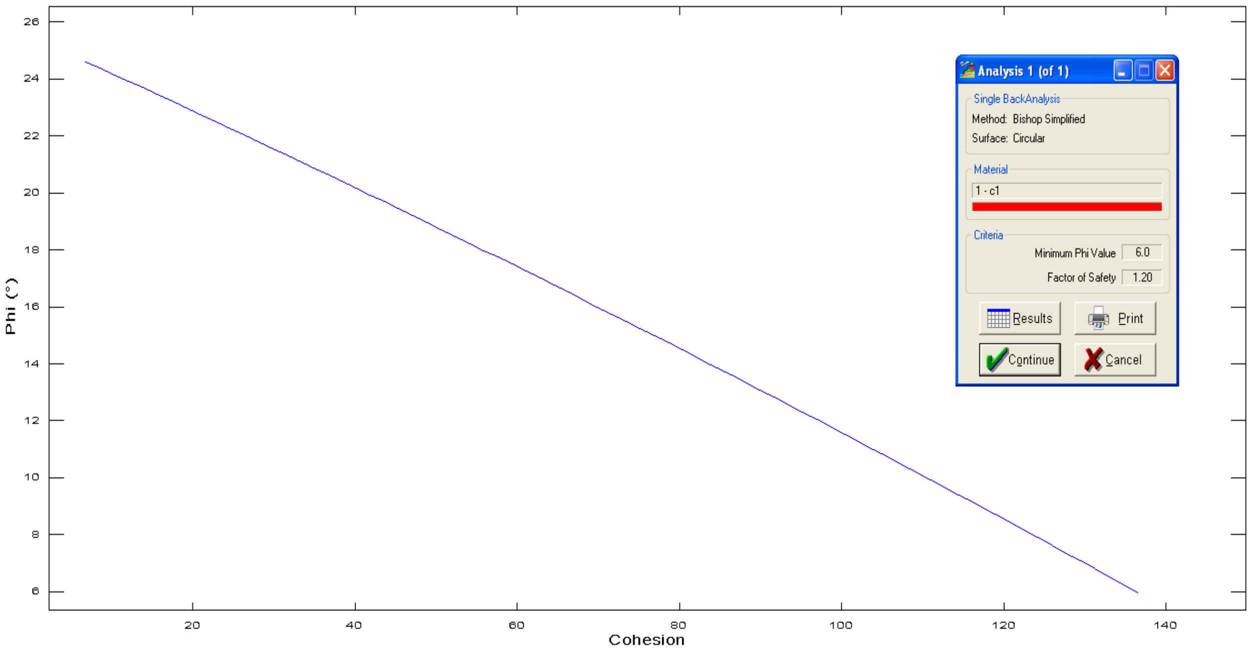
Minimum friction angle-6 degree

Desired safety factor- 1.2



Method: Bishop Simplified
Surface: Circular
1 - c1
Minimum Phi Value 6.0
Factor of Safety 1.20

Fig no-: 6.7 For height 90m



Method: Bishop Simplified
Surface: Circular
1 - c1
Minimum Phi Value 6.0
Factor of Safety 1.20

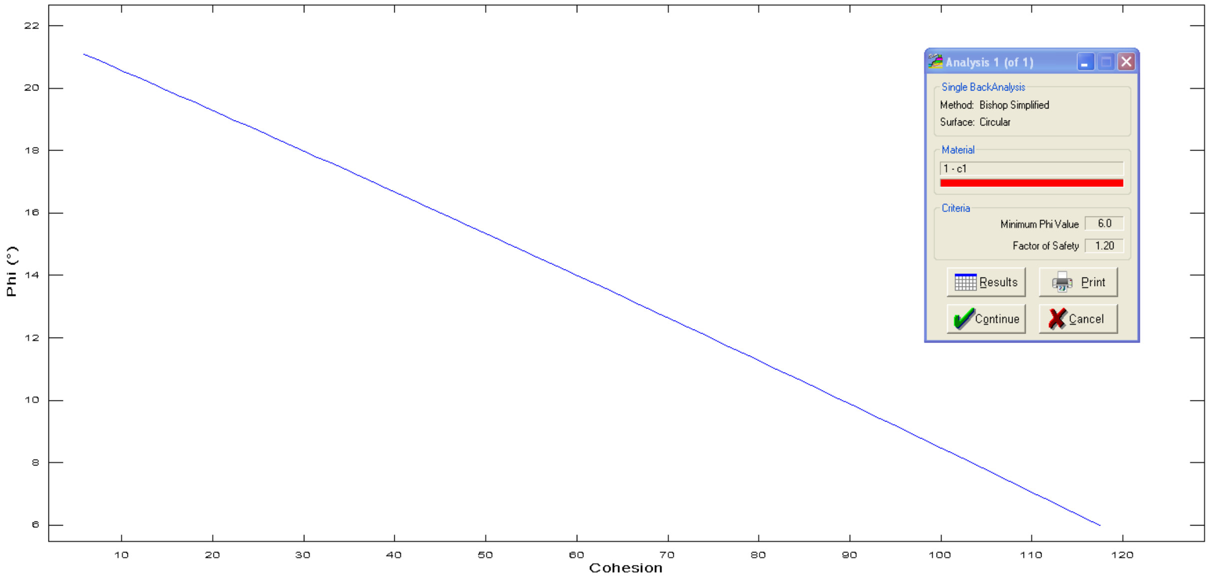
Fig no-: 6.5 for height 80m

### 6.2.2 for section yy

Constants:-desired safety factor-1.2

minimum friction angle-6 degre

Available dumping distance-497

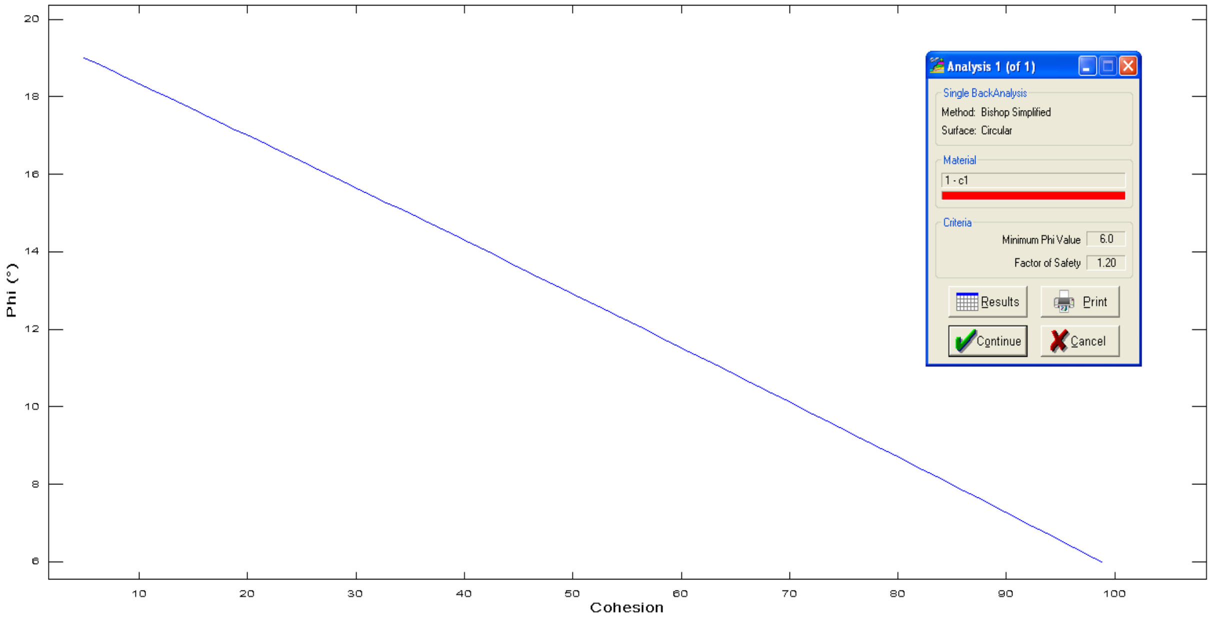


Single BackAnalysis
Method: Bishop Simplified
Surface: Circular

Material
1 - c1

Criteria
Minimum Phi Value 6.0
Factor of Safety 1.20

fig no-: 6.6 for height-90m



Single BackAnalysis
Method: Bishop Simplified
Surface: Circular

Material
1 - c1

Criteria
Minimum Phi Value 6.0
Factor of Safety 1.20

fig no- 6.7 for height 80m

From the above combination we can design a material of desired cohesion and friction angle for making a safe dump slope.  From this analysis defferent combination of cohesion ranging from 0-120 Kpa and frictional angle ranging from $6^0$ -$22^0$ are given for two heights ie- 80m and 90 m for both sections.

# Chapter 7

# CONCLUSION AND RECOMMENDATION

# 7 CONCLUSION AND RECOMMENDATION

## 7.1 Conclusion

In this research a detailed analysis is done on the safety status of the prexisiting dump slope of the studied mine. From the tests the geotechnical parameter are found out and they are $C_{avg=}$57.27 Kpa , frictional $angle_{avg}$=$7.6^0$. From the slope stability analysis it is determined that all the probable profiles have safety factor more than 1.3.

The existing bench have bench angle of $11^0$. So for maximising the deposition of dump in the area here optimisation of bench design is done. Various probable bench design are decided. Firstly single bench designs are laid out by fixing a certain bench angle ie-$37.5^0$. From the analysis it is found out that single bench of height 25 m is safe for maximum allowable angle $37.5^0$ as the safety factor is 1.2. So for a safe bench design in this mine the bench height shouldn't go above 25 meter as found in case of 30 meter bench height which is having factor of safety -1.08.

Another analysis is done on the basis of overall slope angle and it is determined that the bench of height 52 m with overall slope angle $16.54^0$ for section xx and 66 m with overall slope angle $14.84^0$ can be practicable safely.

Besides this optimisation of bench design with respect to material properties is also done. Various combination of cohesion and frictional angle for a desired safety factor has being calculated by the help of back analysis. Different combination of cohesion valu ranging from 0-120 Kpa and frictional value ranging from $6^0$- $28^0$ are given. So for designing a bench of maximum height let 80 or 90 m from the back analysis result we can get the desired combination of cohesion and friction angle.

## 7.2 Recommendation

For further research on this topic more number of samples should be collected from different area of dump like failure surface, phreatic surfaces temporary and permanent overburden.. Besides this for detail study it is advisable to collect sample in both rainy and summer seasons so that both drained and undrained conditions of the samples can be taken into account during lab tests.

# Chapter 8

# REFERENCES

# 8. REFERENCES

1) McCarthy, David F., *Essentials of Soil Mechanics and Foundations*, Pearson Prentice Hall publication, pp 657-718, (2007).
2) Murthy, V.N.S., *Principles of Soil Mechanics and Foundation Engineering*, Fifth Edition, UBS Publisher‟s Ltd, (2001).
3) http://www.sspsb.com.my/publications/Slope%20Stability%20Analysis.pdf
4) Flora C.S., Evaluation of Slope Stability for Waste Rock Dumps in a Mine, (http://www.ethesis.nitrkl.ac.in/1386/1/Thesis_2.pdf), (2008).
5) http://ethesis.nitrkl.ac.in/2504/1/Gora_Das_-_Final.pdf.
6) ASTM Standard D2850,*Standard Test Method for Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils*, ASTM International, West Conshohocken, PA, (2007).
7) ASTM Standard D698, *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort*, ASTM International, West Conshohocken, PA, (2007).
8) GALENA User‟s Guide, version 5.0, Clover Technology, Australia
9) Roclab User‟s Guide, version 4.0 , rocscience.inc canada
10) Stanciucu, Mihaela, Evaluation of waste embankment slope stability: Valea Manastirii, Gorj, Romania, 2005.
11) Das, B. M, *Principle of Geotechnical Engineering,* (Fifth edition), Thompson Learning, United State, (2002).
12) "*Factor of safety and probability of failure*" – Retrieved from www.rocscience.com/.../8_Factor_of_safety_and_probability_of_failure.pdf
13) US Army Corps of Engineers, *Engineering and Design - Slope Stability*, Washington DC, USA: US Army Corps of Engineers, (2003).
14) Lacasse, S. and Nadim, F., *Uncertainties in Characterizing Soil Properties, Proceedings, Uncertainty in the Geologic Environment: from Theory to Practice,* Geotechnical Special Publication No. 58, ASCE, Vol. 1, pp. 49-75 (1996).
15) Husein Malkawi A.I., Hassan W.F., Abdulla F., *Uncertainty and reliability analysis applied to slope stability*. Structural Safety Journal; 22:161–87, (2000).