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**Soil Type Based Mitigation Charts of Chure Landslides in  
Finite Element Framework**

by  
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## ABSTRACT

Chure area is extended as a contiguous landscape from east to west in thirty-six districts in Nepal which is bordered by the Mahabharat range in the north and by the Terai in the south. There are more than five thousands of landslides in the chure area and there is no any methodology for mitigation and conservation of Chure area. There is no possible to go for site and case specific analysis and design of all those landslides. Therefore to find the general mitigation solution a general mitigation model is prepared to suit the chure landslide and prepared a set of mitigation Charts.

This research works out on Site specific analysis and general mitigation analysis in parallel way. Three major landslides are taken for the site specific analysis. FEM based open source commercial software Phase2 is used for the stability analysis with mitigation measure.

The charts developed are from the eight type of soil found in chure area for the plain strain or 2D conditions without considering any seismic loads. Five different slope angles ( $30^\circ$ ,  $35^\circ$ ,  $40^\circ$ ,  $45^\circ$ ,  $50^\circ$ ) have been considered which is either completely dry, saturated or GWT some depth below. The vegetation is applied to soil having ERD 1m and ERD 2m with increase in root cohesion upto  $20 \text{ KN/m}^2$  and friction angle by 5 degree. The retaining wall is applied at the toe of landslide with variation in height (h/H ratio 0.2, 0.3 and 0.4).The slope modification is done with equal cut and fill approach to the original slope angle.

From the analysis of Charts, the effect of mitigation measures seems well significant when the slope is more than 45 degree and water table is more than 4m down from the surface level. Furthermore we found that maximum increase in FOS value is obtained with the application of slope modification mitigation measure and minimum increase in FOS value is obtained with the application of Retaining wall.

The verification of FOS value obtained from the FEM based model is compared with the FOS value obtain from LEM based another tool Slide6 and satisfactory result is obtained with good correlation.

Furthermore the FOS value obtained from the chart is compared with the FOS value obtained from site specific analysis result having real field values and found reliable result. So the charts obtained in this report are quite satisfactory and will be useful in mitigation plan and design of chure landslides.

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## **ABBREVIATION**

|        |  |
|--------|--|
| PI     | Plasticity Index                           |
| LI     | Liquid Limit                               |
| PL     | Plastic Limit                              |
| C      | Cohesion of soil                           |
| RW     | Retaining wall                             |
| $\Phi$ | Internal Friction angle of the soil        |
| FEM    | Finite Element Method                      |
| LEM    | Limit Equilibrium Method                   |
| SSR    | Shear Strength Reduction                   |
| SRF    | Strength Reduction Factor                  |
| FOS    | Factor of Safety                           |
| GL     | Ground Level                               |
| GWT    | Ground Water Table                         |
| USCS   | Unified Soil Classification System         |
| ASTM   | American Society for Testing and Materials |
| MBT    | Main Boundary Thrust                       |
| MFT    | Main Frontal Thrust                        |
| DoR    | Department of Road, Nepal                  |
| ERD    | Effective Root Depth                       |

## CHAPTER ONE: INTRODUCTION

### 1.1 Background

The Chure range is the first and lowest ridges of the Himalayan mountain system which raises steeply from the Terai plains along the whole of its northern border. It is extended as a contiguous landscape from east to west in thirty-six districts in Nepal. Chure is bordered by the Mahabharat range in the north and by the Terai in the south. In the west, the Chure range is separated from the Mahabharat range by valleys known as duns or inner Terai.

Chure hills are formed of very fragile, weak and young sedimentary rocks called the Siwaliks belonging to Middle Miocene, to Upper Pleistocene times. These hills occupy the southern portion of the Himalaya and connected with southernmost Terai of Nepal. Therefore, these young sedimentary rocks are highly weathered and deformed, and interbedding of soft mudstone and hard sandstone beds provide differential weathering providing plenty of options for slope instabilities and occurrence of different types of landslides. The last five and half decades have witnessed the deforestation, over exploitation of forest products, development of road networks, forest encroachment, open grazing and unscientific use of land in the Chure region. Such activities on fragile ecosystem have exacerbated the landslide in the hills and mountains and consequent flood hazards in the river valleys and Terai lowland. Thus, Torrential monsoon, earth tremors and environmental degradation had increased landslides in Chure region.

Landslides refer to the movement of a mass of rock, debris, or earth down a slope (Cruden, 1991). Landslides are the product of a complex interplay of various triggering and conditioning in situ factors. When combined with human interferences, they become complex and hazardous. According to Nepal Disaster Report 2013 (MoHA, 2013), landslides affected 555,705 families and caused 4,511 deaths from 1971 to 2012, listing it as the second most lethal disaster, only next to epidemics. In-depth understanding for mitigation of landslide requires their systematic study with reference to the types and processes, associated risk and their relation to different contributing factors.

Slope stability analysis is a crucial step for the hazard preparedness of the particular landslide prone zone. There are several numerical methods currently in use for slope stability analysis, which can be implemented to evaluate the stability of infinitely long and steep slopes. Griffiths and Lane (1999) presented the finite element method (FEM) as a powerful numerical approach for slope stability analysis, and mentioned an accurate, versatile and fewer priori assumption methods with regards to failure mechanism. With this method, a failure surface can be predicted through the zone in which the shear strength of the soil is insufficient to resist the shear stress.

## **1.2 Statement of the Problem**

The deteriorating environment in the Chure hills has been a matter of concern to all the people over the years. This Region has suffers from mass erosion, landslides and other environmental externalities which make the region vulnerable.

The root cause of problem in Chure region is related with the geology (i.e. evolved from the continent-continent collision between the Indian lithosphere plate and Tibetan Plate). Human induced factors like road construction, forest encroachment, bank scouring and over exploitation of construction materials has triggered landslides as well.

There are more than five thousands landslides are present on chure area. There is no methodology to describe mitigating models of thousands of major landslides like Setebhir, Simalchour and Beteni landslides. There is no possible to go for site and case specific analysis and design of all those landslides. Main challenge of this work is to address thousands of landslides or addressing hundreds of landslide clusters.

Therefore this thesis study focuses on finding the general mitigation solution with safety factor of these thousands of landslide with the application of possible mitigation measures which will be the key to reduce losses and damages from landslides and other related disasters. The mitigation chart developed from the general model will help to design the possible mitigation measures to achieve safety level and gives an idea about the selection of different types of mitigation options.

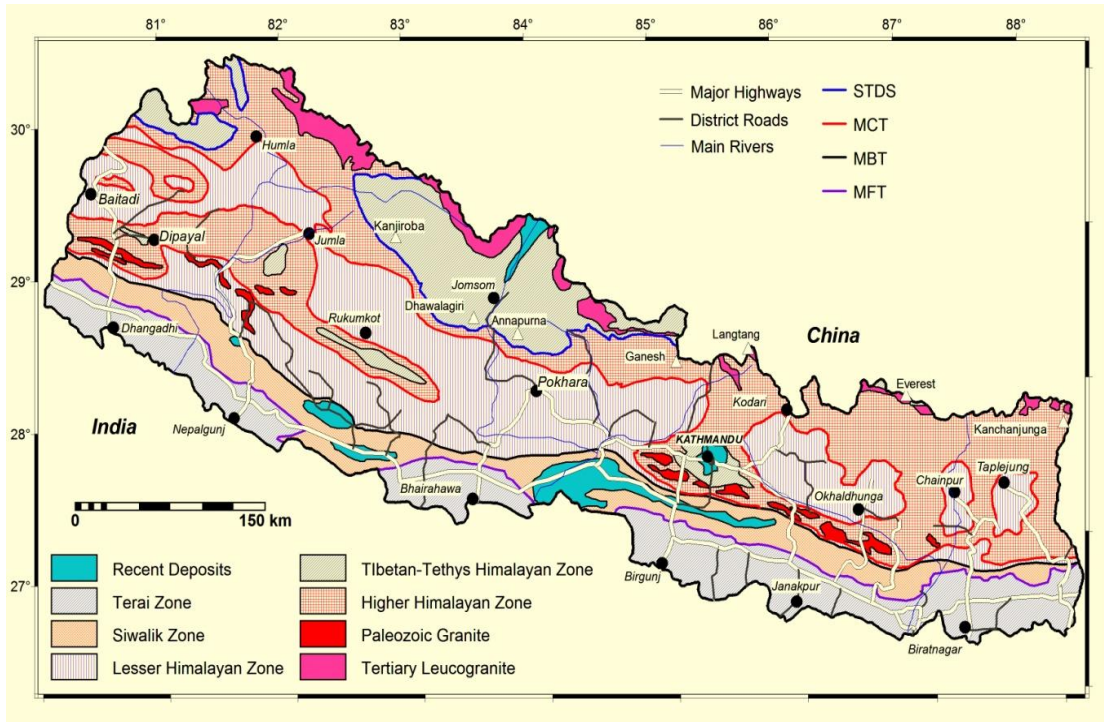


Figure 1.1 Geology of Nepal

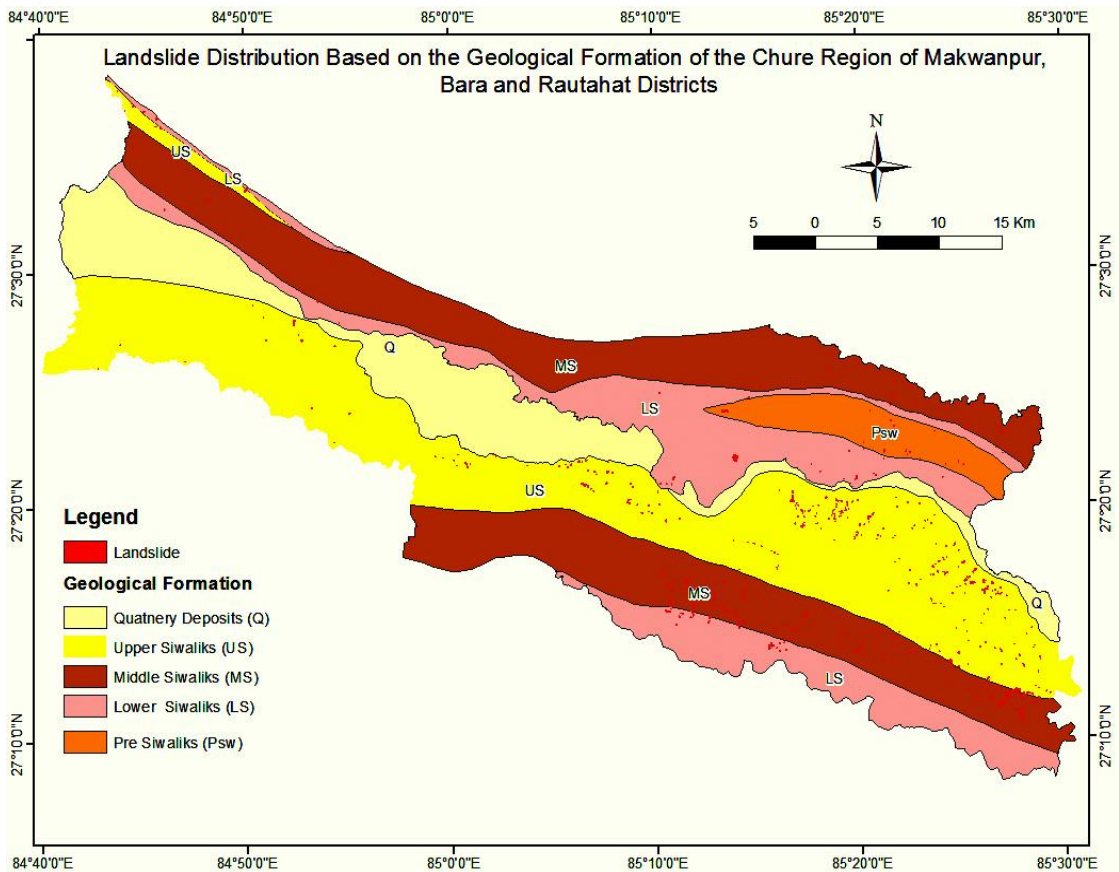


Figure 1.2 Landslides distribution along the Chure region

### **1.3 Objectives**

The main objective of this study is to give landslide mitigation charts of Chure area. The specific objectives have been listed below:

- I. To study and prepare site specific stability analysis of three landslides with proper mitigation measures.
- II. To prepare and analyze general mitigation model for the evaluation of safety factor to suit chure landslides.
- III. To prepare the landslide mitigation chart based on soil type found on chure area.
- IV. Verification and comparison of result from chart and site specific analysis.

### **1.4 Landslide Location and Condition Details**

The study was carried out on three major landslides on chure region of Makawanpur and Bara districts of Nepal. The selection of landslides from chure region was done based on the different geographical region, vulnerability of landslide and its quick mitigation action needed whose location and condition details are hereunder.

#### **Setebhir Landslide**

The Setebhir landslide is located on Makawanpur District at Shripur Chattiwan VDC, at the origin of Setebhir Khola (27 22' 02.57" N, 85 14' 16.73"E) and is one of the most active landslides in the chure area. The length and breadth of landside is 250m and 180 m respectively and slope curvature of concave divergent. The landslide was initiated more than fifty years ago. The landslide is observed in the mudstone and siltstone of Lower Siwalik rock. There are five large scarps which coalesce downstream to form a single complex failure involving several types of mass movement. The toe lays both bank of the Setebhir khola. The mudstones are fresh to highly weathered. The flanks of the landslide are covered by residual soil and colluvial soil with thickness of 2-8 meter. The gullies are narrow to wide (3-20m) and its depth is average about 20 meters.



Figure 1.3 Photograph of Setebhir Landslide

### **Betini Landslide**

The Betini landslide is located on Makawanpur District at Betini VDC, at the origin of seasonal streams (27 23'11.12"N, 85 25'11.89"E) and has the length and breadth of 200m and 100 m respectively.



Figure 1.4 Photograph of Betini Landslide

The landslide is observed in the coarse grained sandstones of Middle Siwalik rock. There are four large scarps which coalesce down slope to form a single complex failure involving several types of mass movement and have concave slope curvature. The sandstones are highly weathered. The flanks of the landslide are covered by residual soil and colluvial soil with thickness of 2-10 meter. The gullies are narrow to wide (3-20m) and its depth is average about 2-3 meters.

### **Simalchaur Landslide**

The Simalchaur landslide is located on Bara District at Bharatgunj Sigaul VDC of Bara district, at the origin of small streams and is one of the most active landslides in the study area. The landslide has length and breadth of 150m and 100m respectively and is observed in siltstones and mudstones of Middle Siwalik rock.

There are 3 large scarps which coalesce down slope to form a single complex failure involving several types of mass movement. The mudstones are highly weathered. The flanks of the landslide are covered by residual soil and colluvial soil with thickness of 2-5meter. The gullies are narrow to wide (1-2m) and its depth is average about1-5 meter.



Figure 1 5 Photograph of Simalchaur Landslide

## **1.5 Scope of the Study**

This thesis study mainly deals with the specific and general mitigation measures of chure landslide with finding factor of safety of homogenous soil slope considering the progressive failure phenomena. Phase2 commercial software is used for the analysis of slope stability. While preparing the material properties on the slope model deformation of soil slope and the effect of uncertainty in the response of soil slope can be evaluated. For this thesis, Mohr-Coulomb failure criteria are used in most of materials and for concrete retaining wall Drucker-prager failure criteria is used, however extension to any other failure criteria is straightforward. Different slope mitigation measures are applied on the specific landslide model and general slope model to check their effect on factor of safety. The specific solution (site specific study) of all more than 3500 landslides on chure area is not possible so the general solution of landslide has been prepared and the landslide mitigation chart is prepared to suit all landslides on chure area. This Thesis would be more beneficial for generating mitigation measure plan of chure landslides before the development of any Infrastructures and also gives the guidelines to select proper mitigation measures to achieve proper safety factor. Recommendations are made for future research in this subject area.

## **1.6 Organization of the Thesis**

The entire thesis is divided into seven chapters along with an Annexes included at the end of thesis. The first chapter consists of introduction which includes background and landslide details. The second chapter is a review of literature of slope stability analysis methods, stability charts and mitigation measures related topics. The third chapter explicitly describes about the methodology and process regarding the thesis progress. Chapter four consists of the 2D Finite element based site specific and general stability and mitigation analysis with their results. The chapter five describes the verification of the work and comparison of results. The chapter six provides conclusions and recommendations and the scope for further research.

## **CHAPTER TWO: LITERATURE REVIEW**

### **2.1 Slope Stability Analysis and Methods**

Slope stability analyses are mainly performed to assess the safety factor of a particular slope in a given geologic and physical conditions. For a slope to be stable the resisting forces in the slope must be sufficiently greater than the forces causing the failure (Duncan and Wright 2005). Stability analysis can be used for the following,

- 1) To assess the safety of a structure in terms of its stability.
- 2) To locate the critical failure surface and to know its shape of failure.
- 3) To understand and numerically evaluate the sensitivity of stability to its geologic Parameters and climatic conditions.
- 4) To assess the movement of the slope.
- 5) To assess remedial measures and aid in their design.

To perform a slope stability analysis the geometry of the slope, external and internal loading, soil stratigraphy and strength parameters and variation of the ground water table all along the slope must be defined. In the current state of practice, there are many number of slope stability analysis methods available. However, the scope of this report is limited to a discussion on the limit equilibrium methods and finite element methods.

#### **2.1.1 Limit Equilibrium Method**

This method of slope stability is the most commonly used approaches for the analysis of slopes. The fundamental assumption in these methods is that failure occurs through sliding of a mass along a slip surface. The reputation of the limit equilibrium methods is principally due to their relative simplicity, the ability to evaluate the sensitivity of stability to various input parameters, and the experience geotechnical engineer have acquired over the years in calculating the factor of safety.

The assumptions in the limit equilibrium methods are that the failing soil mass can be divided into slices and that forces act between the slices whereas different assumptions are made with respect to these forces in different methods. The factor of safety is the factor by which the shear strength of the soil would have to be divided to carry the slope into a state of barely stable equilibrium.

The findings related to the accuracy of the limit equilibrium methods can be reviewed as follows:

1) For effective stress analysis of flat slopes, the ordinary method of slices is highly inaccurate. The computed factor of safety is too low. This method is accurate for  $\phi = 0$  analysis, and fairly accurate for any type of total stress analysis using circular slip surfaces.

2) For most conditions, the Bishop's modified method is reasonably accurate. Because of numerical problems, sometimes encountered, the computed factor of safety using the Bishop's modified method is different from the factor of safety for the same circle calculated using the ordinary method of slices.

3) Computed factor of safety using force equilibrium methods are sensitive to the assumption of the inclination of side forces between slices. A bad assumption concerning side force inclination will result in an inaccurate factor of safety.

The limitation of limit equilibrium method in slope stability analysis has been demonstrated by Krahn (2003). This limitation is caused by the absence of a stress-strain relationship in the method of analysis. The limit equilibrium method lacks a suitable procedure for slope stability analysis under rapid loading condition as illustrated by Baker et al. (1993). Some common features and limitation for equilibrium methods in slope stability analysis are summarized as:

Table 2.1 Feature of Different Methods Based on Limit Equilibrium Method

| Method   | Features and Limitation  |
|--|--|
| Slope Stability Charts (Janbu, 1968, Duncan et al, 1987) | - Accurate enough for many purposes.<br>- Faster than detailed computer analysis.  |
| Ordinary Method of Slices (Fellenius, 1927)              | - Only for circular slip surfaces.<br>- Satisfies moment equilibrium.<br>- Does not satisfy horizontal or vertical force equilibrium.                                |
| Bishop's Modified Method (Bishop, 1955)                  | - Only for circular slip surfaces.<br>- Satisfies moment equilibrium.<br>- Satisfies vertical force equilibrium.<br>- Does not satisfy horizontal force equilibrium. |

|   |   |
|---|---|
| Force Equilibrium Methods<br>(e.g. Lowe and Karafiath, 1960,<br>Army Corps of Engineers,<br>1970) | <ul style="list-style-type: none"> <li>- Any shape of slip surfaces.</li> <li>- Does not satisfy moment equilibrium.</li> <li>- Satisfies both vertical and horizontal force equilibrium.</li> </ul>  |
| Janbu's Generalized Procedure of Slices (Janbu, 1968)   | <ul style="list-style-type: none"> <li>- Any shape of slip surfaces.</li> <li>- Satisfies all conditions of equilibrium.</li> <li>- Permit side force locations to be varied.</li> <li>- More frequent numerical problems than some other methods.</li> </ul> |
| Morgenstern and Price's Method (Morgenstern and Price, 1965)                                      | <ul style="list-style-type: none"> <li>- Any shape of slip surfaces.</li> <li>- Satisfies all conditions of equilibrium.</li> <li>- Permit side force orientations to be varied.</li> </ul>   |
| Spencer's Method (Spencer, 1967)  | <ul style="list-style-type: none"> <li>- Any shape of slip surfaces.</li> <li>- Satisfies all conditions of equilibrium.</li> <li>- Side forces are assumed to be parallel.</li> </ul>  |

### 2.1.2 Finite Element Method

The finite element method was first introduced to geotechnical engineers in 1966 Berkeley conference on stability of slopes and embankments by Clough and Woodward (1967). Unlike the limit equilibrium method, the finite element method considers linear and non-linear stress- strain behaviour of the soil in calculating the shear stress for the analysis. Hence, the results obtained from this analysis are considered to be more realistic compared to limit equilibrium method (Griffiths and Lane 1999). Finite element methods are well known for the estimating the realistic deformations of the slopes and embankments. Some of the advantages of using a finite element analysis over limit equilibrium methods are,

- 1) The movement of the slopes at a particular location can be calculated. This helps in monitoring the movement of the slope. Also, soil stresses and pore water pressure responses to different external factors such as load, water level, reservoir level etc. can be calculated.
- 2) Stability of the slope during staged construction such as step by step excavation or construction of embankments, levees etc. can be calculated by performing incremental analysis.

The types of soil stress-strain relationships that can be used are linear elastic, elastoplastic, hyperbolic, Modified Cam Clay, elastoviscoplastic and multilinear elastic models. The determination of soil properties in the field involves a large amount of uncertainty and so the application of finite element analyses imposes complexity on the stability problem (Griffiths and Lane 1999).

Traditionally, the slope stability analysis with a finite element approach is performed by Strength reduction method (SRM). In this method, the factor safety is defined as the factor by which the original shear strength parameters must be divided to bring the slope to be in failure mode (Griffiths and Lane 1999). Hence, the factor shear strength parameters ( $c'_f$  and  $\phi'_f$ ) are shown as follows,

$$c'_f = c' / \text{SRF}$$

$$\phi'_f = \arctan (\tan \phi' / \text{SRF})$$

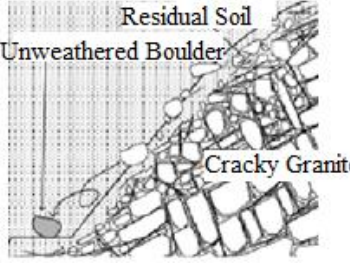
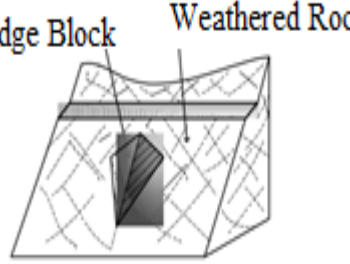
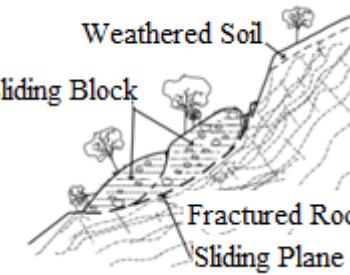
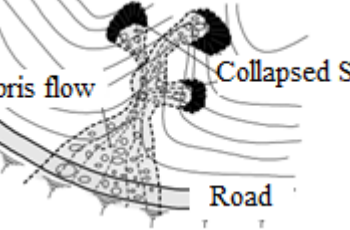
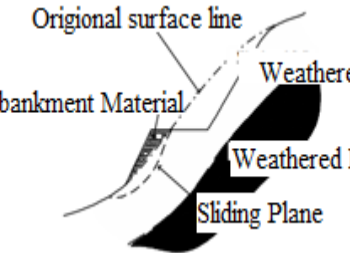
Where, SRF is the Strength Reduction Factor.

A systematic estimation is required for the SRF value to find out the value which will just cause the slope to fail. The SRF value, at which the slope will just to fail, is known as the factor of safety. The failure condition in this method could be when 1) the non-linear equation solver cannot achieve convergence after a few iterations, 2) sudden rate of change in displacement and 3) a failure mechanism is developed. However, this method has some limitations such as appropriate selection of constitutive model and geologic parameters, boundary conditions and defining a failure condition (Krahn 2007).

## 2.2 Modes of Slope Failure

Table 2.2 Different modes of slope failure

| Failure Type  | Characteristics   | Schematic Illustration |
|---------------|---|------------------------|
| Collapse (CL) | <ul style="list-style-type: none"> <li>• Collapsing material are residual soils and highly weathered or jointed rocks.</li> <li>• Prone to occur on steep slopes.</li> <li>• Mostly triggered by rainfall infiltration.</li> <li>• Size is generally less than 1000 cum.</li> </ul> |                        |

|                                |  |  |
|--------------------------------|--|--|
| <p>Rock Fall (RF)</p>          | <ul style="list-style-type: none"> <li>• Free fall or rolling down of hard rocks and boulders.</li> <li>• Occur on steep slope and cliff.</li> <li>• Falls occur due to gravity and jointed failure.</li> <li>• Size generally less than 5 cum.</li> </ul> |    |
| <p>Rock Mass Failure (RM)</p>  | <ul style="list-style-type: none"> <li>• Materials are hard jointed rocks.</li> <li>• Failure modes include wedge slide, plane slide and toppling.</li> <li>• Size generally more than 5000 cum</li> </ul>   |    |
| <p>Landslide (LS)</p>          | <ul style="list-style-type: none"> <li>• Materials may be soil, debris and or highly weathered rocks.</li> <li>• Marked by gentle and deformed topographic features.</li> <li>• Size generally more than 5000 cum.</li> </ul>                              |   |
| <p>Debris Flow (DB)</p>        | <ul style="list-style-type: none"> <li>• Rapid flow of boulder, gravel, sand, silt and clay mixed with large quantity of water.</li> <li>• Occurs in a contributory area that contains collapsible slopes.</li> </ul>                                      |  |
| <p>Embankment Failure (EB)</p> | <ul style="list-style-type: none"> <li>• Slumps or collapse of embankment slope.</li> <li>• Settlement of road surface.</li> <li>• Scouring of toe part.</li> </ul>  |  |

### 2.3 Landslide Disaster Mitigation Options

According to Mihail E. Popescu (2001), landslide remedial measures are arranged in four practical groups, namely: modification of slope geometry, drainage, retaining structures and internal slope reinforcement. Selection of an appropriate remedial

measure depends on: a) engineering feasibility, b) economic feasibility, c) legal/regulatory conformity, d) social acceptability, and e) environmental acceptability. There are a number of levels of effectiveness and levels of acceptability that may be applied in the use of these measures, for while one slide may require an immediate and absolute long-term correction, another may only require minimal control for a short period. As many of the geological features, such as sheared discontinuities are not known in advance, it is more advantageous to put remedial measures in hand on a “design as you go basis”. That is the design has to be flexible enough to accommodate changes during or subsequent to the construction of remedial works. The possible mitigation measures could be as describe hereunder.

Table 2.3 Possible Slope Mitigation Measures by Mihail E. Popescu (2001)

|          |  |
|----------|--|
| <b>1</b> | <b>Modification of Slope Geometry</b>  |
|          | Removing material from the area driving the landslide (with possible substitution by lightweight fill)         |
|          | Adding material to the area maintaining stability (counterweight berm or fill)                                 |
|          | Reducing general slope angle   |
| <b>2</b> | <b>Drainage Management</b>   |
|          | Surface drains to divert water from flowing onto the slide area (collecting ditches and pipes)                 |
|          | Shallow or deep trench drains filled with free-draining geomaterials (coarse granular fills and geosynthetics) |
|          | Buttress counter forts of coarse-grained materials (hydrological effect)                                       |
|          | Vertical (small diameter) boreholes with pumping or self draining  |
|          | Vertical (large diameter) wells with gravity draining  |
|          | Sub horizontal or sub vertical boreholes   |
|          | Drainage tunnels, galleries  |
|          | Vacuum dewatering  |
|          | Drainage by siphoning  |
|          | Electro osmotic dewatering   |
|          | Vegetation planting (hydrological effect)  |
| <b>3</b> | <b>Retaining Structures</b>  |
|          | Gravity retaining walls  |

|   |
|---|
| Crib-block walls  |
| Gabion walls  |
| Passive piles, piers and caissons   |
| Cast-in situ reinforced concrete walls  |
| Reinforced earth retaining structures with strip/ sheet - polymer/metallic reinforcement elements |
| Buttress counter forts of coarse-grained material (mechanical effect)                             |
| Retention nets for rock slope faces   |
| Rock fall attenuation or stopping systems (rock trap ditches, benches, fences and walls)          |
| Protective rock/concrete blocks against erosion   |
| <b>4 Internal Slope Reinforcement</b>   |
| Rock bolts  |
| Micro piles   |
| Soil nailing  |
| Grouting  |
| Stone or lime/cement columns  |
| Heat treatment  |
| Freezing  |
| Vegetation planting (root strength mechanical effect)   |

## 2.4 Stability Charts

Development of slope stability charts is quite cumbersome and steady process. Most of the designed charts are based on two-dimensional limit equilibrium analysis with or without some modifications on it and are developed for simple homogeneous slopes having circular slip surfaces. Charts such as Taylor (1937), Bishop and Morgenstern (1960), Janbu (1956), Bell (1966), Hoek and Bray (1974), Cousin (1977), etc. are developed for static condition only and do not consider seismic effects.

### Michalowski Charts

Michalowski Charts are based on the limit analysis method and can be applied for two dimensional and three dimensional slopes. As the process of chart development is the continuous process, the charts were developed in sequential order as:

- a) Iterative charts for dry slopes (1995)
- b) Non- iterative charts for dry and saturated slopes (1995)
- c) Non- iterative charts for 2D seismic dry slopes (1998)
- d) Non-iterative charts for 3D seismic dry slopes undrained condition (2010)
- e) Non-iterative charts for 3D seismic dry slopes drained condition (2010)

The iterative charts developed by Michalowski in 1995 is similar to that of Taylor's chart (1937, developed using the friction circle method). This chart is developed for two dimensional fully dry and homogeneous slopes with log-spiral failure surface. The chart has been developed by plotting a dimensionless parameter, stability number against the slope angle ( $\beta$ ). The stability number for  $\Phi=0$  becomes independent of slope inclination for  $\beta$  is less than  $50^\circ$ .

In 1995, Michalowski developed a non-iterative chart which considered pore water pressure. The distribution of the pore water pressure is described by coefficient  $r_u$  defined by Bishop and Morgenstern (1960) as:  $r_u = u / \gamma h$

where,  $u$ = pore water pressure,

$\gamma$ = unit weight of soil and  $h$ = depth of the point on the failure surface below the slope surface. Stability charts for slopes with  $r_u = 0, 0.25$  and  $0.50$  were developed.

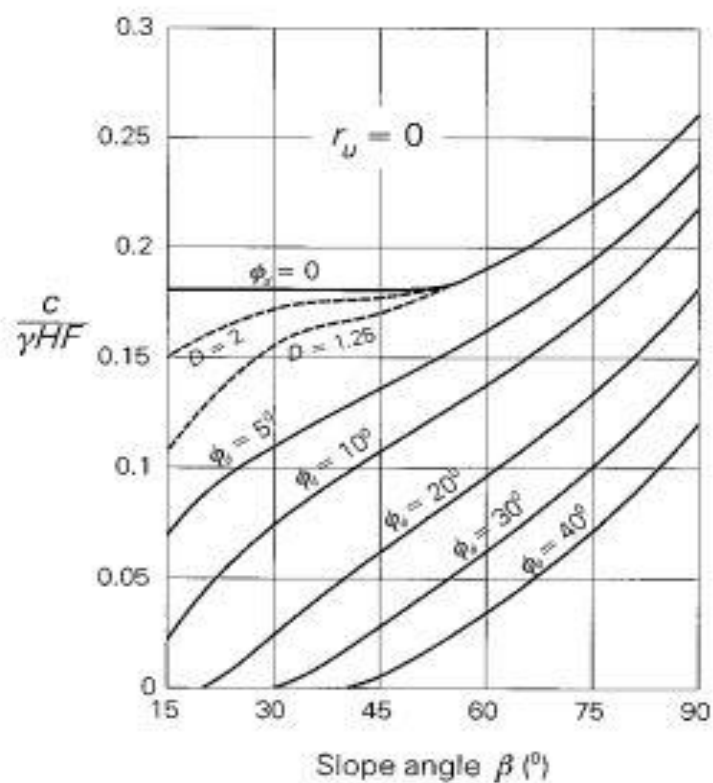


Figure 2.1 Michalowski Charts (1995, iterative) for dry slopes

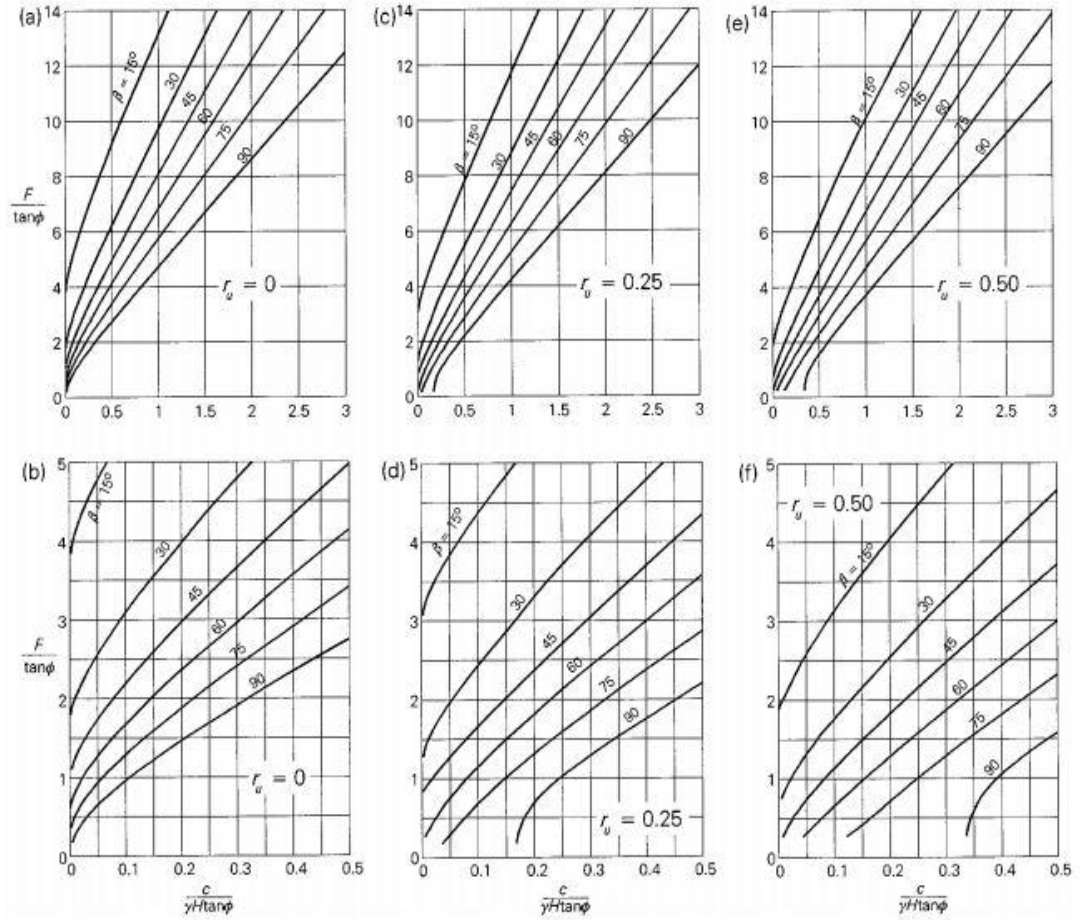


Figure 2.2 Michalowski Chart (1995, non-iterative) considering pore water pressure

## **CHAPTER THREE: METHODOLOGY**

This section of the thesis will magnifies the general approach to the research progression and put up an attempt to study the methodology aspects in brief. The methodology section is divided into two parts. First part of the section is the specific mitigation measures which include site specific analysis and mitigation of three landslides on Chure area. The second part of the section is a general mitigation measure which includes analysis and mitigation of overall landslides on chure area.

### **3.1 Site Specific Mitigation Methodology**

The specific mitigation measures include site specific analysis and mitigation of three landslides on Chure area. This involves the primary, secondary data collection and laboratory investigation and their analysis with mitigation measures.

#### **3.1.1 Primary Data Collection**

Firstly the desk study was started with the study of several published and unpublished reports regarding the geology of the chure area and landslide causes related problems. Then after for the other primary data collection, field visit on the landslide location was conducted for the collection of soil samples, technical information and facts regarding soil strength properties (cohesion and friction angle). Data collected from the site were:

- i. The topographic data from the GPS, Abney level and tapes
- ii. Representative soil samples(five soil samples from different landslides and sections) and loose soil samples to evaluate the soil parameters
- iii. Different socio economic data and photographs from the local people.

#### **3.1.2 Laboratory Investigations**

Various test values is inputted in standard format. Different test were performed in Central Material Testing laboratory, Pulchowk Campus from the soil sample collected from the landslide zone to obtain the different properties like particle size distribution, Specific gravity, Liquid limit and plastic limit and shear parameters ( $c$  &  $\phi$ ). The test from the four samples collected from the three different landslide sites were calculated, sample of calculation table and graph were shown on ANNEX I.

The calculated friction angle of different section of landslide from the laboratory is again calculated and checked from the method describe in Roadside geo-technical Problems, a handbook published by Department of Road. The process of calculating the friction angle is shown on ANNEX I

### **3.1.3 Finite Element Modeling**

The numerical analysis is carried out using a finite element formulation provided in the PHASE2 (Rocscience, 2012). PHASE2 can carry slope stability analysis using shear strength reduction (SSR) method. This option is fully automated and can be used with either Mohr–Coulomb or Hoek–Brown strength parameters. Displacement within the element is related to displacement at nodes through shape function. Transmission of internal forces between the edges of adjacent elements is represented by interactions at the nodes of the elements. Matrix oriented solution implicit the method of solving equation in every element communicating with other element in every step. Gaussian elimination is used to solve the compatibility equations. For the current study, an energy tolerance of 0.1 % is used.

### **Discretization and meshing**

Phase2 software has its inbuilt discretization and meshing function. Two dimension six noded triangles are used to discretize across the slope profile, uniform meshing option has been used.

### **Boundary condition**

Fixed boundary conditions are assumed along the lateral side and base of the Numerical model such that the displacement is restrained in both the x and y directions. The slope face and surface of the landslide is taken free and is kept free to move.

### **Gravity loading**

In the loading step, each finite element is given both an initial stress and a body force (self-weight). The initial vertical stress is estimated from the weight of the material above the element. Phase2 automatically determines the ground surface above the element and the stress due to the material above the element. The horizontal to-vertical stress ratio  $\sigma_H / \sigma_V$  is kept as 1.0 (Pal et al. 2012).

## Factor of safety

Method for the calculation of factor of safety using finite element method (FEM) differs from the conventional limit equilibrium approach. The factor of safety of a slope is defined here is the factor by which the original shear strength parameter is divided in order to bring the slope to the verge of failure. For Mohr–Coulomb material model, the factored shear strength parameters  $C_f$  and  $\phi_f$  are calculated as:

$$C_f = C / SRF$$

$$\phi_f = \tan^{-1} (\tan \phi / SRF)$$

Where SRF is the “strength reduction factor (SRF).” This method is referred to as the “shear strength reduction (SSR) technique” (Matsui & Sam, 1992). In the finite element formulation, the same factor is always used for both the terms. To find the true factor of safety, PHASE2 performs a systematic search for the value of SRF starting from SRF = 1 that will just cause the slope to fail. The final value obtained in the process is the FOS or SRF.

## Failure criterion

Mohr-Coulomb criterion remains the one most widely used failure criterion in geotechnical practice and has been used most of cases except the failure criteria of concrete retaining wall. Mohr-Coulomb criterion is effective for the soil possessing both of the components of cohesion and friction. In terms of principal stresses and assuming a compression- negative sign convention, the criterion can be written as follows:

$$F = \frac{\sigma_1' + \sigma_3'}{2} \sin \phi' - \frac{\sigma_1' - \sigma_3'}{2} - c' \cos \phi'$$

Where,  $\sigma_1'$  and  $\sigma_3'$  are major and minor principal effective stresses.

The failure function F can be interpreted as follows:

F < 0 stress is inside envelope (elastic)

F = 0 stress on failure envelope (yielding)

F > 0 stresses outside failure envelope (yielding and must be redistributed)

The concrete retaining wall has failure criteria of Drucker-Prager

Calculating Drucker-Prager strength parameters from Mohr-Coulomb strength

Parameters for use in Phase2:

$$q = \frac{\sin \phi}{\sqrt{1 + \frac{1}{3} \sin^2 \phi}} \quad k = \frac{c \cos \phi}{\sqrt{1 + \frac{1}{3} \sin^2 \phi}}$$

For non-associated flow (zero dilatancy):

$$q = \sin \phi \quad k = c \cos \phi$$

### Input parameters

Different properties of the soil are determined from laboratory test are verified by back analysis which will be describe on next section.

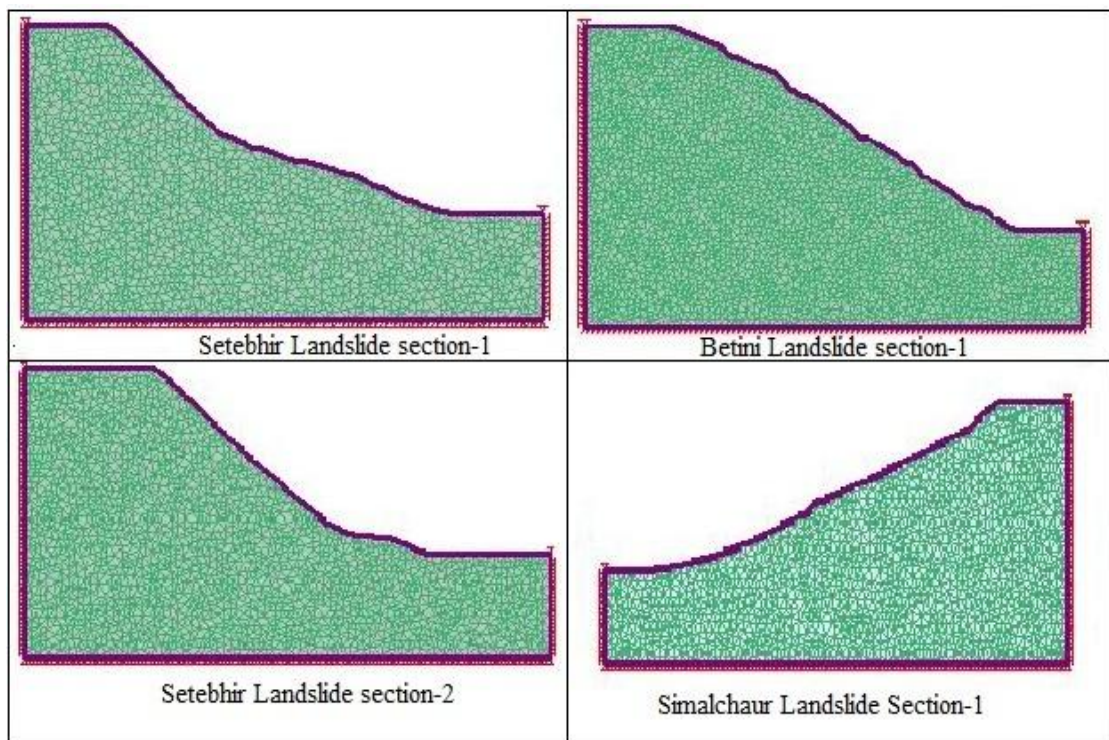


Figure 3.1 Landslide profile sections

### Material properties for dry soil

Material: Clayey silt

Failure Criteria: Mohr-coulomb

Unit weight = 20 KN/m<sup>3</sup>

Elastic Properties (Griffiths & Lane, 1999)

Modulus of elasticity = 10<sup>5</sup> Kpa

Poisson ratio = 0.3

Ψ Dilation angle (= 0)

Shear parameters: (from laboratory test)

### Material Property for vegetative soil

Grasses and small shrubs can have a significant reinforcing effect down to depth of 0.75 to 1.5m. Trees have deeper seated anchorage effects and can enhance soil strength to depth of 3m or more depending upon the root morphology of the species (Oloughlin 1984). For the changes on shear parameter by vegetative effect the studies have shown that the value of friction angle changes from 1-5 degree and additionally corresponds with the cohesion factor by 3.5-6.3  $\text{KN/m}^2$ , owing to the presence of vegetation cover stituting roots upto 0.5mm in diameter at a maximum water content of 18 percentage (Hoyos et.al.,2010). Similarly Tiwari et.al (2012) used the value of root cohesion upto 20  $\text{KN/m}^2$  in his research paper. Coppin and Richards (1990) gives the vegetative property parameter as increase in 5  $\text{KN/m}^2$  on root cohesion value. So on this thesis work for the vegetative soil, the root depth is consider in two cases 1m and 3m and maximum increase in value of root cohesion is form 6  $\text{KN/m}^2$  to 20  $\text{KN/m}^2$  and increase in friction angle upto 5 degree. The all other parameters remain same as the property of dry soil.

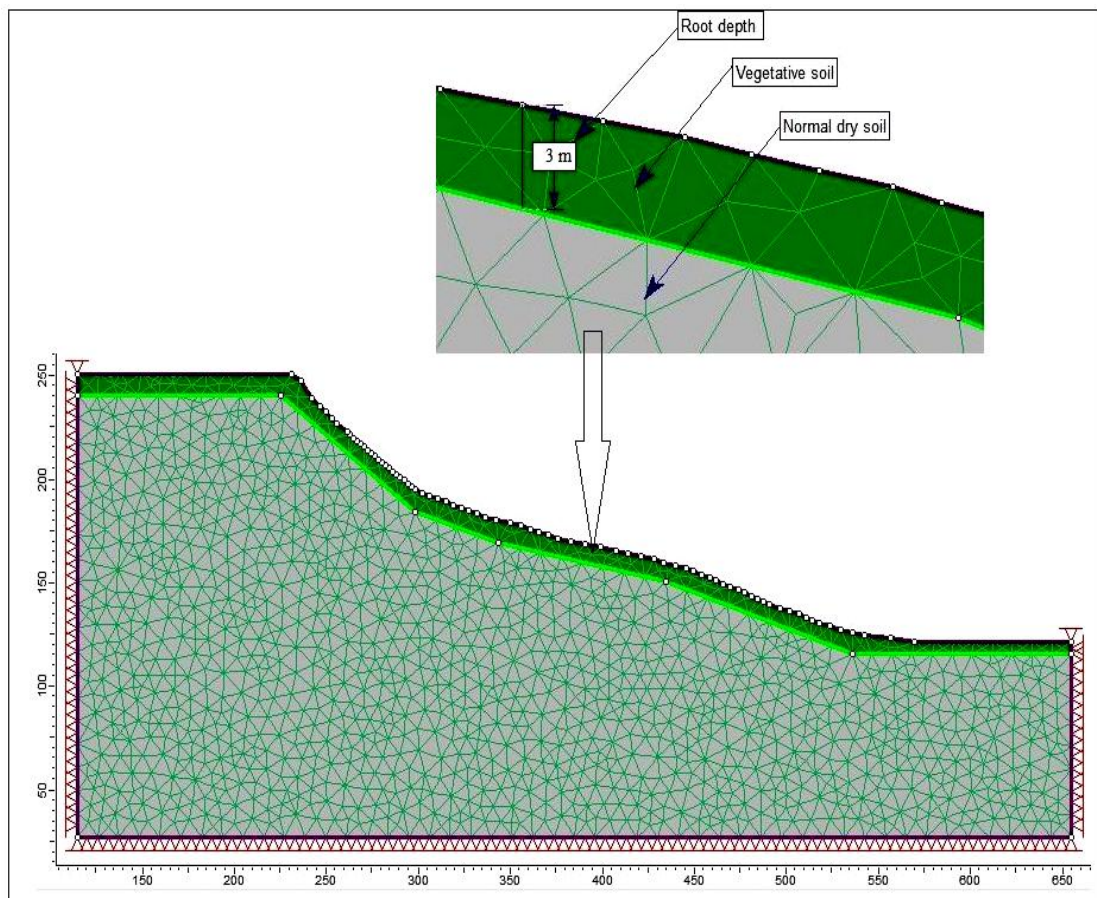


Figure 3.2 Application of vegetative effect on landslide model

### Material Property for Retaining wall

The retaining wall used on the modeling is concrete retaining wall and the failure criteria used is Drucker-Prager failure criteria. The retaining wall is kept at the toe of the slope with varying its height by taking ratio of height of retaining wall to height of landslide. Following parameters are used for the retaining wall:

Material: Retaining wall

Failure Criteria: Drucker Prager

Unit weight = 24 KN/m<sup>3</sup>

Elastic Properties (P. Jimenez Montoya 1971)

Modulus of elasticity = 25000 Kpa

Poisson ratio = 0.2,  $\Psi$  Dilation angle (= 0)

Dimension less parameter:

$q = 0.5$ ,  $K = 409.57$

Equivalent  $c$  and  $\Phi$  parameter are 500 Kpa and 35 degree respectively assigned from range given by P. Jimenez Montoya 1971 for concrete.

Tensile strength of concrete= 450 kpa (for M20 concrete)

The joint is assigned between the material interface between soil and retaining wall and has property as below:

Joint normal stiffness = 0.1 GPa/m

Joint shear stiffness = 0.01 GPa/m (10% of normal stiffness)

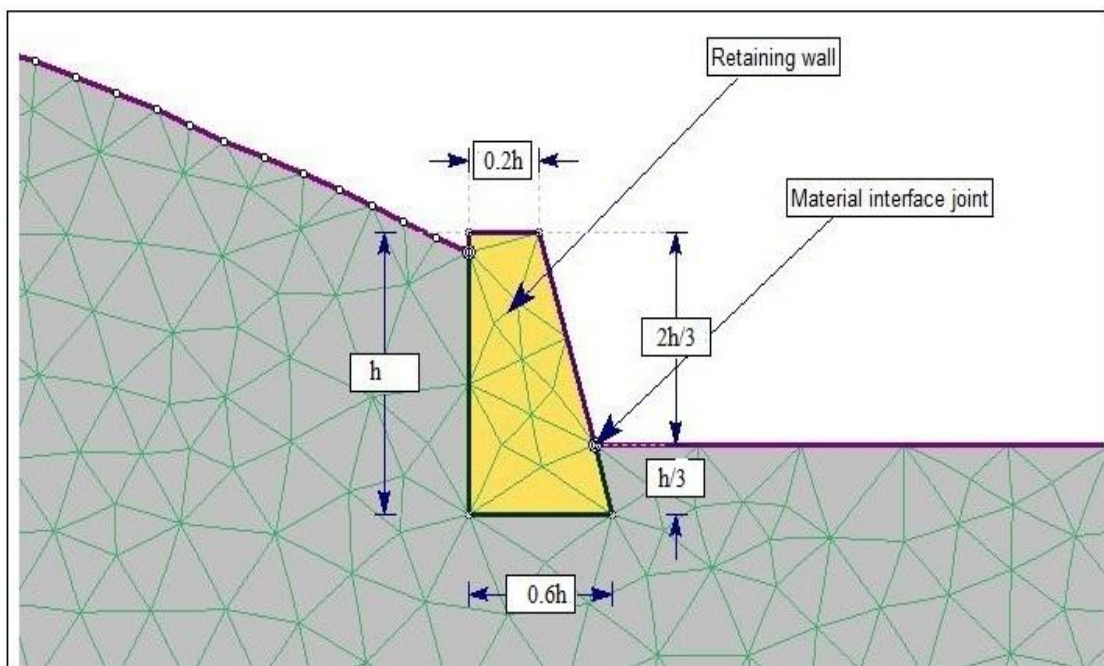


Figure 3.3 Assigning retaining wall on landslide model

### Material Property for using combine mitigation measures

The mitigation measures are also used in combine form. The use of retaining wall, vegetation and water table variation are applied on same model and change in factor of safety is evaluated. The material properties while using combine are kept same as that of using single mitigation measures.

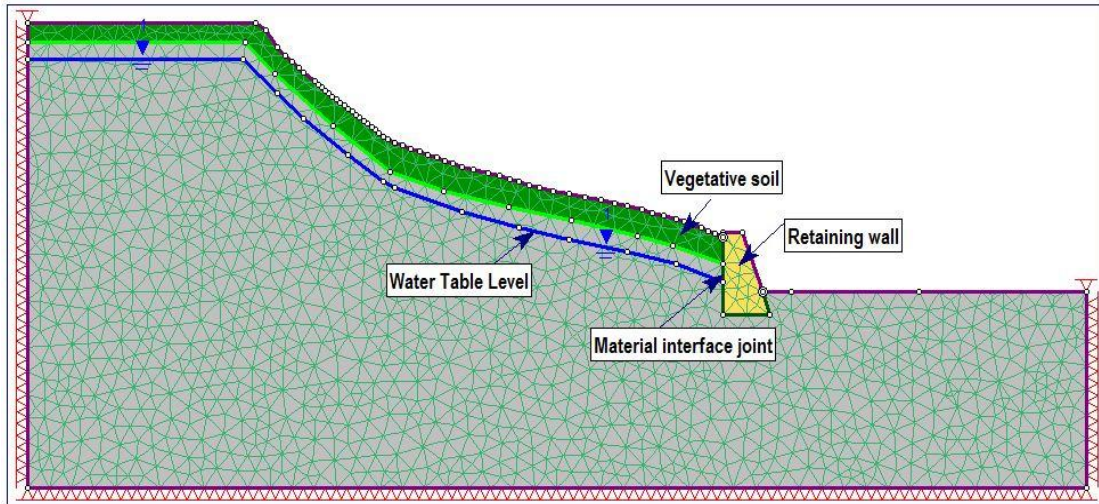


Figure 3.4 Assign of combine mitigation measures on landslide model

#### 3.1.4 Back Analysis

Due to the insufficient financial condition and technical support soil collected from the landslide zone is not representative, from which the parameters like friction angle and cohesion obtained will not be so representative to the site location. Also the test performed on the lab is not well functioned. So to obtain the representative parameters of soil back calculation was performed. During this the cohesion of soil is assumed to be constant and the friction angle is varied to obtain the factor of safety as one. Varying the friction value SRF of the landslide is calculated and the corresponding friction value on which the SRF value is one is considered as friction value of that section. Using this friction value further calculation is performed. Result of back calculation from the Phase2 software is shown on are shown on ANNEX I.

### 3.2 General Mitigation Methodology

#### 3.2.1 Model Geometry

For the general cases the slope having inclinations below  $30^\circ$  are generally stable and steeper slopes (composed only of soil materials) greater than  $50^\circ$  are generally

unstable. The thesis work has been performed on five slope angles within this range (30°, 35°, 40°, 45°, 50). For other slope angles the safety factor can be obtained by interpolation between the charts.

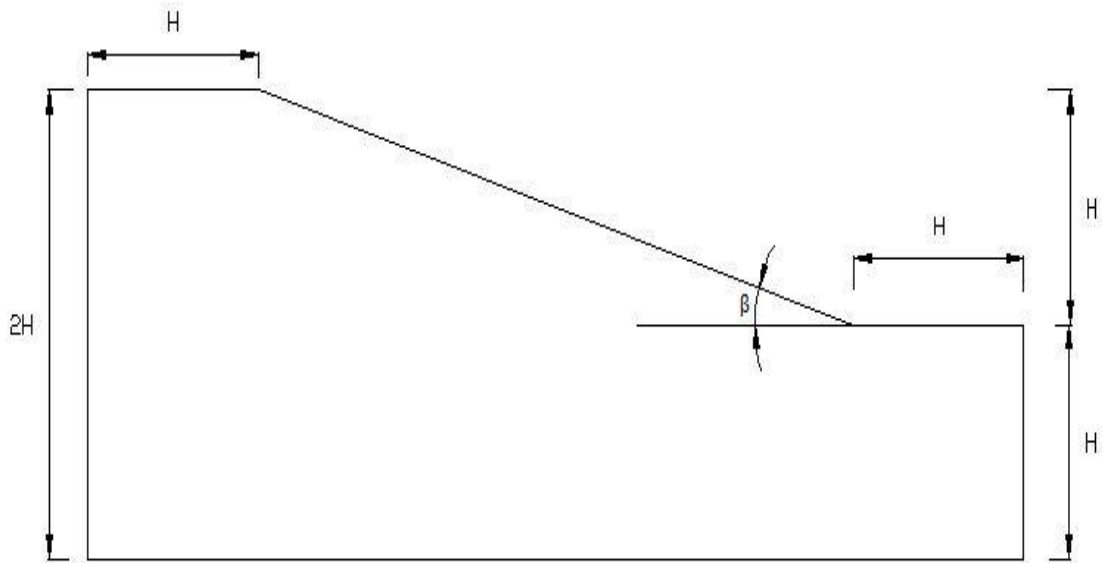


Figure 3.5 Model Geometry given by Tiwari et.al 2013

The model geometry is tested on the height of 10 meter at different ground slope angle.

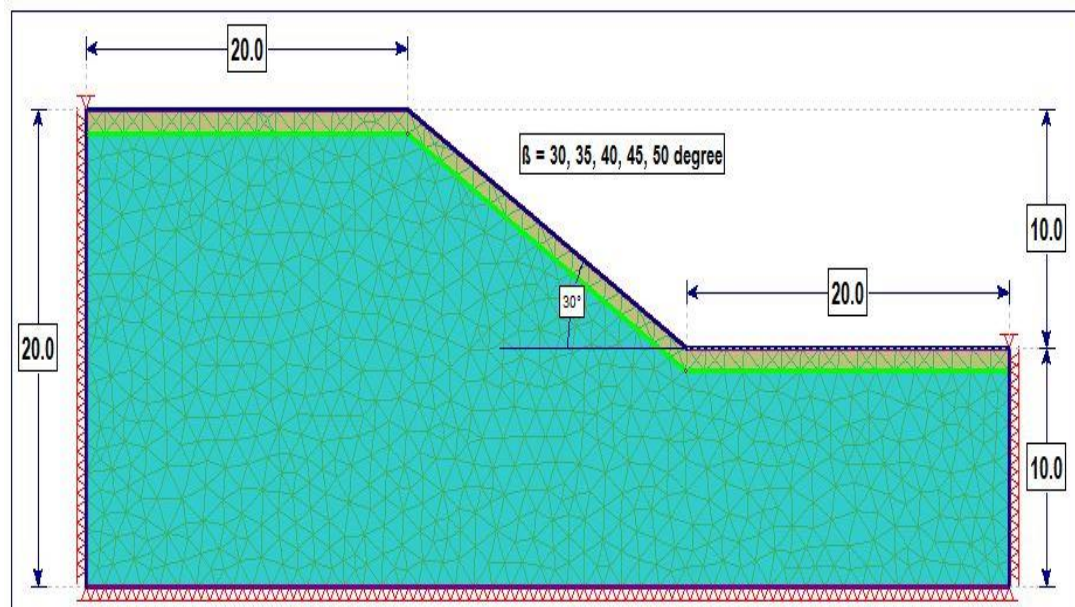


Figure 3.6 Model geometry on Phase2 software

### Slope geometry after slope modification

The factor of safety is checked on the model after slope modification also. The pattern of modification of original slope geometry is shown below.

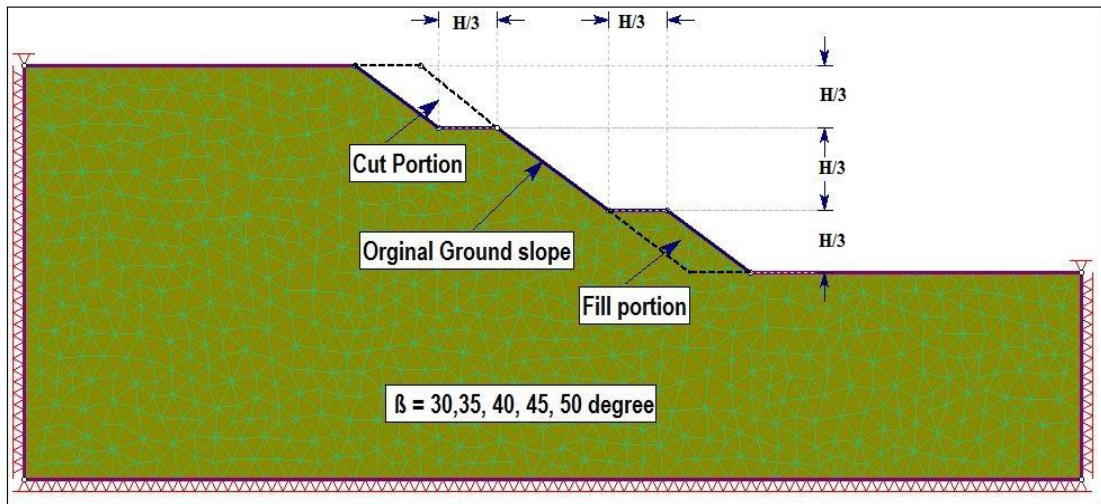


Figure 3.7 Slope modification detail on Phase2

### 3.2.2 Soil Properties

The properties of soil materials vary in wide range. To find the exact physical properties of the soil, they should be tested in laboratory in perfect conditions. Unified Soil Classification System (USCS) presents the approximate properties of the soil materials which can be used in crude geotechnical problems.

The mitigation chart is prepared based on soil types and using their properties. Eight types of soil founded on chure area are selected and their average value of properties is taken from the value given by USCS classification (adopted by Wagner and Krahenbuhl).

Table 3.1 Average engineering properties of soil as per USCS classification

| Group | Classification            | Unit weight<br>(kN/m <sup>3</sup> ) | Friction angle<br>(°) | Cohesion<br>(kN/m <sup>2</sup> ) |
|-------|---------------------------|-------------------------------------|-----------------------|----------------------------------|
| GM-GC | Silty to clayey gravel    | 21.9 ± 2.0                          | 33.0 ± 3.0            | 2.0 ± 2.0                        |
| SP    | Clean sand, poorly graded | 18.5 ± 2.5                          | 36.0 ± 6.0            | 0.0                              |
| SM    | Silty sand, little fines  | 20.0 ± 2.5                          | 34.0 ± 3.0            | 0.0                              |
| SC    | Clayey sand, little fines | 19.6 ± 2.0                          | 32.0 ± 4.0            | 0.0                              |
| SM-SC | Silty to clayey sand      | 21.0 ± 2.0                          | 31.0 ± 3.0            | 5.0 ± 5.0                        |
| ML    | Silt                      | 19.0 ± 2.5                          | 33.0 ± 4.0            | 0.0.                             |
| CL-ML | Silt to clayey silt       | 21.0 ± 1.5                          | 30.0 ± 4.0            | 15.0 ± 10.0                      |
| CL    | Clayey silt               | 20.0 ± 1.5                          | 27.0 ± 4.0            | 20.0 ± 10.0                      |

### 3.2.3 Load Parameter Variation

The analysis has been performed on four types of mitigation options and their combinations. The model is analyzed on dry, fully saturated, two meter and four meter of water table position with every types of mitigation option with five types of slopes. The vegetation is applied at one meter of effective root depth. The retaining wall is applied at the toe of slope with the variation of height of wall. The height variation is done with the ratio of height of retaining wall to height of slope value at 0.2, 0.3 and 0.4 at different water table variation at different slope. The slope modification is done as described on previous section and loaded with water table variations. The slope modification and vegetation are combined used along with the water table variation. The retaining wall and vegetation combination are also loaded with water table variation.

#### Summary of slope geometry models

Table 3.2 Summary of slope geometry models

|   |
|---|
| Slope angle: 30, 35, 40, 45, 50 degrees   |
| Soil type: GM-GC, SP, SM, SC, SM-SC, ML, CL-ML, CL                                  |
| Water table conditions: Dry, saturated, WT 2m below, WT 4m below                    |
| Vegetation: Effective root depth 1m   |
| Retaining wall: h/H value 0.2,0.3,0.4(h=ht. of retaining wall, H= ht. of landslide) |
| Slope modification: cut and fill type   |
| Vegetation and slope modification: ERD 1m, cut and fill type                        |
| Retaining wall and vegetation: h/H=0.3, ERD=1m                                      |

More than 1500 iterations are performed on Phase2 software on various combinations.

### 3.3 Result interpretation and plotting

After finding the factor of safety from iterations of different combination those data are plotted on graph. The graph are plotted on Tecplot open source software and chart are exported on different formats.

## CHAPTER FOUR: RESULT AND OUTCOMES

### 4.1 Site Specific Mitigation Result

#### 4.1.1 Laboratory Investigation Result

The summary of the laboratory investigation result are presented below.

Table 4.1 Laboratory investigation summary

| S.N | Parameters                       | Landslide |       |        |            |
|-----|----------------------------------|-----------|-------|--------|------------|
|     |                                  | Setebhir  |       | Betini | Simalchaur |
|     |                                  | Sec-1     | Sec-2 | Sec-1  | Sec-1      |
| 1   | Cohesion, C (KN/m <sup>2</sup> ) | 8.5       | 8     | 7      | 8          |
| 2   | Friction angle, $\phi$ (degree)  | 31        | 30    | 32     | 27         |
| 3   | Specific Gravity, G              | 2.140     | 2.253 | 1.968  | 2.033      |
| 4   | Liquid Limit, LL (%)             | 35.50     | 32.50 | 32.75  | 25.00      |
| 5   | Plastic Limit, PL (%)            | 18.37     | 21.14 | 14.40  | 11.87      |
| 6   | Soil Classification<br>(USCS)    | CL        | CL    | CL     | CL         |

The detail of the laboratory investigation tables and graphs of different tests are shown on ANNEX I

#### 4.1.2 Stability Analysis with Mitigation Measures

##### FOS value

The factor of safety value is recorded with the application of mitigation measures. The FOS value goes on increasing with the level of water table decreasing down from surface level and have maximum at dry condition. The FOS value goes on increasing with the root depth of vegetation and increases with the height of retaining wall. The tabulated form of FOS value is shown below.

Table 4.2 FOS value form numerical modeling

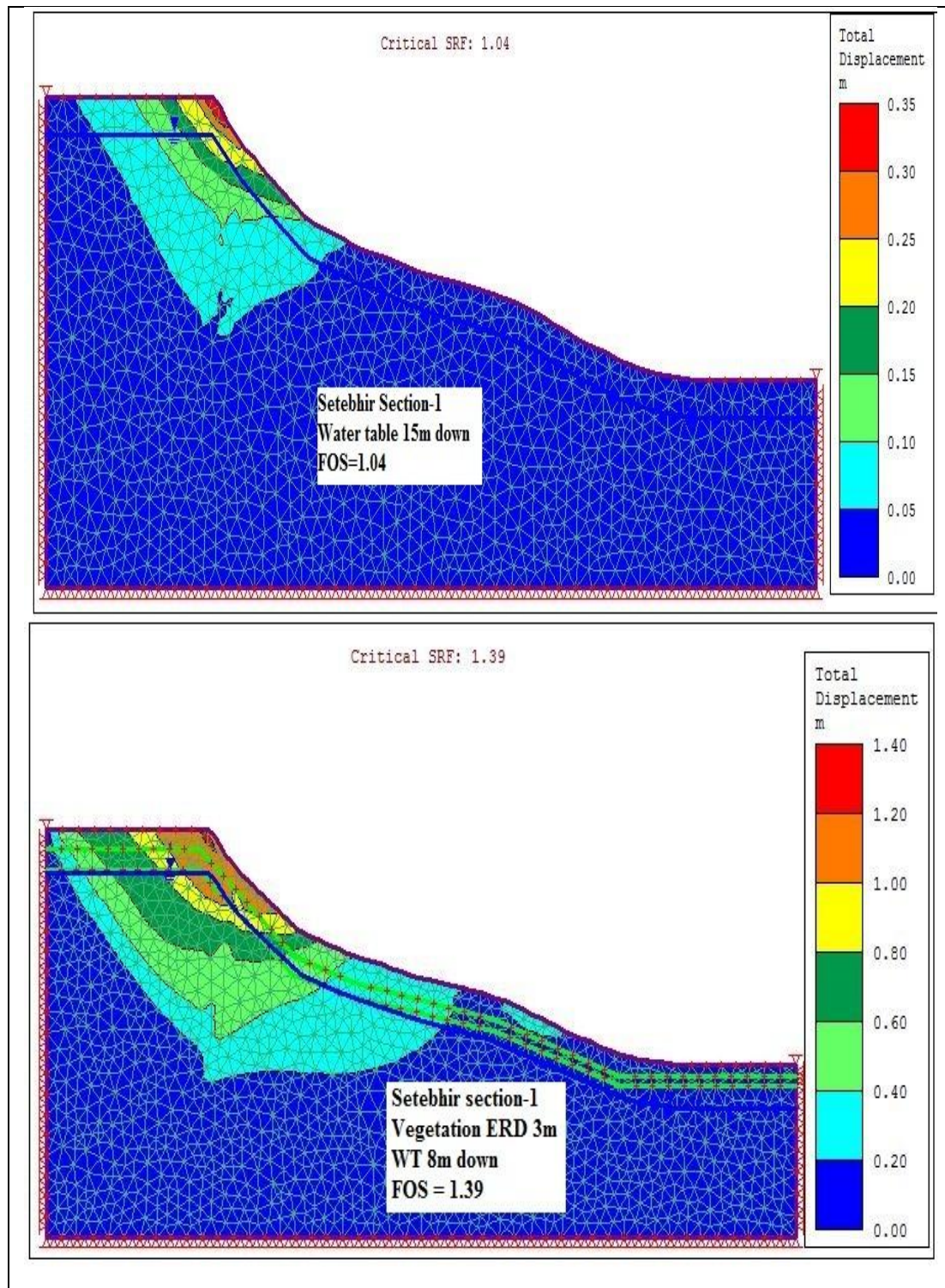
| S.N | Mitigation Measures   | GWT<br>Level | Landslides |            |        |            |
|-----|-----------------------|--------------|------------|------------|--------|------------|
|     |                       |              | Setebhir-1 | Setebhir-2 | Betini | Simalchaur |
| 1   | Water Table Variation | Sat          | 0.37       | 0.37       | 0.29   | 0.4        |
|     |                       | 2m           | 0.57       | 0.52       | 0.48   | 0.66       |
|     |                       | 4m           | 0.64       | 0.62       | 0.58   | 0.71       |
|     |                       | 6m           | 0.74       | 0.68       | 0.66   | 0.8        |

|   |  |     |      |      |      |      |
|---|--|-----|------|------|------|------|
|   |  | 8m  | 0.82 | 0.75 | 0.74 | 0.87 |
|   |  | 10m | 0.9  | 0.8  | 0.82 | 0.95 |
|   |  | 12m | 0.96 | 0.87 | 0.89 | 0.98 |
|   |  | 15m | 1.04 | 0.96 | 0.97 | 1    |
|   |  | 17m |      | 1.05 | 1.04 |      |
|   |  | Dry | 1    | 1    | 1    | 1    |
| 2 | Vegetation (ERD=1m)                              | Sat | 0.5  | 0.43 | 0.38 | 0.57 |
|   |  | 4m  | 1.06 | 0.78 | 0.68 | 0.77 |
|   |  | 8m  | 1.15 | 0.94 | 0.79 | 0.92 |
|   |  | Dry | 1.24 | 1.11 | 1.08 | 1.3  |
| 3 | Vegetation (ERD=3m)                              | Sat | 0.6  | 0.48 | 0.42 | 0.6  |
|   |  | 4m  | 1.11 | 0.83 | 0.71 | 0.79 |
|   |  | 8m  | 1.39 | 0.95 | 0.83 | 0.94 |
|   |  | 12m |      | 1.01 | 1.01 | 1.02 |
|   |  | Dry | 1.43 | 1.17 | 1.12 | 1.34 |
| 4 | Retaining wall<br>(h/H=0.3)                      | dry | 1.04 | 1.06 | 1.06 | 1.02 |
|   |  | 4m  | 0.75 | 0.6  | 0.57 | 0.75 |
|   | Retaining wall<br>(h/H=0.4)                      | dry | 1.05 | 1.07 | 1.08 | 1.03 |
|   |  | 4m  | 0.76 | 0.63 | 0.64 | 0.76 |
|   |  | 8m  | 0.93 | 0.87 | 0.75 | 0.79 |
|   |  | 12m | 1.08 | 1.01 | 0.83 | 0.91 |
| 5 | Retaining wall<br>(h/H=0.3)+vegetation<br>ERD 3m | dry | 1.43 | 1.17 | 1.13 | 1.35 |
|   |  | 4m  | 1.1  | 0.83 | 0.72 | 0.8  |
| 6 | Retaining wall<br>(h/H=0.4)+vegetation<br>ERD 3m | dry | 1.44 | 1.18 | 1.16 | 1.36 |
|   |  | 4m  | 1.17 | 0.84 | 0.72 | 0.8  |
|   |  | 8m  | 1.41 | 0.96 | 0.86 | 0.95 |
|   |  | 12m |      | 1.1  | 1.02 | 1.03 |

From the above result we see that use of single mitigation measure did not gave the satisfactory safety level so use of mitigation option more than one and their combination should be applied to achieve satisfactory safety level on all section of landslide.

## Displacement contours

All of the results of the work cannot be presented in this report due to voluminous in nature. Here is some displacement contours while using different mitigation option. The result of Setebhir section-1 while using different mitigation options are shown below and other results are shown on ANNEX II



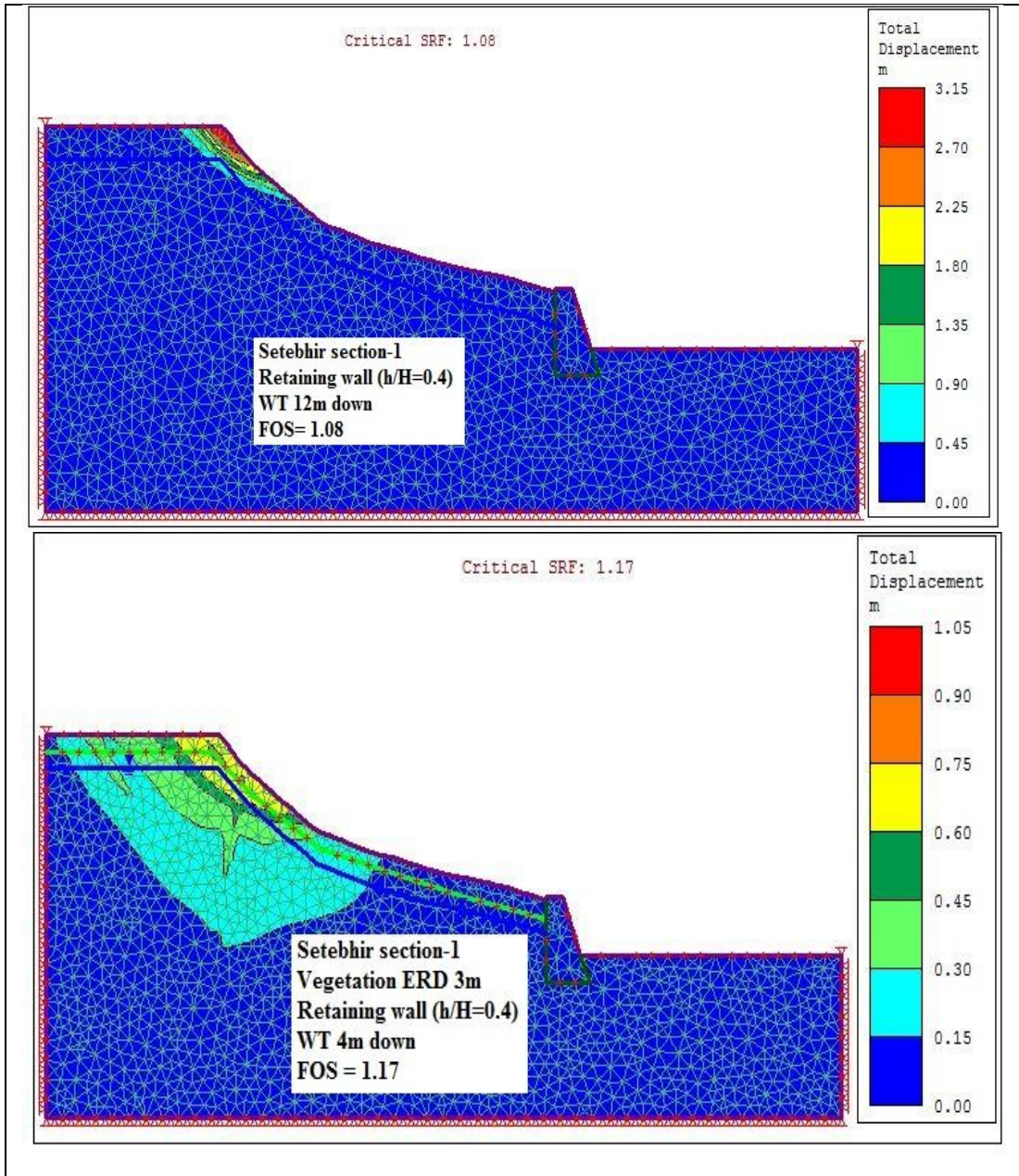


Figure 4.1 Displacement contours of site specific analysis

### SRF vs Displacement plot

The failure of the material model is defined as the point, from which the material in elastic zone enters the plastic zone. This effect is seen by the sudden increase in the displacement. Within the elastic zone, lower value of displacement has been observed and in plastic zone, higher value of displacement has been observed. From the SRF vs displacement plot we have seen that the total displacement will go on decreasing with the increasing factor of safety. The result of plot of Setebhir section-1 is shown below and other results are shown on ANNEX II.

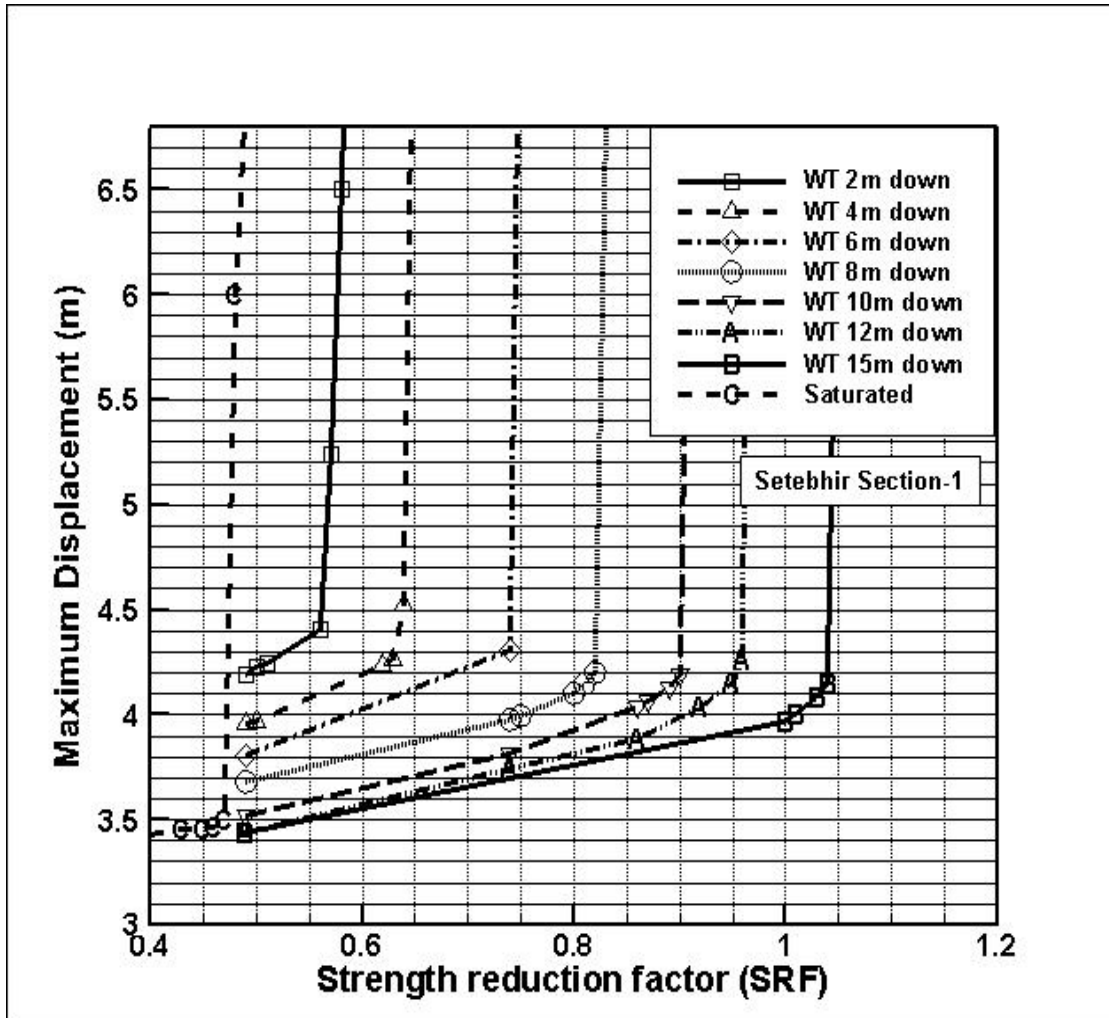


Figure 4.2 SRF vs Displacement plot on Setebhir section -1

## 4.2 General Mitigation Result

### FOS value

The factor of safety value is recorded with the application of mitigation measures at different ground slope. The result of FOS value on tabulated form is shown in ANNEX III.

### Displacement contours

All of the results of the work cannot be presented in this report due to voluminous in nature. Here is one random result of one slope and its displacement contours while using different mitigation option. Other some results are shown on ANNEX III.

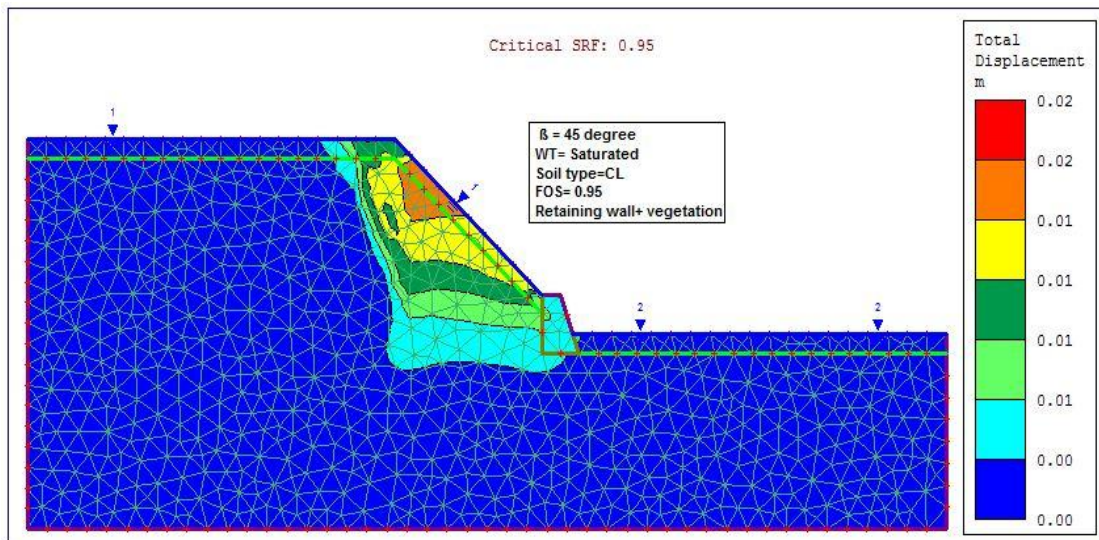


Figure 4.3 Displacement contour of general mitigation analysis

### Mitigation Chart

The final chart is the mitigation chart plotted between  $C/\gamma H \tan \phi$  vs  $F/\tan \phi$  as mentioned by Michalowski. The safety factor for various slope angles, different mitigation measures and water table variation as per the result tabulated on ANNEX III are presented. The value of  $C/\gamma H \tan \phi$  more than 0.25 is not covered by this chart because the type of eight soil selected from the soil found on chure area does not have value higher than 0.25. There are five mitigation charts for different slope angle at dry and saturated conditions. There are three other separate charts which shows the effect of water table condition, effect of vegetation and effect of height of retaining wall at different slope conditions. From this chart we can easily find out the factor of safety for using different mitigation measures for different type of soil and ground slope condition at various variations of water table conditions.

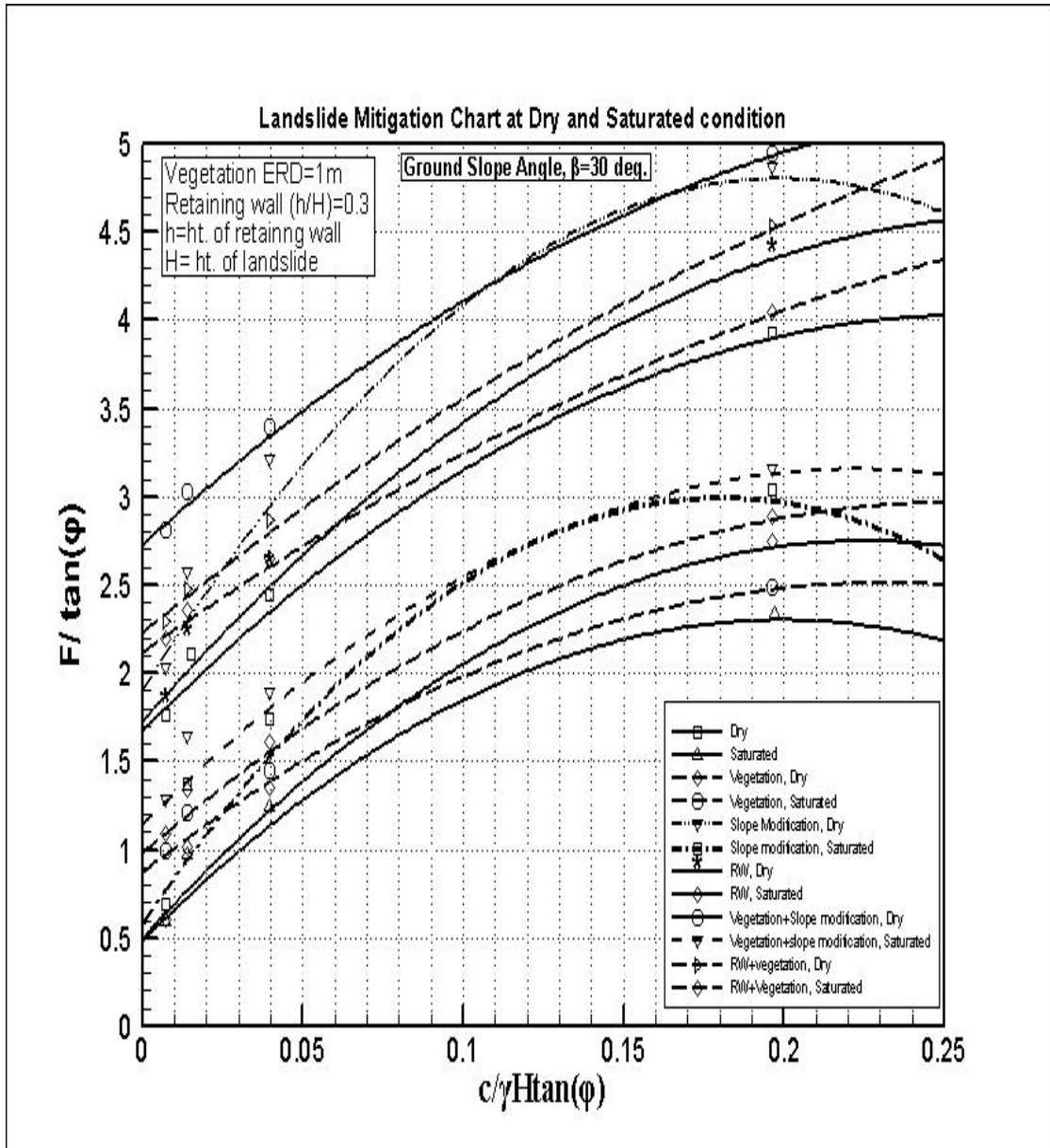


Figure 4.4 Mitigation chart at 30 degree slope angle

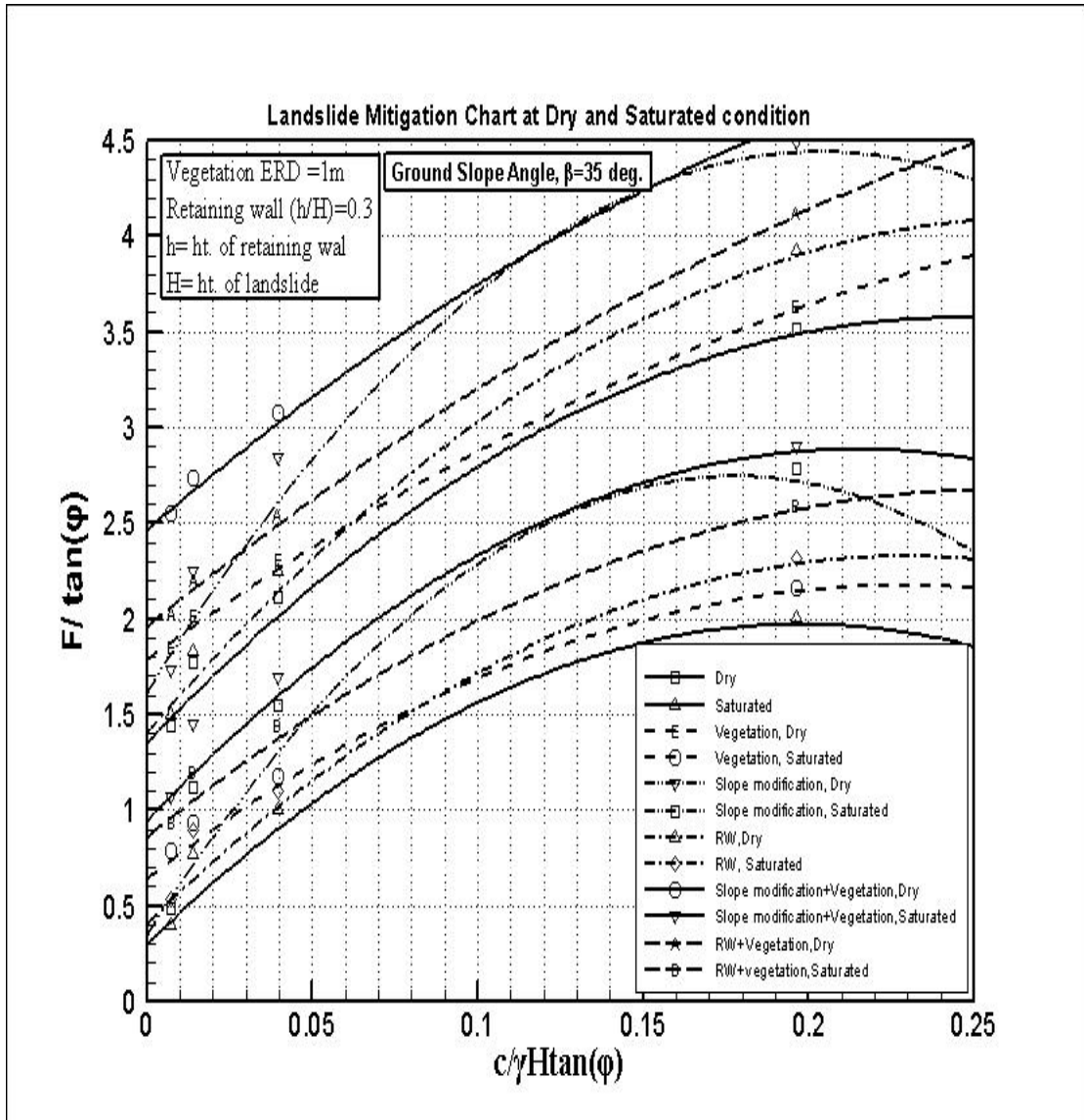


Figure 4.5 Mitigation chart at 35 degree slope angle

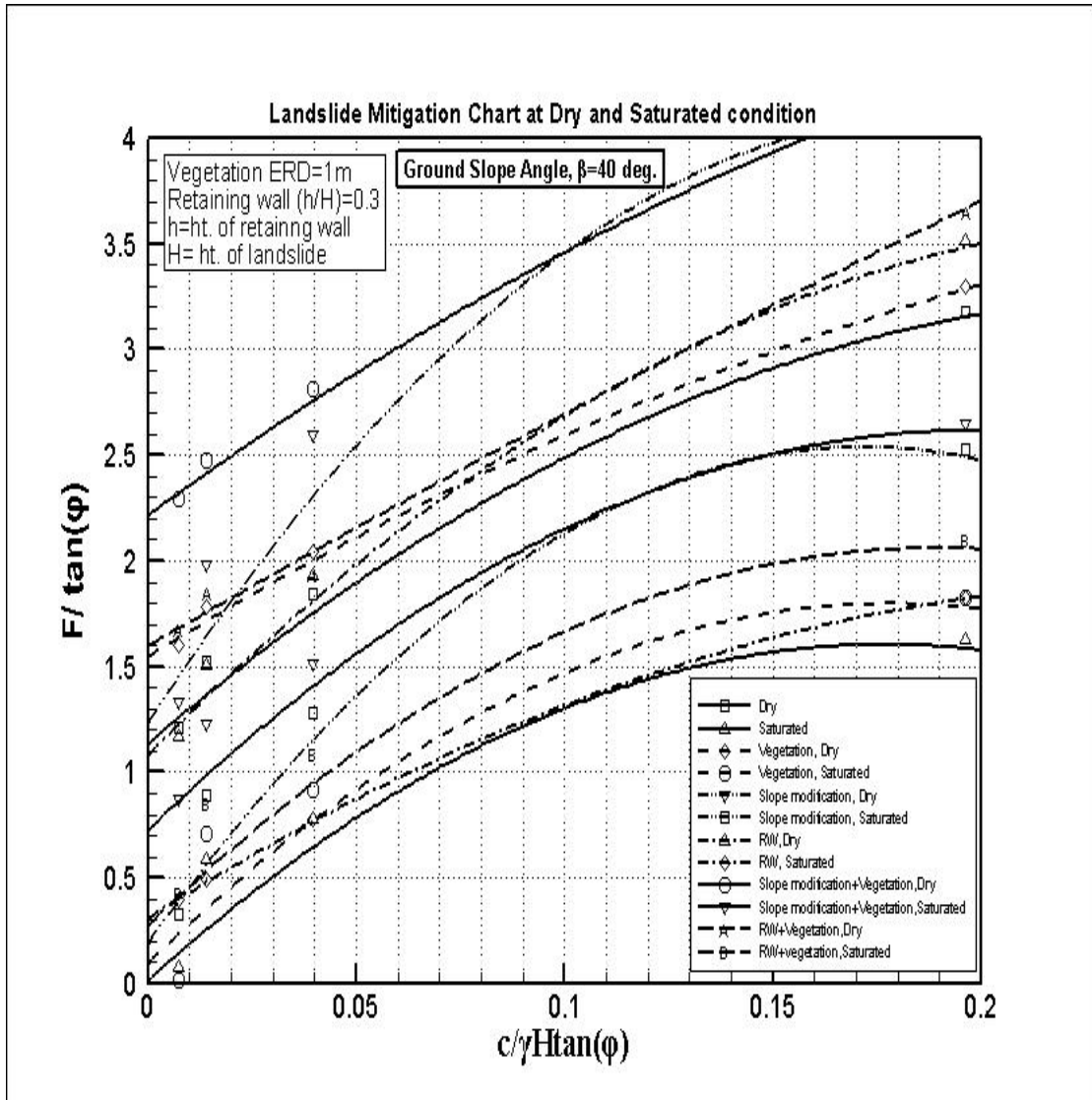


Figure 4.6 Mitigation chart at 40 degree slope angle

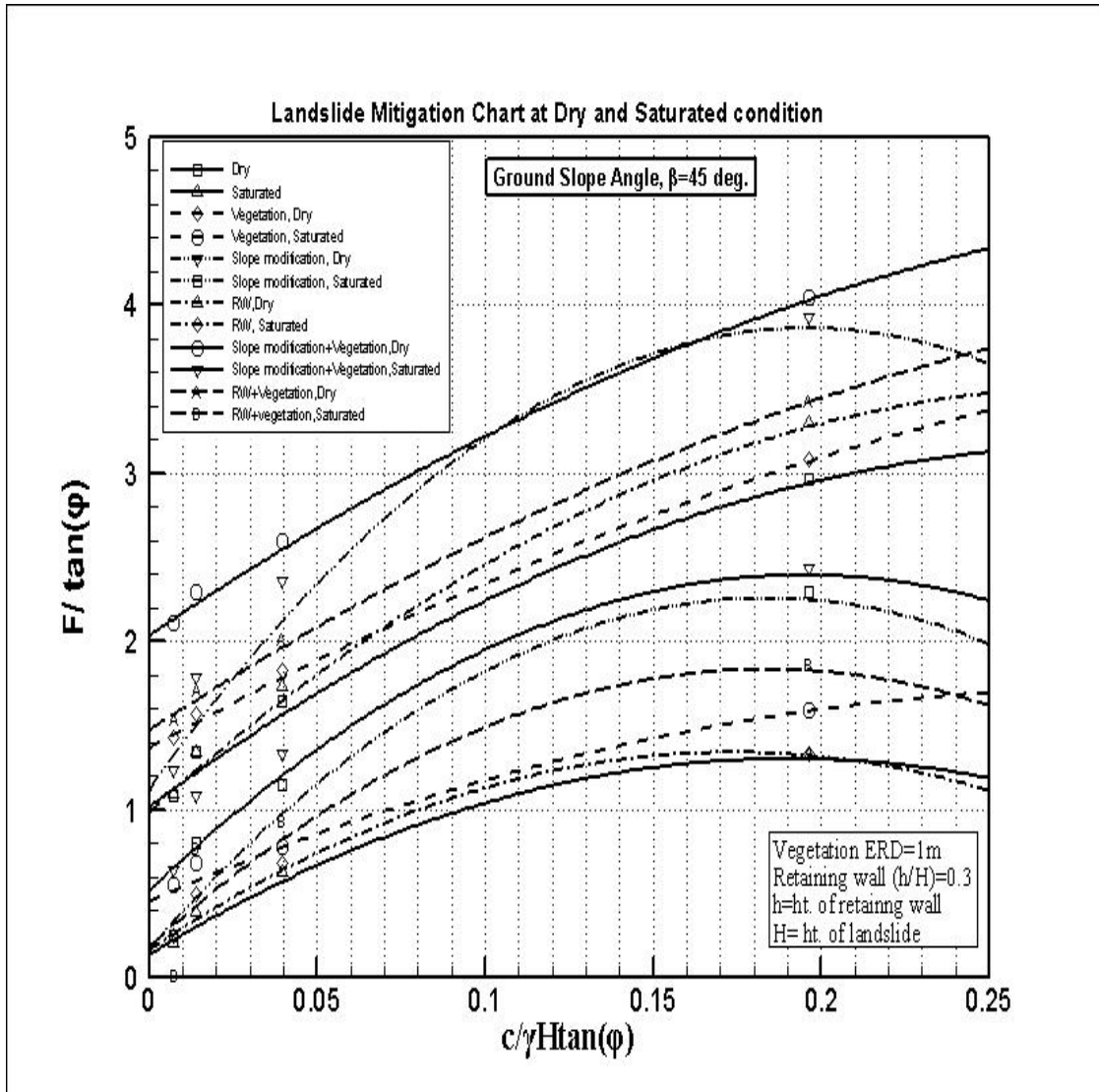


Figure 4.7 Mitigation chart at 45 degree slope angle

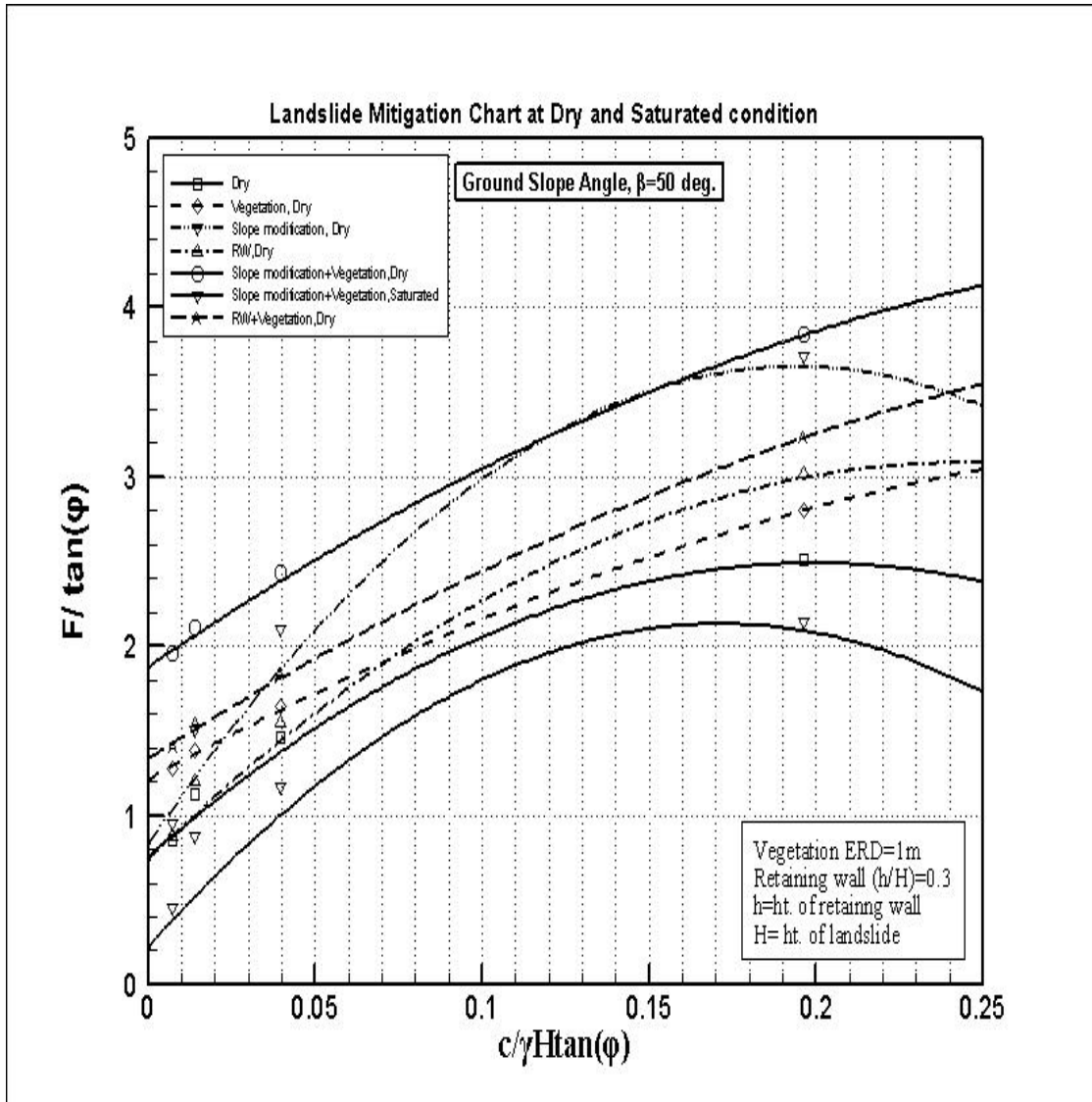


Figure 4.8 Mitigation chart at 50 degree slope angle

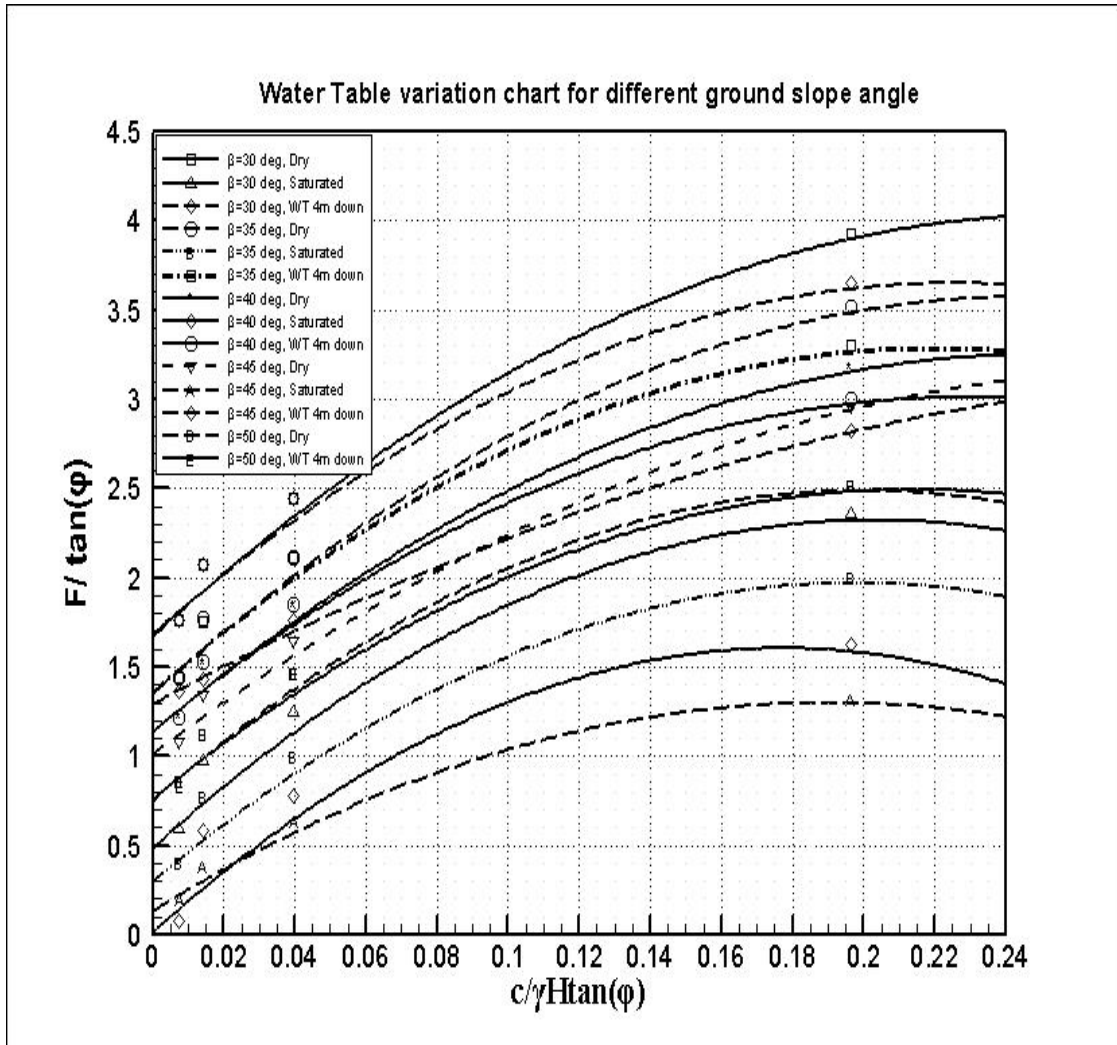


Figure 4.9 Mitigation chart for water table variation

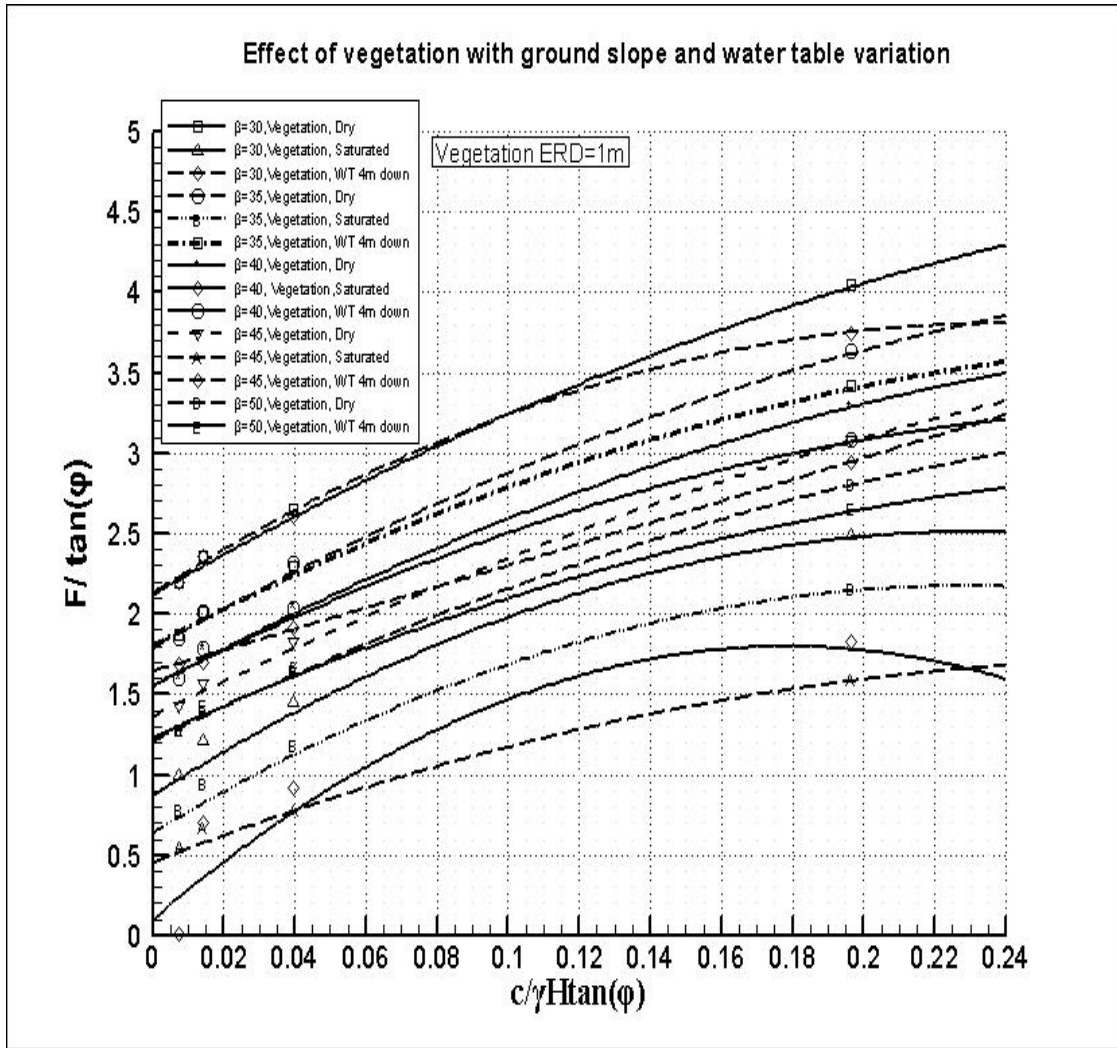


Figure 4.10 Mitigation chart for vegetative soil with WT variation

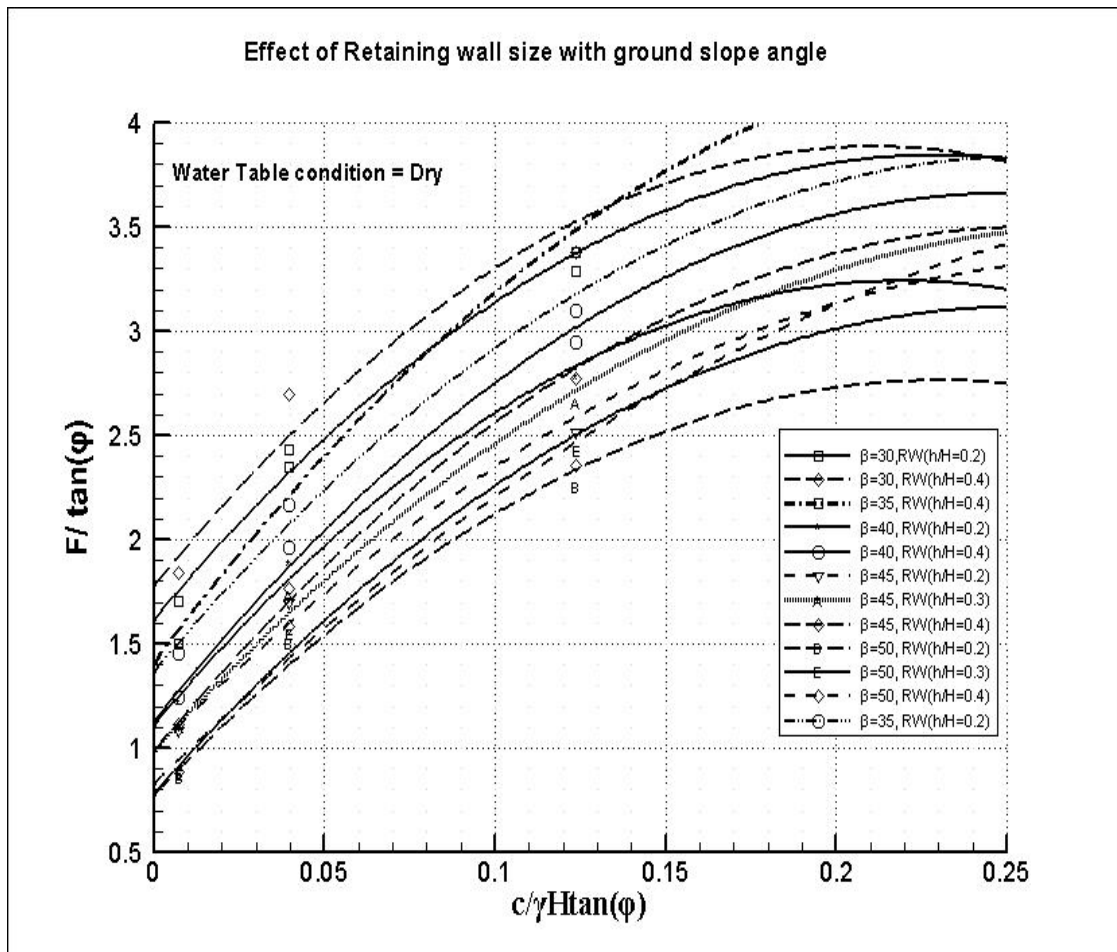


Figure 4.11 Mitigation chart for different size retaining wall

### Chart Analysis and Discussion

From the chart showing the water table variation with different slope angle we found that the slope angle which is less than 45 degree and water table level more than 4 m down from surface level gives the significant safety and stability. So the effect of mitigation measures will be well effective when the slope is more than 45 degree and water table is more than 4m down from the surface level.

Furthermore with the analysis of eight different chart of different slope angle we found that maximum increase in FOS value is obtained with the application of slope modification mitigation measure and minimum increase in FOS value is obtained with the application of Retaining wall with considering overall cases.

### Use of chart

The mitigation chart can be used very easily. If we take the soil sample form the landslide site and tasted to the laboratory to find the respective  $c$ ,  $\phi$ ,  $\gamma$  value and find

out the height of landslide than we can calculate the value of  $C/\gamma H \tan\phi$  in the horizontal axis. Then we will extend towards the desired curve and then respective  $F/\tan\phi$  value is achieved by extending to the vertical axis. For example we have the parameter as  $c= 8.5 \text{ KN/m}^2$  ,  $\phi= 34$ ,  $\gamma= 21.4 \text{ KN/m}^3$ ,  $H= 28 \text{ m}$  then  $C/\gamma H \tan\phi = 0.021$   
For the  $\beta=35$  degree curve at saturated condition,  
 $F/\tan\phi = 0.65$  So  $F= 0.438$  at saturated condition.

## CHAPTER FIVE: VARIFICATION OF WORK

The result obtained from numerical simulation can be verified by either by experimental investigation or by comparison with the worldwide accepted literatures or by using other analysis tools.

### 5.1 Verification with other analysis tool

The factor of safety obtained from the FEM based Phase2 software is compared to the factor of safety achieved by LEM based Slide software in both site specific and general mitigation models.

#### Site specific mitigation model

The FOS value comparison is tabulated below.

Table 5.1 FOS value comparison of site specific analysis

| Landslide:<br>Simalchaur   | Tools            |                      |                 |                 |                      |                 |
|----------------------------|------------------|----------------------|-----------------|-----------------|----------------------|-----------------|
|                            | FEM based Phase2 |                      |                 | LEM based Slide |                      |                 |
| Water<br>Table<br>position | WT<br>variation  | Vegetation<br>ERD 3m | RW<br>(h/H=0.3) | WT<br>variation | Vegetation<br>ERD 3m | RW<br>(h/H=0.3) |
| Sat                        | 0.4              | 0.6                  |                 | 0.395           | 0.597                |                 |
| 2m                         | 0.66             |                      |                 | 0.654           |                      |                 |
| 4m                         | 0.71             | 0.79                 | 0.75            | 0.71            | 0.78                 | 0.72            |
| 6m                         | 0.8              |                      |                 | 0.798           |                      |                 |
| 8m                         | 0.87             | 0.94                 |                 | 0.865           | 0.92                 |                 |
| 10m                        | 0.95             |                      |                 | 0.96            |                      |                 |
| 12m                        | 0.98             | 1.02                 |                 | 0.976           | 1.02                 |                 |
| 15m                        | 1                |                      |                 | 1.03            |                      |                 |
| Dry                        | 1                | 1.34                 | 1.02            | 1.093           | 1.33                 | 0.98            |

Correlation between the result obtain from these two software are tentative same and are in best correlation. The correlation coefficient between the SRF obtain from two methods is 0.9915.

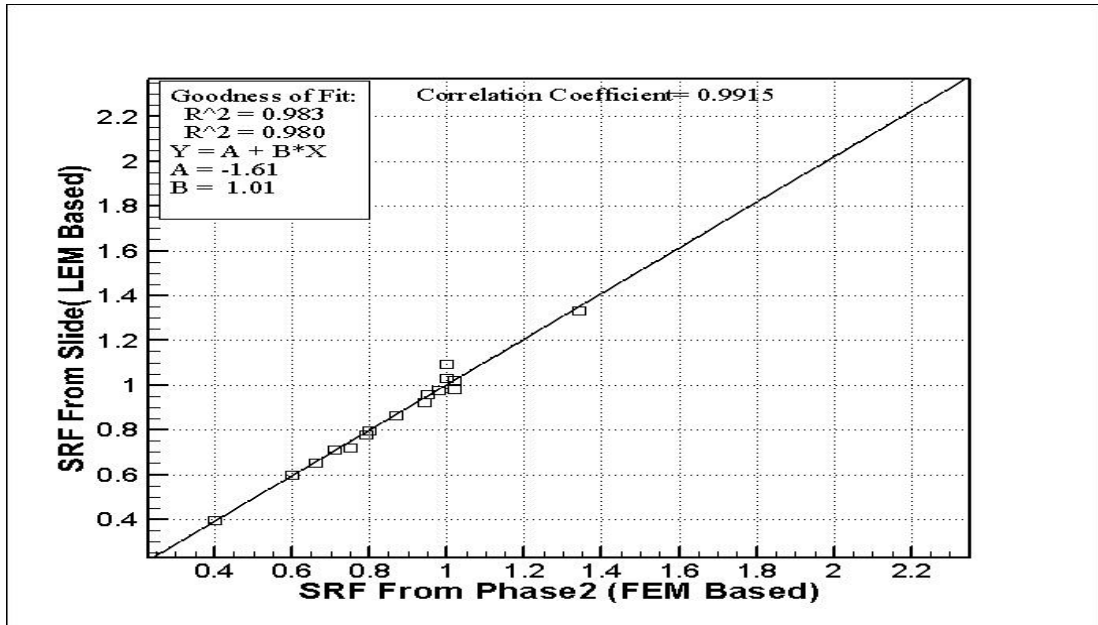


Figure 5.1 Correlation curve for site specific analysis

### General mitigation model

The FOS value is checked at ground slope angle of 35 degree. Most of the mitigation is selected for four type of soil and comparison is done which is tabulated below.

Table 5.2 FOS value comparison of general mitigation analysis

| Mitigation Measures             | Result From Phase2 (FEM Based) |       |      |      |       | Result From Slide (LEM Based), Bishop Simplified |      |      |       |
|---------------------------------|--------------------------------|-------|------|------|-------|--|------|------|-------|
|                                 | Slope Angle                    | 35    |      |      |       | 35   |      |      |       |
|                                 | Soil type                      | SM-SC | SP   | CL   | CL-ML | SM-SC  | SP   | CL   | CL-ML |
| Water table variation           | Dry                            | 1.27  | 1.04 | 1.79 | 1.7   | 1.26   | 1.03 | 1.80 | 1.69  |
|                                 | Sat                            | 0.6   | 0.23 | 1.02 | 0.95  | 0.62   | 0.22 | 1.14 | 1.02  |
|                                 | 2m                             | 1.06  | 0.99 | 1.44 | 1.38  | 1.05   | 0.98 | 1.45 | 1.38  |
|                                 | 4m                             | 1.27  | 1.04 | 1.68 | 1.63  | 1.26   | 1.03 | 1.69 | 1.63  |
| Vegetation (ERD=1m)             | Dry                            | 1.39  | 1.35 | 1.85 | 1.76  | 1.38   | 1.36 | 1.86 | 1.77  |
|                                 | Sat                            | 0.71  | 0.47 | 1.1  | 1.04  | 0.79   | 0.49 | 1.19 | 1.08  |
|                                 | 2m                             | 1.13  | 1.09 | 1.5  | 1.44  | 1.10   | 1.07 | 1.51 | 1.45  |
|                                 | 4m                             | 1.38  | 1.35 | 1.74 | 1.69  | 1.40   | 1.35 | 1.74 | 1.70  |
| Slope Modify                    | Dry                            | 1.71  | 1.29 | 2.29 | 2.21  | 1.63   | 1.30 | 2.30 | 2.23  |
|                                 | Sat                            | 0.93  | 0.28 | 1.42 | 1.34  | 0.9  | 0.49 | 1.49 | 1.44  |
|                                 | 2m                             | 1.43  | 1.16 | 1.82 | 1.77  | 1.46   | 1.14 | 1.83 | 1.74  |
|                                 | 4m                             | 1.71  | 1.24 | 2.09 | 2.08  | 1.63   | 1.22 | 2.11 | 2.01  |
| Retaining wall at toe (h/H=0.3) | Sat                            | 0.66  | 0.3  | 1.18 | 1.06  | 0.63   | 0.23 | 1.16 | 1.02  |
|                                 | 2m                             | 1.19  | 1.01 | 1.57 | 1.46  | 1.18   | 1.03 | 1.57 | 1.42  |

|                                |     |      |      |      |      |      |      |      |      |
|--------------------------------|-----|------|------|------|------|------|------|------|------|
| Slope<br>modify,<br>vegetation | Dry | 1.85 | 1.85 | 2.35 | 2.28 | 1.86 | 1.87 | 2.36 | 2.29 |
|                                | Sat | 1.76 | 1.82 | 2.05 | 2.04 | 1.74 | 1.82 | 2.05 | 2.04 |
|                                | 2m  | 1.80 | 1.87 | 2.14 | 2.14 | 1.80 | 1.86 | 2.14 | 2.13 |

Correlation between the result obtain from these two software are tentative same and are in best correlation. The correlation coefficient between the SRF obtain from two methods is 0.995.

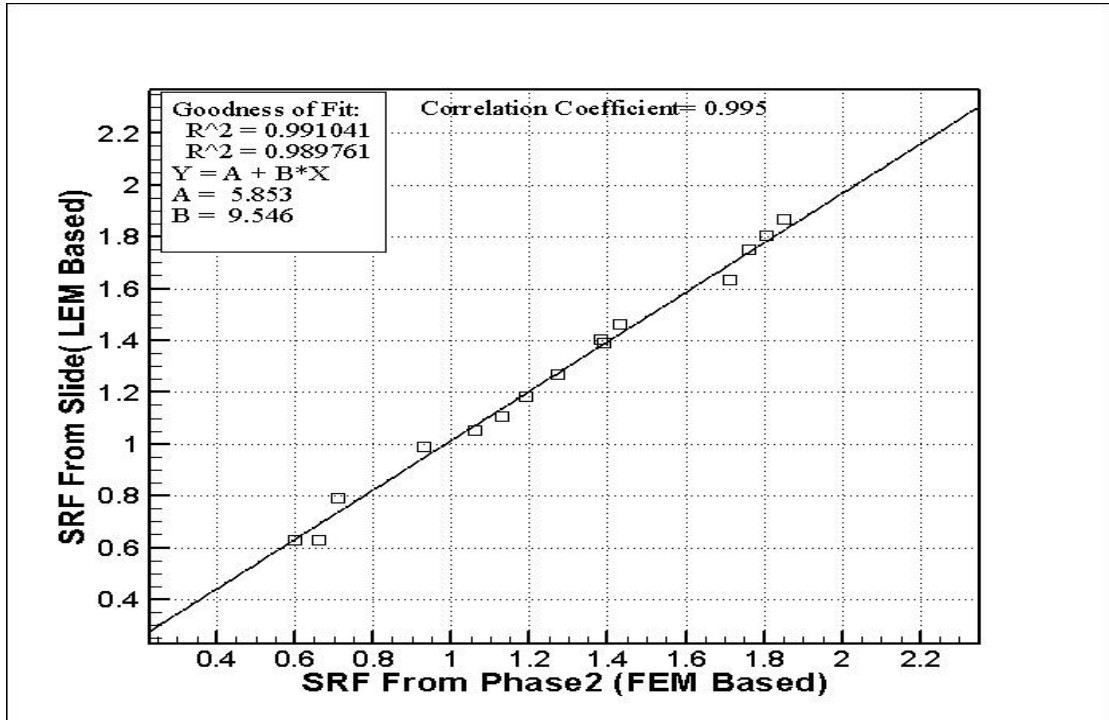


Figure 5.2 Correlation curve for general mitigation analysis data

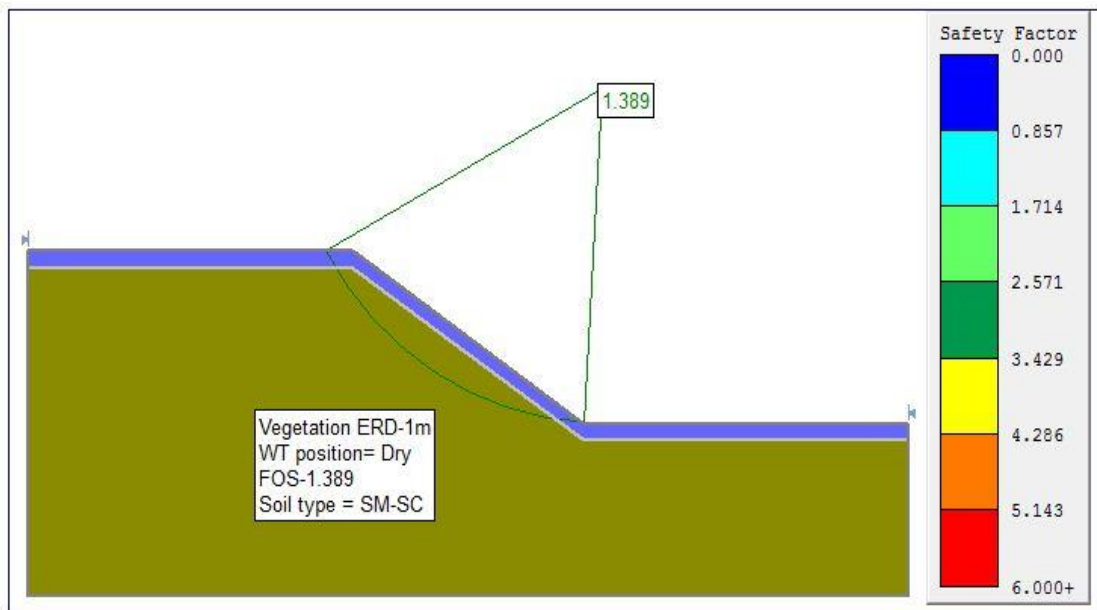


Figure 5.3 Result from the Slide 6 software

## 5.2 Verification with Literatures

We verify the model output during back calculation with the literature “Road Side Geo-Technical Problems\_ A Practical Guide to their Solutions” which is published by the Department of Roads which is shown on table below. The process of calculating the friction angle by Roadside Geo-technical Problems is already described on previous section of this thesis.

Table 5.3 Result of friction angle comparison

| S.N | Frictional angle        | Landslide |       |        |            |
|-----|-------------------------|-----------|-------|--------|------------|
|     |                         | Setebhir  |       | Betini | Simalchaur |
|     |                         | Sec-1     | Sec-2 | Sec-1  | Sec-1      |
| 1   | Back Analysis           | 34        | 30    | 34     | 30         |
| 2   | Roadside Geotechnical's | 31.84     | 32.84 | 31.52  | 31.98      |

Stability Charts such as Taylor (1937), Bishop and Morgenstern (1960), Janbu (1956), Bell (1966), Hoek and Bray (1974), Cousin (1977), etc. are developed for the normal stability condition without considering different mitigation options. The charts obtained after numerical simulation are compared to Michalowski Charts (1998). Michalowski (1998) has not mentioned and used different types of mitigation measures on the chart, so for such cases safety factors is just compared with the other tool.

## 5.3 Comparison of Result

The factor of safety given by the mitigation chart is compared with the site specific result having the real data of soil parameter and other variables. The soil properties form laboratory, ground slope and height of landslide is tabulated below. The FOS obtained from the chart and respective FOS value from site specific analysis is then compared.

Table 5.4 Soil and landslide parameters form site

| Parameters | C<br>KN/m <sup>2</sup> | $\phi$<br>(degree) | $\gamma$<br>(KN/m <sup>3</sup> ) | Ht of<br>slope ,m | angle of<br>slope |
|------------|------------------------|--------------------|----------------------------------|-------------------|-------------------|
| Setebhir-2 | 8                      | 30                 | 20                               | 95                | 30                |
| Betini     | 7                      | 34                 | 20                               | 80                | 30                |

Table 5.5 FOS value comparison from char to actual value

| <b>Comparison of Factor of safety From chart to the actual value</b> |                     |      |      |                   |             |                         |                                 |
|--|---------------------|------|------|-------------------|-------------|-------------------------|---------------------------------|
| <b>Landslide</b>   | Conditions          | Sat  | Dry  | Veg.<br>Saturated | Veg.<br>Dry | RW<br>(h/H=0.3),<br>Dry | RW<br>(h/H=0.3),<br>Veg.<br>Dry |
| <b>Betini</b>  | From<br>chart       | 0.39 | 1.15 | 0.66              | 1.38        | 1.15                    | 1.35                            |
|  | Actual<br>From site | 0.29 | 1    | 0.42              | 1.12        | 1.06                    | 1.13                            |
| <b>Setebhir</b>  | From<br>chart       | 0.35 | 1.04 | 0.58              | 1.27        | 1.07                    | 1.27                            |
|  | Actual<br>From site | 0.37 | 1    | 0.48              | 1.17        | 1.06                    | 1.17                            |

The satisfactory result has been achieved with the comparison of factor of safety value giving the correlation coefficient of 0.972. So from this comparison we can say that our mitigation chart is reliable and can be used for the estimation of factor of safety and for the mitigation design.

## CHAPTER SIX: CONCLUSION AND RECOMENDATIONS

### 6.1 Conclusion

Chure area has more than five thousands of landslides distributed over thirty six districts. The mitigation of those landslides is very urgent for environmental protection and land degradation. The mitigation measures normally determined based on the field condition of landslide area (condition, size, type of landslide). One or more type of mitigation measures may be fit for the site. Various Stability charts are useful for preliminary design of slopes, and allow the designer to assess the effects of various parameters on stability “at a glance”. The charts might not be applicable to each and every slope problems which demands case and site specific analysis.

Site specific analysis of three active landslide of chure area is analyzed by finite element method based open source software Phase2. The stability analysis is done with using mitigation measures alone and with combinations. From the result we conclude that use of single mitigation measure did not gave the satisfactory safety level so use of mitigation option more than one and their combination should be applied to achieve satisfactory safety level on all section of landslide.

There is no methodology to describe mitigating models of thousands of major landslides of chure area like Setebhir, Simalchour and Beteni landslides. There is no possible to go for site and case specific analysis and design of all those landslides. Therefore to find the general mitigation solution a general mitigation model is prepared to suit the chure landslide. Eight different types of soil property are used in the model and soil type based mitigation chart is prepared within the finite element framework.

The charts developed are for the plain strain or 2D conditions without considering any seismic loads. Five different slope angles have been considered which is either completely dry, saturated or GWT some depth below.

From the analysis of Charts, the effect of mitigation measures will be well significant when the slope is more than 45 degree and water table is more than 4m down from the surface level. Furthermore we found that maximum increase in FOS value is obtained with the application of slope modification mitigation measure and minimum increase

in FOS value is obtained with the application of Retaining wall with considering overall cases.

The verification of FOS value obtained from the FEM based model is compared with the FOS value from LEM based another tool and satisfactory result is obtained with good correlation. Furthermore the FOS value obtained from the chart is compared with the FOS value obtained from site specific analysis result having real field values and found reliable result. So the charts obtained in this report are quite satisfactory and will be useful in mitigation plan and design of chure landslides.

## **6.2 Recommendations**

The chure region has large area of extent and contains large variability but the attempt is done for the generalization of more than five thousands of landslides. The following recommendations are made for the further improvement on the research.

- The sensitivity analysis of strength parameters are recommended for the further analysis within the whole area of chure region.
- Two-dimension slope stability analysis is used for the analysis which seems not enough for some of the case. The study can be enhanced to reliable 3d slope stability analysis using the real parameters from the field.
- The mitigation measures used in this research are limited and will not cover all landslide of chure area so more number of mitigation measures like check dam, Geo-synthetics, Gabion wall, rock net, drainage galleries etc. can also be analyzed.
- The mitigation chart on this thesis only consider the eight type of soil parameter which will not satisfactorily work out on other type of soil having higher cohesion value so mitigation chart considering all soil types is recommended for further analysis.
- The mitigation charts considering the pore water pressure and seismic effect is recommended for the further study.

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**ANNEX I**

**LABORATORY INVESTIGATION DETAILS  
BACK ANALYSIS RESULTS**

|                                  |                |                    |                     |                                |                  |
|----------------------------------|----------------|--------------------|---------------------|--------------------------------|------------------|
| Tribhuvan University             |                |                    |                     |                                |                  |
| Institute of Engineering         |                |                    |                     |                                |                  |
| M.SC in Geotechnical Engineering |                |                    |                     |                                |                  |
| <b>SIEVE ANALYSIS</b>            |                |                    |                     |                                |                  |
| Project:                         | Thesis work    |                    | Landslide:          | Setebhir                       |                  |
| Location:                        | Makawanpur     |                    | Section:            | (2-2)                          |                  |
| Name of student:                 | Anil pokhrel   |                    | Lab test date :     |                                |                  |
| Weight of sample taken           |                |                    | 512 gm              |                                |                  |
| S.N                              | OBSERVATION    |                    | CALCULATION         |                                |                  |
|                                  | sieve size, mm | soil retained (gm) | Percentage retained | Cumulative percentage retained | Percentage finer |
| 1                                | 4.750          | 12.2               | 2.383               | 2.383                          | 97.617           |
| 2                                | 2.000          | 31.9               | 6.230               | 8.613                          | 91.387           |
| 3                                | 0.840          | 46.4               | 9.063               | 17.676                         | 82.324           |
| 4                                | 0.420          | 26.9               | 5.254               | 22.930                         | 77.070           |
| 5                                | 0.250          | 18.9               | 3.691               | 26.621                         | 73.379           |
| 6                                | 0.149          | 12.7               | 2.480               | 29.102                         | 70.898           |
| 7                                | 0.075          | 83.6               | 16.328              | 45.430                         | 54.570           |
| 8                                | pan            | 279.4              | 54.570              | 100.000                        | 0.000            |
|                                  |                | 512                | 100.000             |                                |                  |

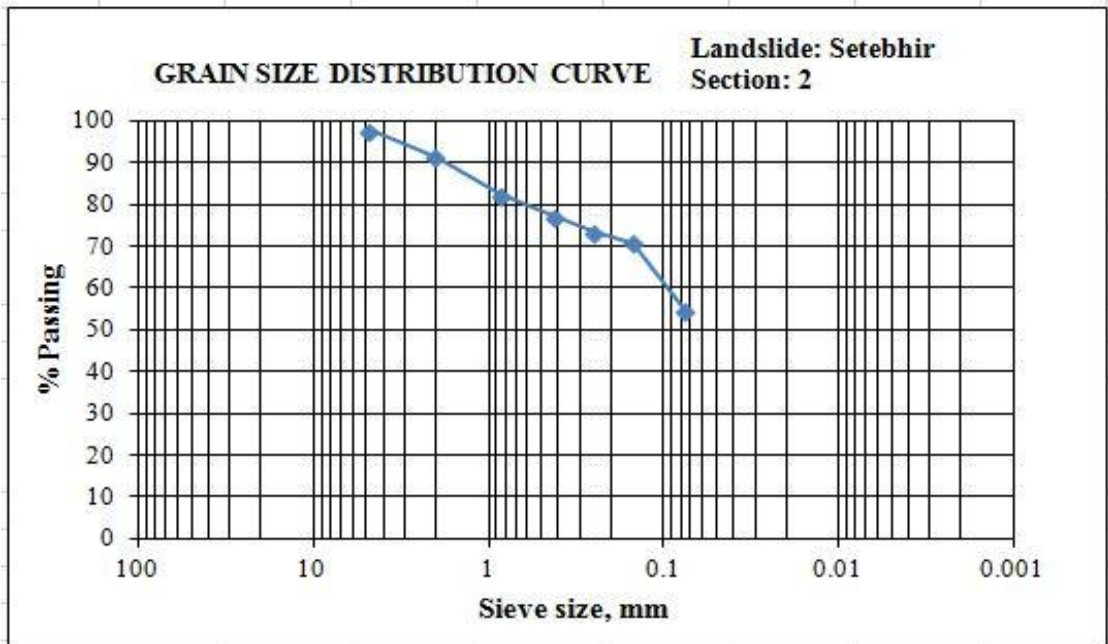


Figure 6.1 Sieve analysis and Grain size distribution curve of Setebhir landslide sec-2

|                                  |                |                    |                     |                                |                  |
|----------------------------------|----------------|--------------------|---------------------|--------------------------------|------------------|
| Tribhuvan University             |                |                    |                     |                                |                  |
| Institute of Engineering         |                |                    |                     |                                |                  |
| M.SC in Geotechnical Engineering |                |                    |                     |                                |                  |
| <b>SIEVE ANALYSIS</b>            |                |                    |                     |                                |                  |
| Project:                         | Thesis work    |                    | Landslide:          | Setebhir                       |                  |
| Location:                        | Makawanpur     |                    | Section:            | (1-1)                          |                  |
| Name of student:                 | Anil pokhrel   |                    | Lab test date :     |                                |                  |
| Weight of sample taken           |                |                    | 486 gm              |                                |                  |
| S.N                              | OBSERVATION    |                    | CALCULATION         |                                |                  |
|                                  | sieve size, mm | soil retained (gm) | Percentage retained | Cumulative percentage retained | Percentage finer |
| 1                                | 4.750          | 9.2                | 1.893               | 1.893                          | 98.107           |
| 2                                | 2.000          | 33.9               | 6.975               | 8.868                          | 91.132           |
| 3                                | 0.840          | 49.4               | 10.165              | 19.033                         | 80.967           |
| 4                                | 0.420          | 19.9               | 4.095               | 23.128                         | 76.872           |
| 5                                | 0.250          | 23.9               | 4.918               | 28.045                         | 71.955           |
| 6                                | 0.149          | 9.7                | 1.996               | 30.041                         | 69.959           |
| 7                                | 0.075          | 83.6               | 17.202              | 47.243                         | 52.757           |
| 8                                | pan            | 256.4              | 52.757              | 100.000                        | 0.000            |
|                                  |                | 486                | 100.000             |                                |                  |

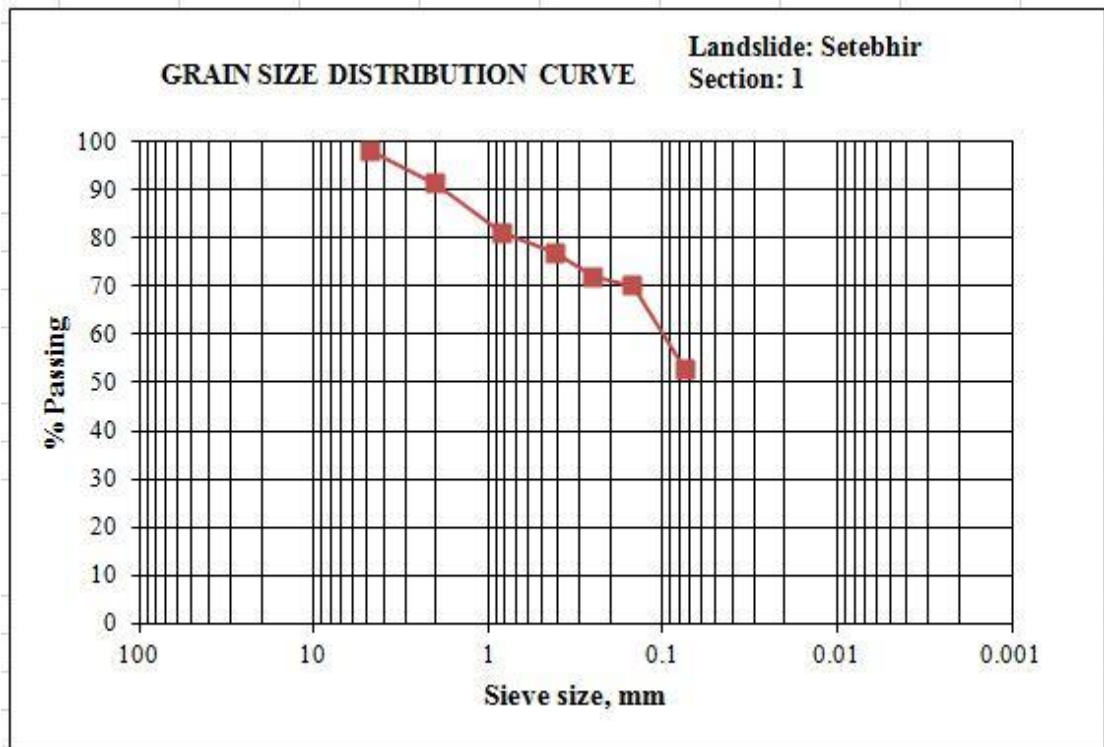


Figure 6.2 Sieve analysis and Grain size distribution curve of Setebhir landslide sec-1

|                                  |                |                    |                     |                                |                  |
|----------------------------------|----------------|--------------------|---------------------|--------------------------------|------------------|
| Tribhuvan University             |                |                    |                     |                                |                  |
| Institute of Engineering         |                |                    |                     |                                |                  |
| M.SC in Geotechnical Engineering |                |                    |                     |                                |                  |
| <b>SIEVE ANALYSIS</b>            |                |                    |                     |                                |                  |
| Project:                         | Thesis work    |                    | Landslide:          | Betini                         |                  |
| Location:                        | Makawanpur     |                    | Section:            | (1-1)                          |                  |
| Name of student:                 | Anil pokhrel   |                    | Lab test date :     |                                |                  |
| Weight of sample taken           |                |                    | 600                 | gm                             |                  |
| S.N                              | OBSERVATION    |                    | CALCULATION         |                                |                  |
|                                  | sieve size, mm | soil retained (gm) | Percentage retained | Cumulative percentage retained | Percentage finer |
| 1                                | 4.750          | 10.1               | 1.683               | 1.683                          | 98.317           |
| 2                                | 2.000          | 28.2               | 4.700               | 6.383                          | 93.617           |
| 3                                | 0.840          | 39.6               | 6.600               | 12.983                         | 87.017           |
| 4                                | 0.420          | 24.7               | 4.117               | 17.100                         | 82.900           |
| 5                                | 0.250          | 28                 | 4.667               | 21.767                         | 78.233           |
| 6                                | 0.149          | 39.5               | 6.583               | 28.350                         | 71.650           |
| 7                                | 0.075          | 34                 | 5.667               | 34.017                         | 65.983           |
| 8                                | pan            | 395.9              | 65.983              | 100.000                        | 0.000            |
|                                  |                | 600                | 100.000             |                                |                  |

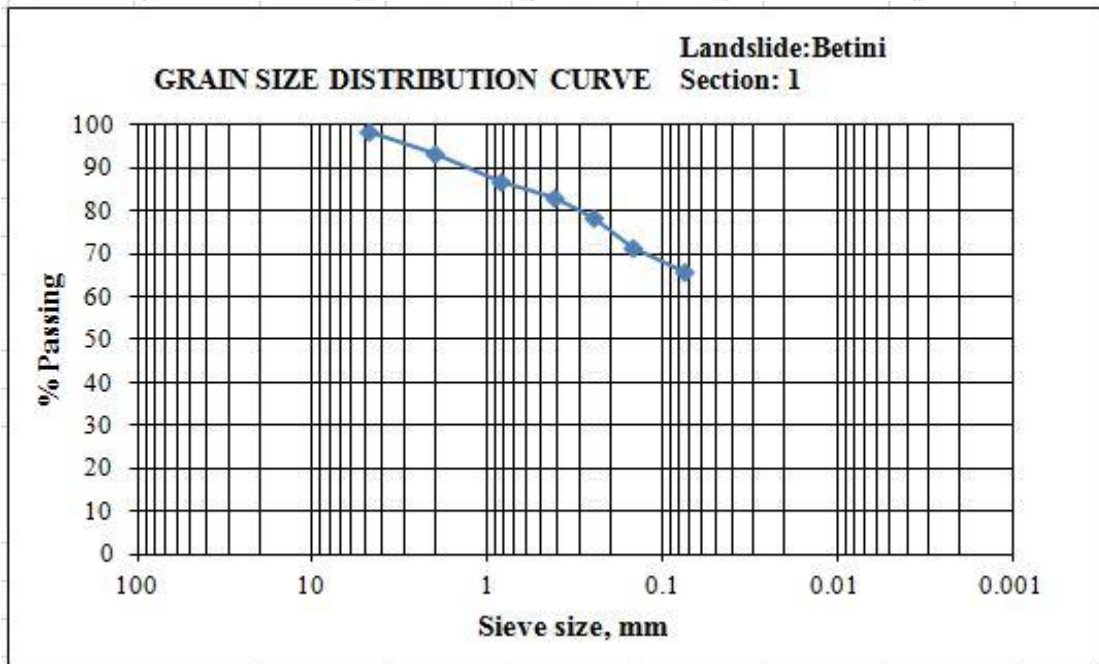


Figure 6.3 Sieve analysis and Grain size distribution curve of Betini landslide

|                                  |                |                    |                     |                                |                  |
|----------------------------------|----------------|--------------------|---------------------|--------------------------------|------------------|
| Tribhuvan University             |                |                    |                     |                                |                  |
| Institute of Engineering         |                |                    |                     |                                |                  |
| M.SC in Geotechnical Engineering |                |                    |                     |                                |                  |
| <b>SIEVE ANALYSIS</b>            |                |                    |                     |                                |                  |
| Project:                         | Thesis work    |                    | Landslide:          | Simalchaur                     |                  |
| Location:                        | Bara           |                    | Section:            |                                |                  |
| Name of student:                 | Anil pokhrel   |                    | Lab test date :     |                                |                  |
| Weight of sample taken           |                |                    | 476                 | gm                             |                  |
| S.N                              | OBSERVATION    |                    | CALCULATION         |                                |                  |
|                                  | sieve size, mm | soil retained (gm) | Percentage retained | Cumulative percentage retained | Percentage finer |
| 1                                | 4.750          | 13.1               | 2.752               | 2.752                          | 97.248           |
| 2                                | 2.000          | 31.9               | 6.702               | 9.454                          | 90.546           |
| 3                                | 0.840          | 39                 | 8.193               | 17.647                         | 82.353           |
| 4                                | 0.420          | 24.8               | 5.210               | 22.857                         | 77.143           |
| 5                                | 0.250          | 17.6               | 3.697               | 26.555                         | 73.445           |
| 6                                | 0.149          | 19                 | 3.992               | 30.546                         | 69.454           |
| 7                                | 0.075          | 83.6               | 17.563              | 48.109                         | 51.891           |
| 8                                | pan            | 247                | 51.891              | 100.000                        | 0.000            |
|                                  |                | 476                | 100.000             |                                |                  |

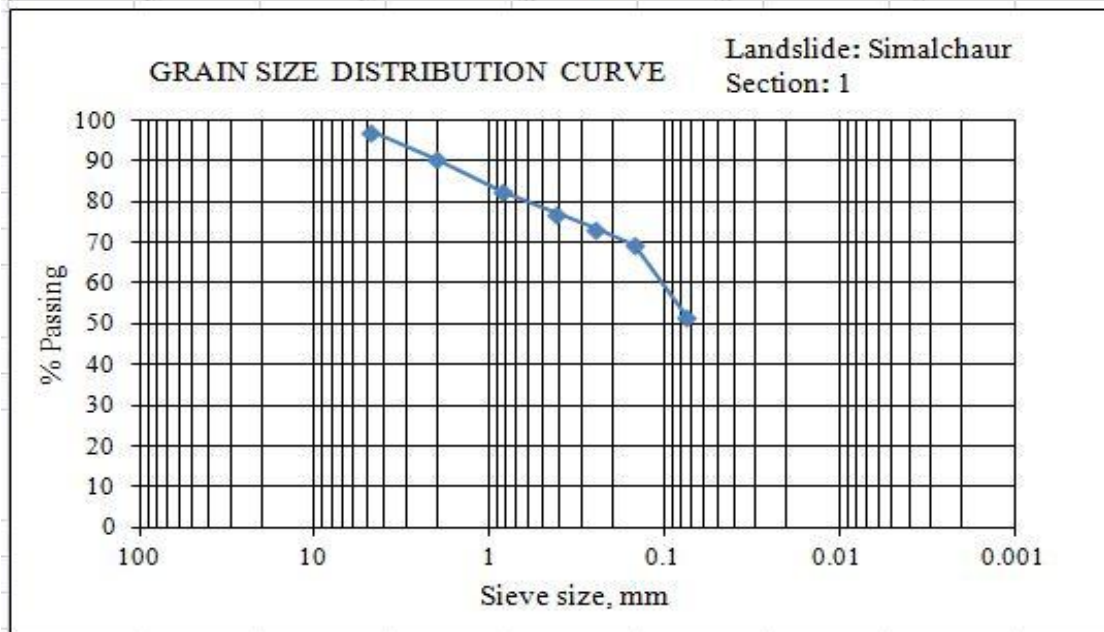


Figure 6.4 Sieve analysis and Grain size distribution curve of Simalchaur landslide

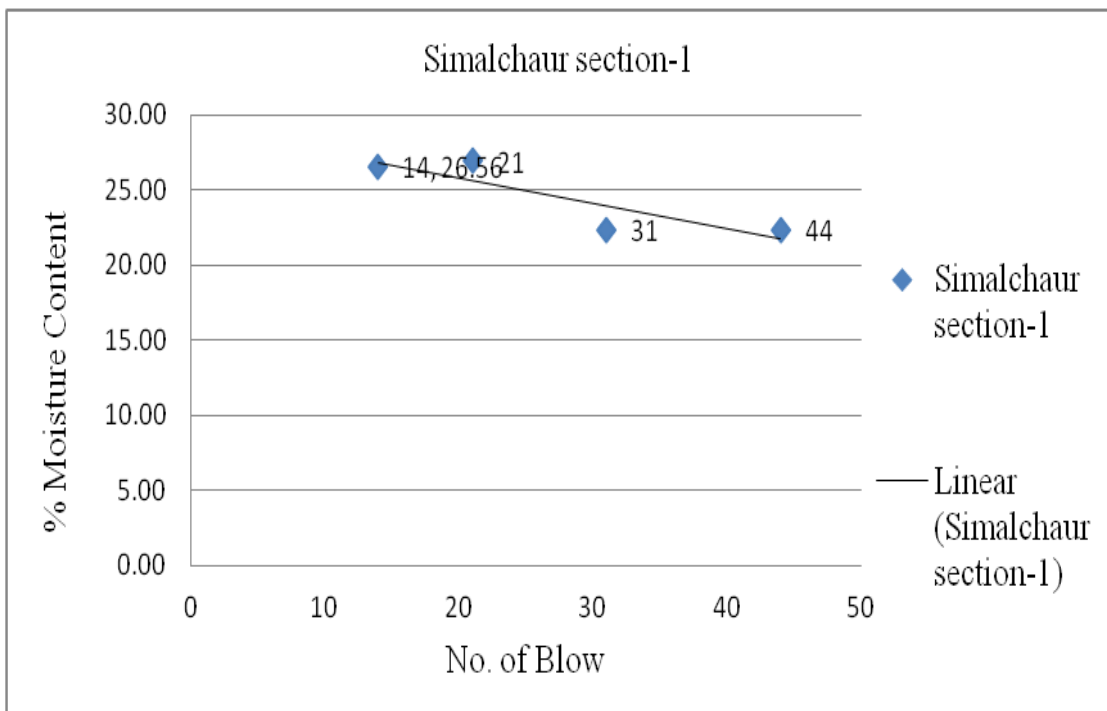
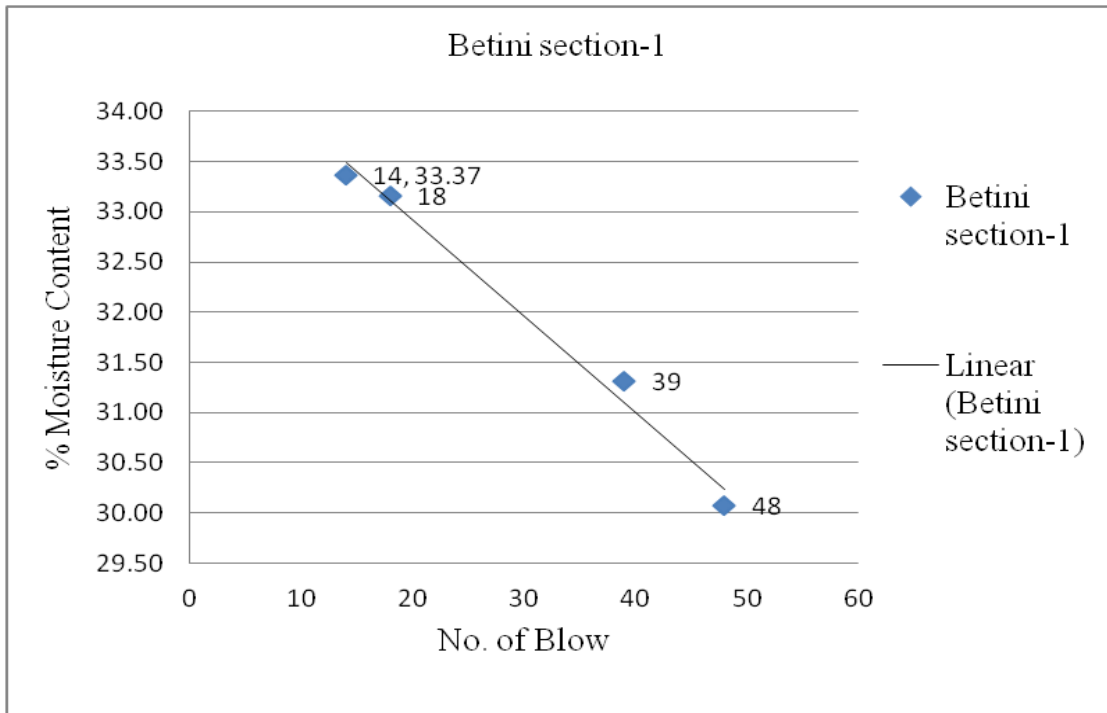


Figure 6.5 Liquid limit plots of Simalchaur and Betini Landslide

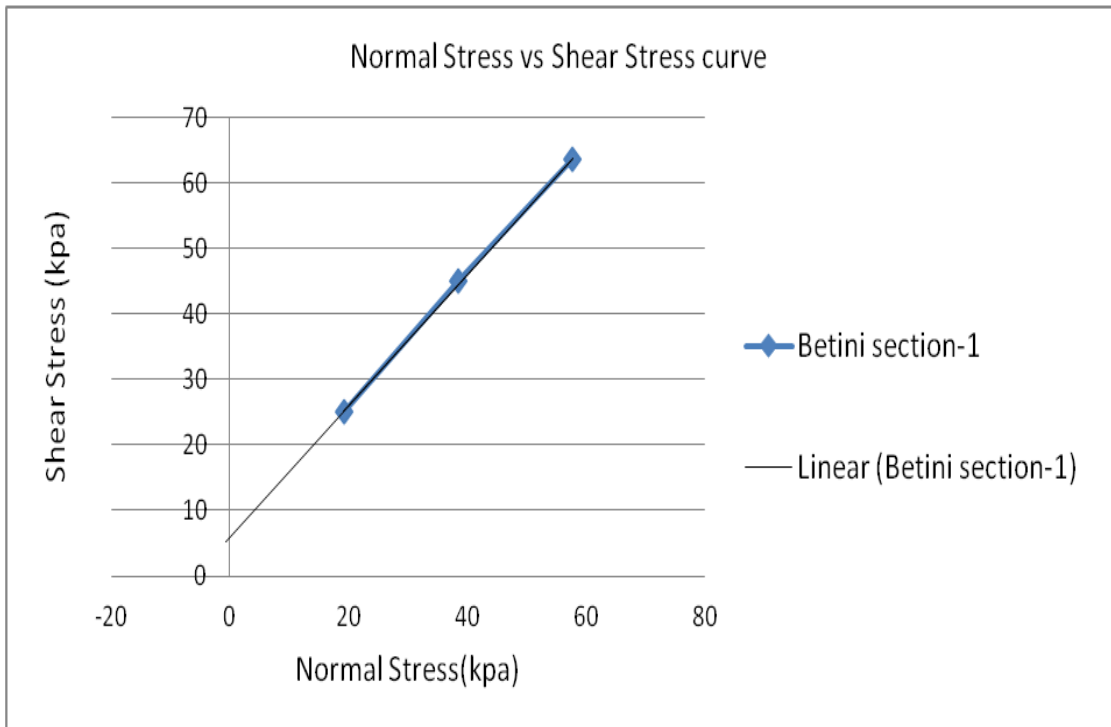
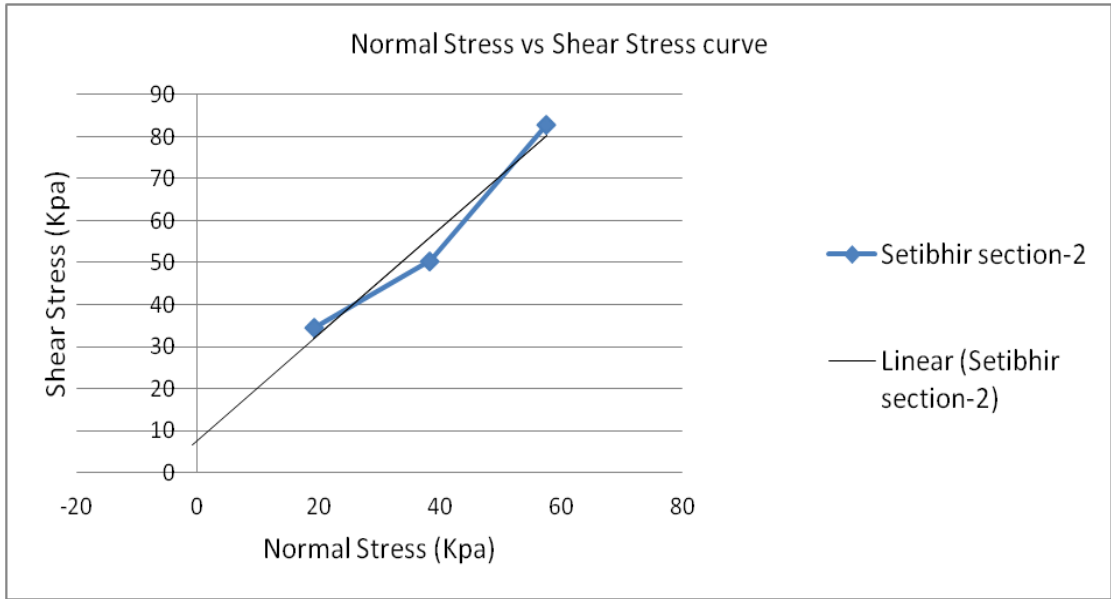


Figure 6.6 Normal stress vs shear stress plot of Setebhir section-2 and Betini landslide

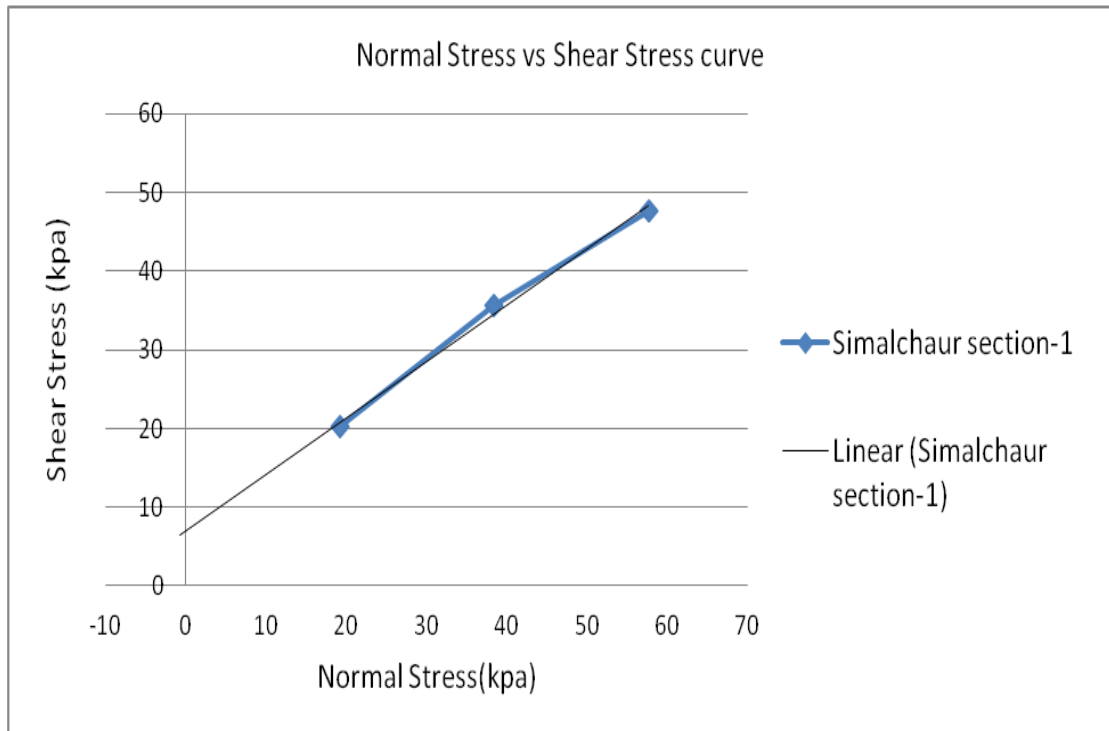


Figure 6.7 Normal stress vs shear stress plot of Simalchaur landslide

### Back Analysis Results

Table 6.1 Result of Back analysis

| SRF Value Obtained at Different Section of Landslide |                            |                          |                          |                          |
|--|----------------------------|--------------------------|--------------------------|--------------------------|
| $\phi$ value   | Landslide                  |                          |                          |                          |
|  | Setebhir-1                 | Setebhir-2               | Betini                   | simalchaur               |
|  | C=8.5 (KN/m <sup>2</sup> ) | C=8 (KN/m <sup>2</sup> ) | C=7 (KN/m <sup>2</sup> ) | C=8 (KN/m <sup>2</sup> ) |
| 26   |                            |                          |                          | 0.86                     |
| 27   |                            |                          |                          | 0.89                     |
| 28   |                            | 0.94                     |                          | 0.92                     |
| 29   |                            | 0.97                     |                          | 0.96                     |
| 30   |                            | 1.01                     |                          | 1                        |
| 31   | 0.92                       | 1.05                     | 0.91                     | 1.04                     |
| 32   | 0.94                       |                          | 0.95                     |                          |
| 33   | 0.98                       |                          | 0.995                    |                          |
| 34   | 1.02                       |                          | 1.03                     |                          |
| 35   | 1.05                       |                          | 1.05                     |                          |
| Final value ( $\phi$ )                               | 34                         | 30                       | 34                       | 30                       |

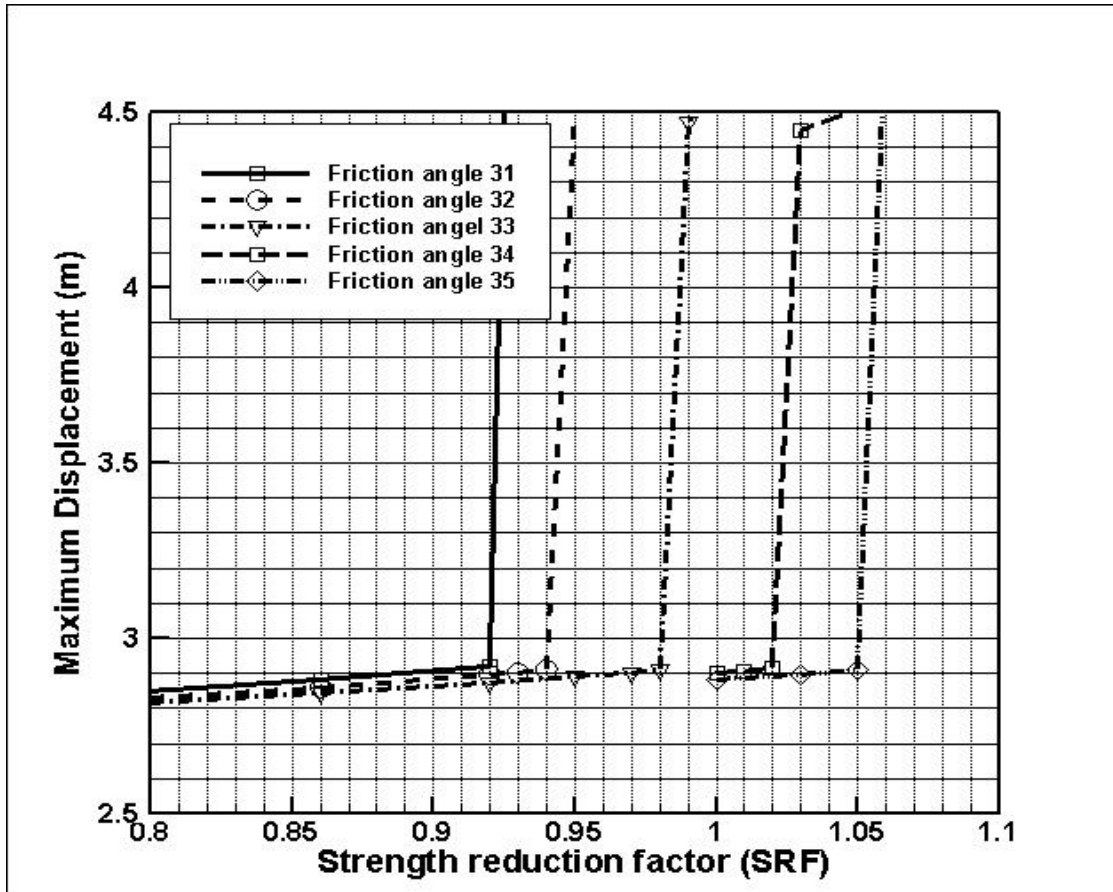


Figure 6.8 SRF vs Displacement plot for different friction angle

Table 6.2 Comparison of Laboratory and Back analysis results

| S.N | Methods       | Parameters                    | Landslide |       |        |            |
|-----|---------------|-------------------------------|-----------|-------|--------|------------|
|     |               |                               | Setebhir  |       | Betini | Simalchaur |
|     |               |                               | Sec-1     | Sec-2 | Sec-1  | Sec-1      |
| 1   | Laboratory    | Cohesion (KN/m <sup>2</sup> ) | 8.5       | 8     | 7      | 8          |
|     |               | Friction angle degrees        | 31        | 30    | 32     | 27         |
| 2   | Back analysis | Cohesion (KN/m <sup>2</sup> ) | 8.5       | 8     | 7      | 8          |
|     |               | Friction angle degrees        | 34        | 30    | 34     | 30         |

## Friction Angle Calculation from Road Side Geotechnical

Table 6.3 Friction Angle Calculation from Road Side Geotechnical

| <b>Friction Angle without correction</b> |                     |          |            |                |
|--|---------------------|----------|------------|----------------|
| <b>Landslide</b>                         | Setebhir            | Section  | 2          |                |
| <b>Grain size range</b>                  | Fraction weight (%) | Dividers | Parameters | Quotient(deg.) |
| <0.002 mm                                | 11                  | 7        | A          | 1.57           |
| 0.002-0.01 mm                            | 16                  | 5        | B          | 3.20           |
| 0.01-0.2 mm                              | 32                  | 3        | C          | 10.67          |
| 0.2-60 mm                                | 41                  | 2.5      | D1         | 16.40          |
| >60 mm                                   | 0                   | 2.5      | D2         | 0.00           |
| <b>Total</b>                             | 100                 |          | sum        | 31.84          |
| <b>Landslide</b>                         | Setebhir            | Section  | 1          |                |
| <b>Grain size range</b>                  | Fraction weight (%) | Dividers | Parameters | Quotient(deg.) |
| <0.002 mm                                | 18                  | 7        | A          | 2.57           |
| 0.002-0.01 mm                            | 14                  | 5        | B          | 2.80           |
| 0.01-0.2 mm                              | 26                  | 3        | C          | 8.67           |
| 0.2-60 mm                                | 42                  | 2.5      | D1         | 16.80          |
| >60 mm                                   | 0                   | 2.5      | D2         | 0.00           |
| <b>Total</b>                             | 100                 |          | sum        | 30.84          |
| <b>Landslide</b>                         | Betini              | Section  | 1          |                |
| <b>Grain size range</b>                  | Fraction weight (%) | Dividers | Parameters | Quotient(deg.) |
| <0.002 mm                                | 20                  | 7        | A          | 2.86           |
| 0.002-0.01 mm                            | 10                  | 5        | B          | 2.00           |
| 0.01-0.2 mm                              | 35                  | 3        | C          | 11.67          |
| 0.2-60 mm                                | 35                  | 2.5      | D1         | 14.00          |
| >60 mm                                   | 0                   | 2.5      | D2         | 0.00           |
| <b>Total</b>                             | 100                 |          | sum        | 30.52          |
| <b>Landslide</b>                         | Simalchaur          | Section  | 1          |                |
| <b>Grain size range</b>                  | Fraction weight (%) | Dividers | Parameters | Quotient(deg.) |
| <0.002 mm                                | 19                  | 7        | A          | 2.71           |
| 0.002-0.01 mm                            | 12                  | 5        | B          | 2.40           |

|                    |           |     |     |       |
|--------------------|-----------|-----|-----|-------|
| <b>0.01-0.2 mm</b> | <b>26</b> | 3   | C   | 8.67  |
| <b>0.2-60 mm</b>   | <b>43</b> | 2.5 | D1  | 17.20 |
| <b>&gt;60 mm</b>   | <b>0</b>  | 2.5 | D2  | 0.00  |
| <b>Total</b>       | 100       |     | sum | 30.98 |

Formula:  $\phi_0 = A + B + C + D$

Where,  $\phi_0$  = friction angle without correction

A =  $1/7 \times$  [fraction weight (%) of grains < 0.002 mm]

B =  $1/5 \times$  [fraction weight (%) of grains between 0.002 mm and 0.01 mm]

C =  $1/3 \times$  [fraction weight (%) of grains between 0.01 mm and 0.2 mm]

D =  $1/2.5 \times$  [fraction weight (%) of grains between 0.2 mm and 60 mm + fraction weight of grains > 60 mm]

Table 6.4 Corrected friction angles

| Corrections on friction angle      |   |            |       |        |            |
|------------------------------------|---|------------|-------|--------|------------|
| Property                           | Criteria                                  | Correction |       |        |            |
|                                    |   | Setebhir   |       | Betini | Simalchaur |
|                                    |   | Sec-1      | Sec-2 | Sec-1  | Sec-1      |
| Grain shape                        | + 1° for sharp angular grains             | 1          | 1     | 1      | 1          |
|                                    | ± 0° for medium angular grains            |            |       |        |            |
|                                    | - 3° for rounded grains                   |            |       |        |            |
| Distribution curve                 | - 3° for poor gradation (or uniform size) | 0          | 0     | 0      | 0          |
|                                    | ± 0° for medium gradation                 |            |       |        |            |
|                                    | + 6° for well distributed grain sizes     |            |       |        |            |
| Compactness of soil                | - 6° for loose layer of soil              | 0          | 0     | 0      | 0          |
|                                    | ± 0° for medium loose layer of soil       |            |       |        |            |
|                                    | + 6° for compact layer of soil            |            |       |        |            |
| Corrected effective friction angle |   | 31.84      | 32.84 | 31.52  | 31.98      |

Corrections:  $\phi_{\text{effective}} = \phi_0 + \phi_1 + \phi_2 + \phi_3$

Where,

$\phi_1$  = correction of grain shape

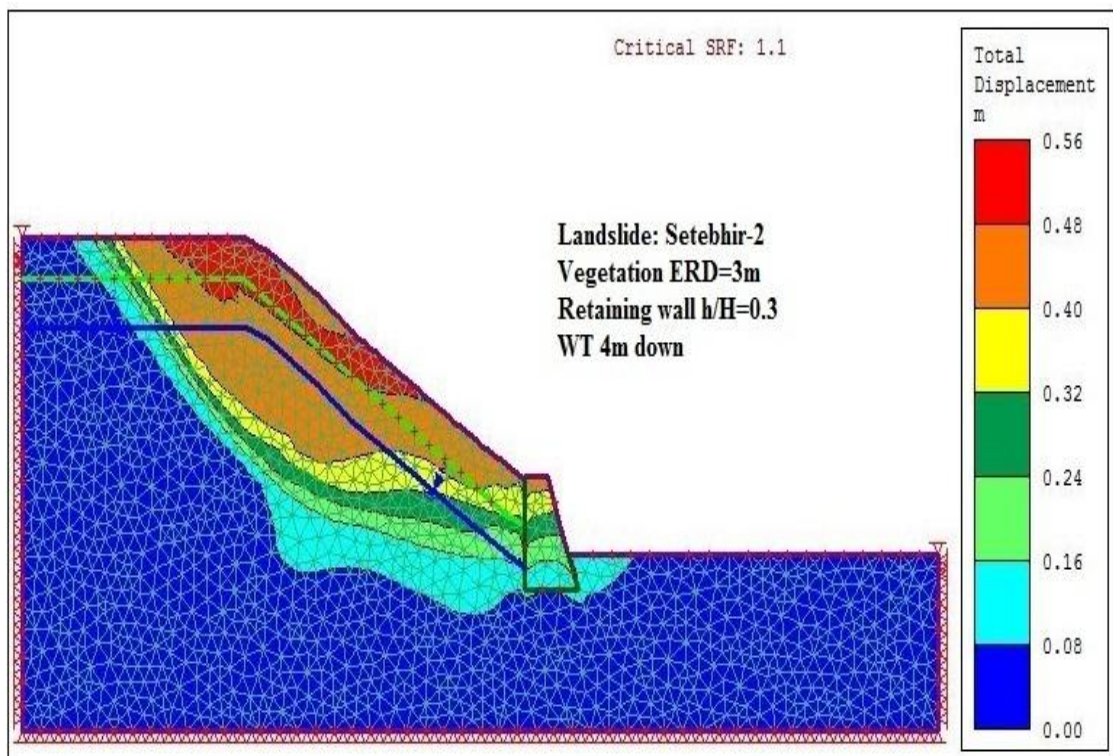
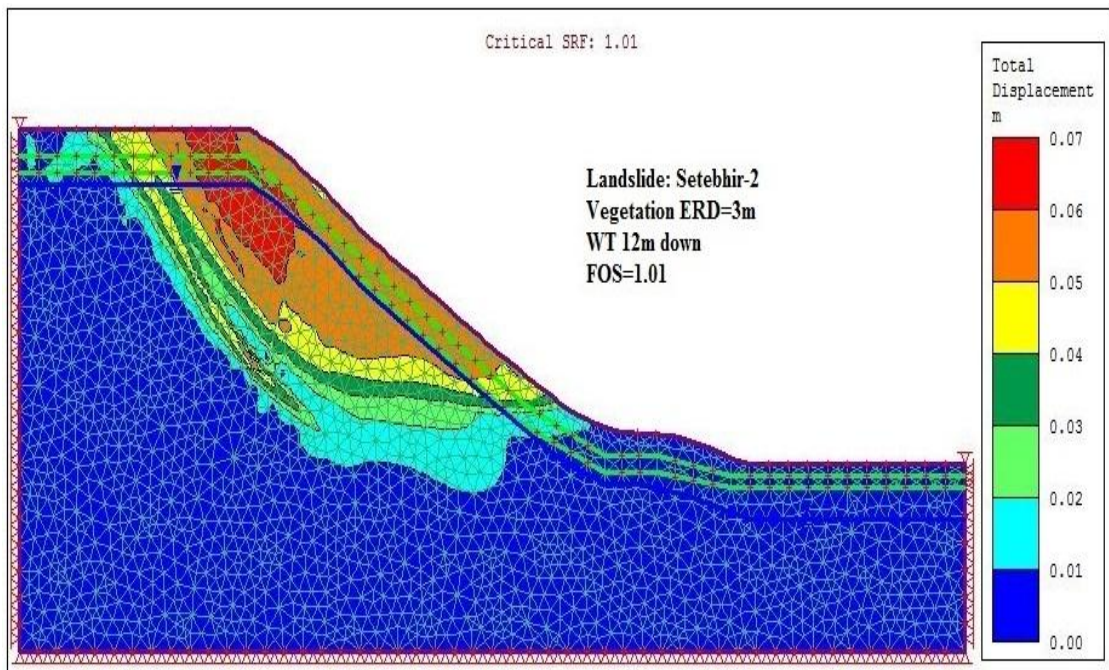
$\phi_2$  = correction for form of distribution curve

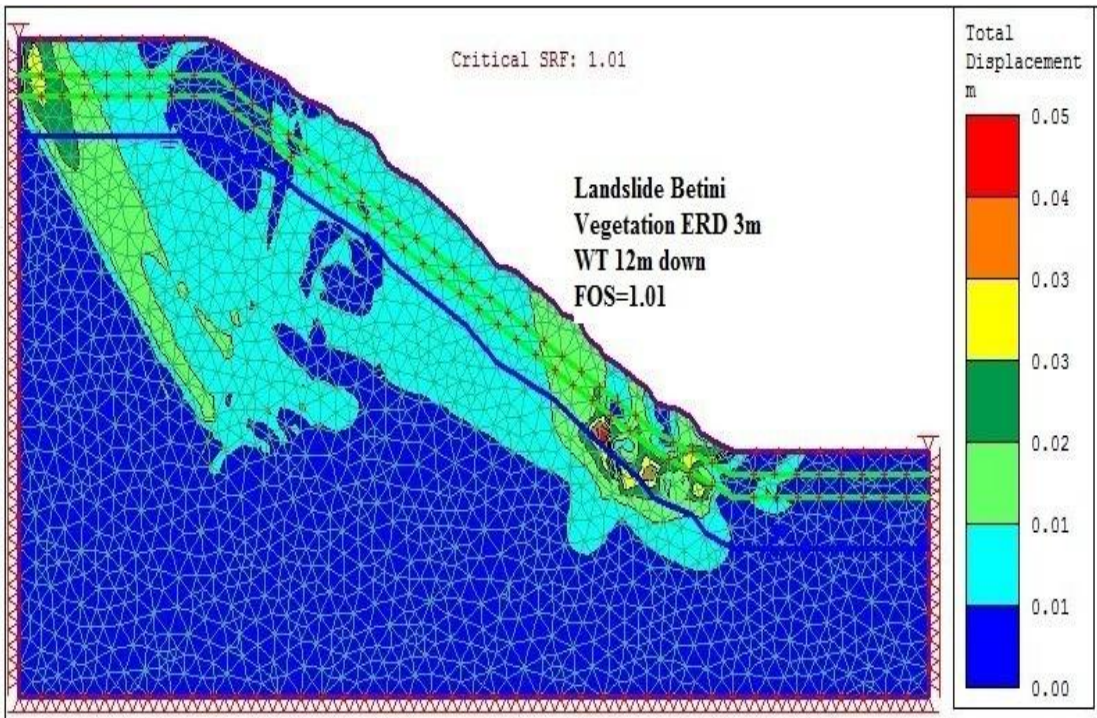
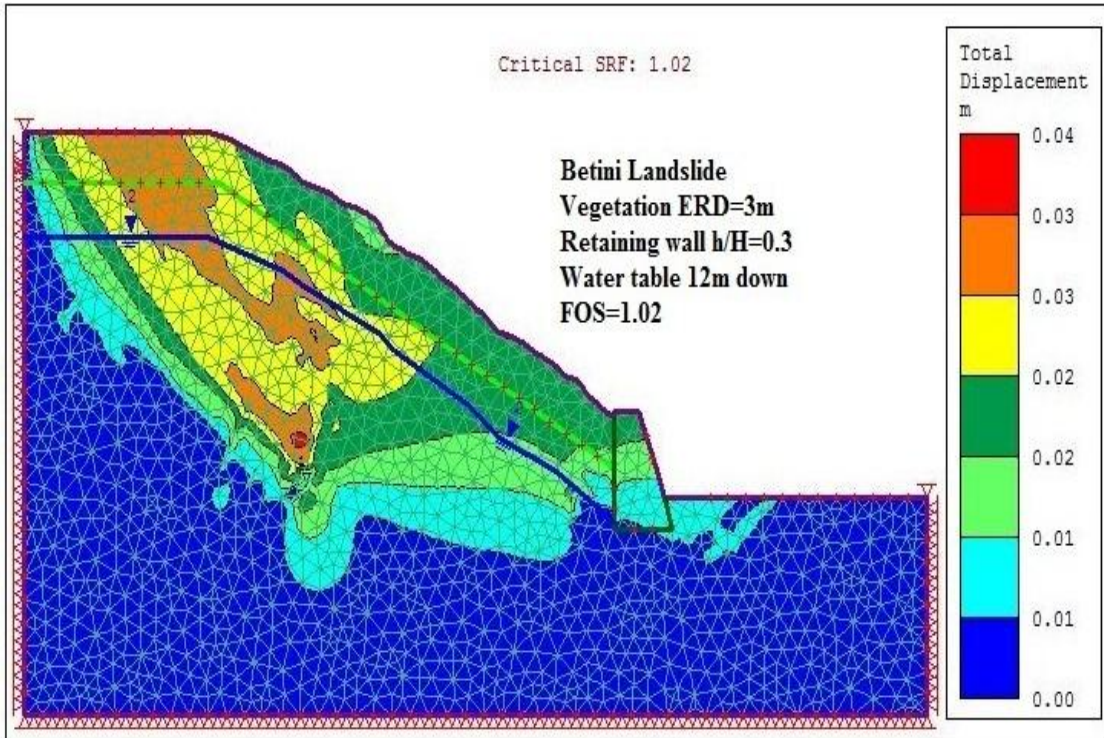
$\phi_3$  = correction for compactness of soil

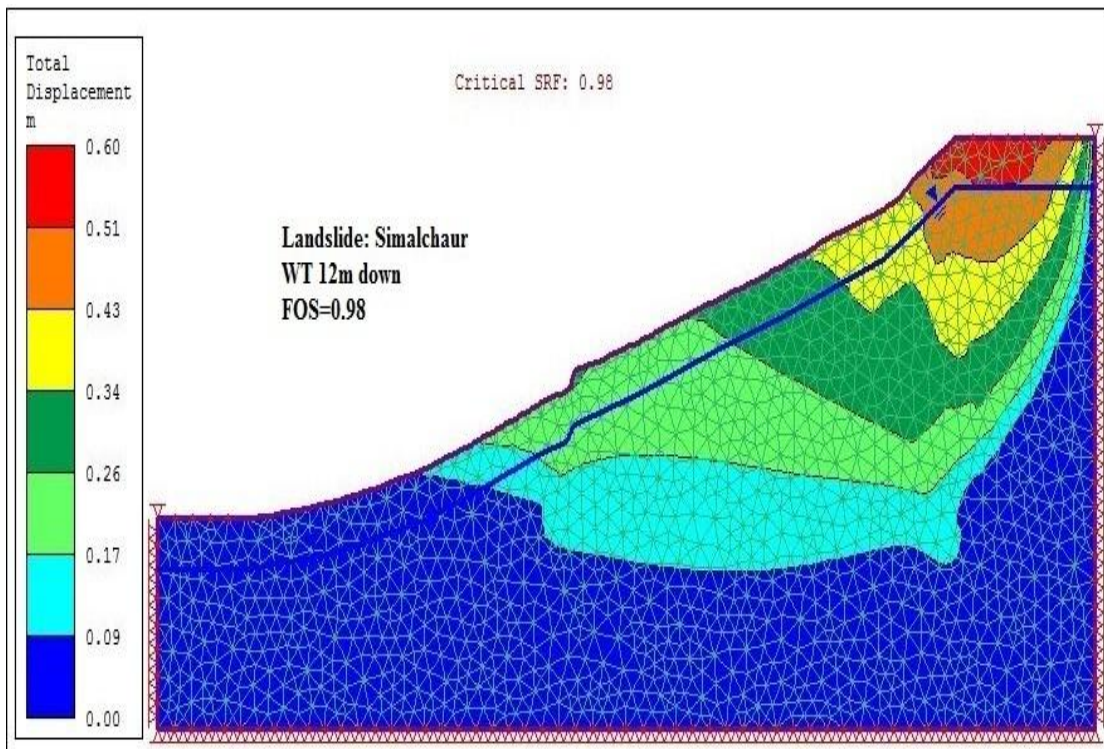
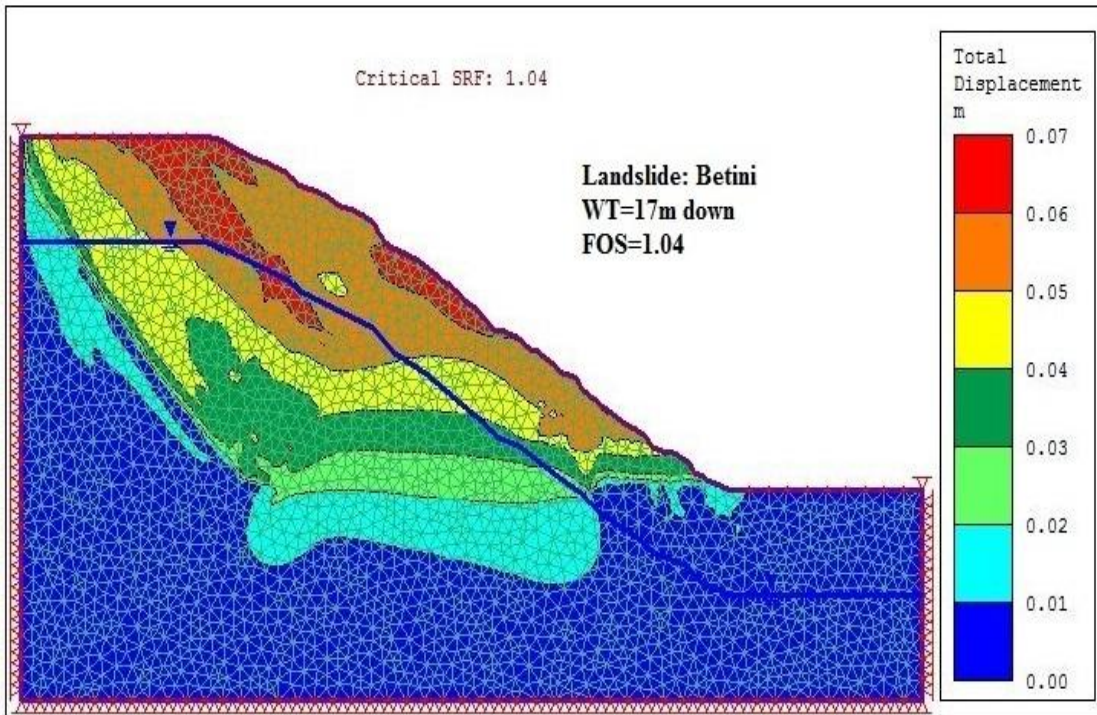
**ANNEX II**

**SITE SPECIFIC ANALYSIS DETAILS**

## Displacement contours







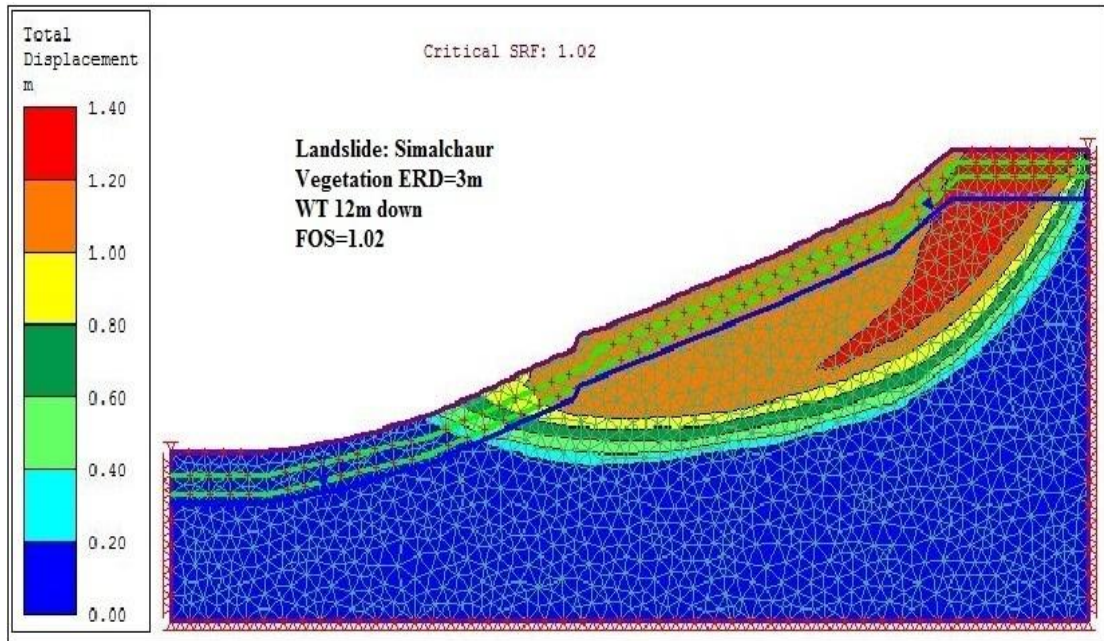
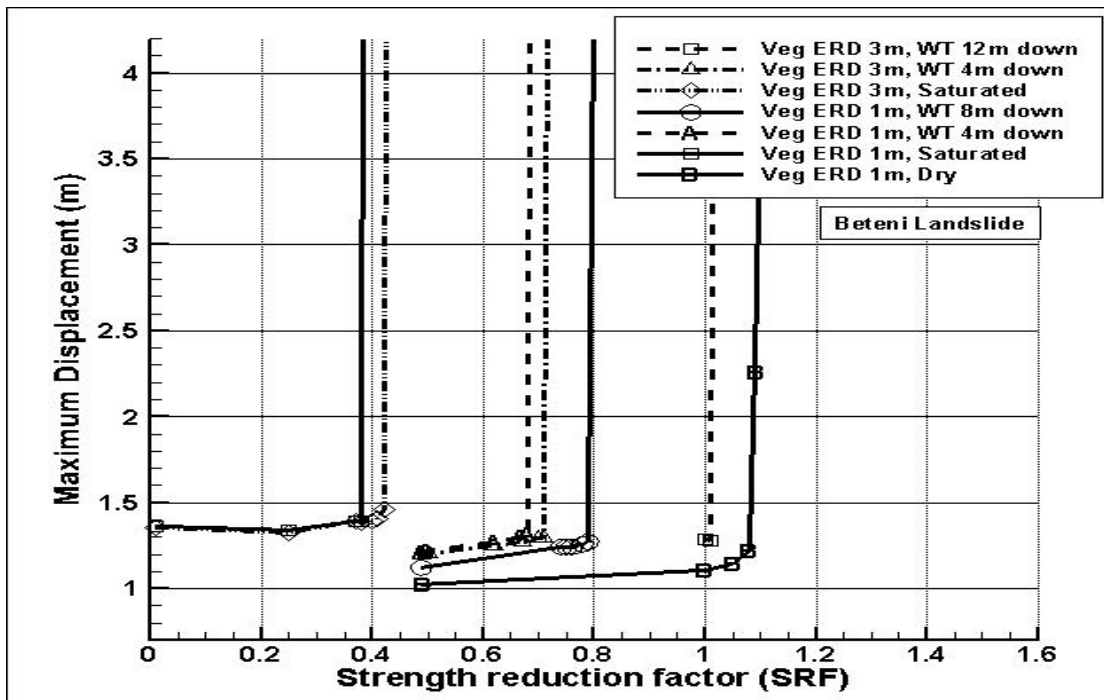
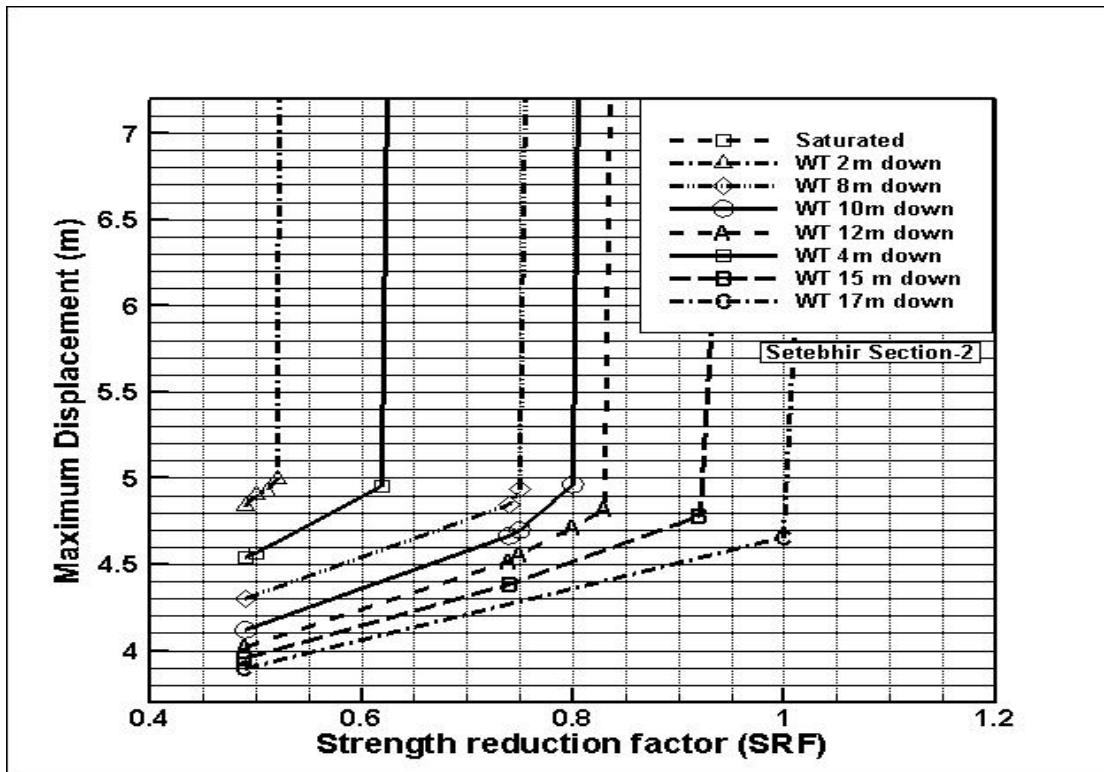


Figure 6.9 Displacement contours of site specific analysis result

### SRF vs Displacement Plot



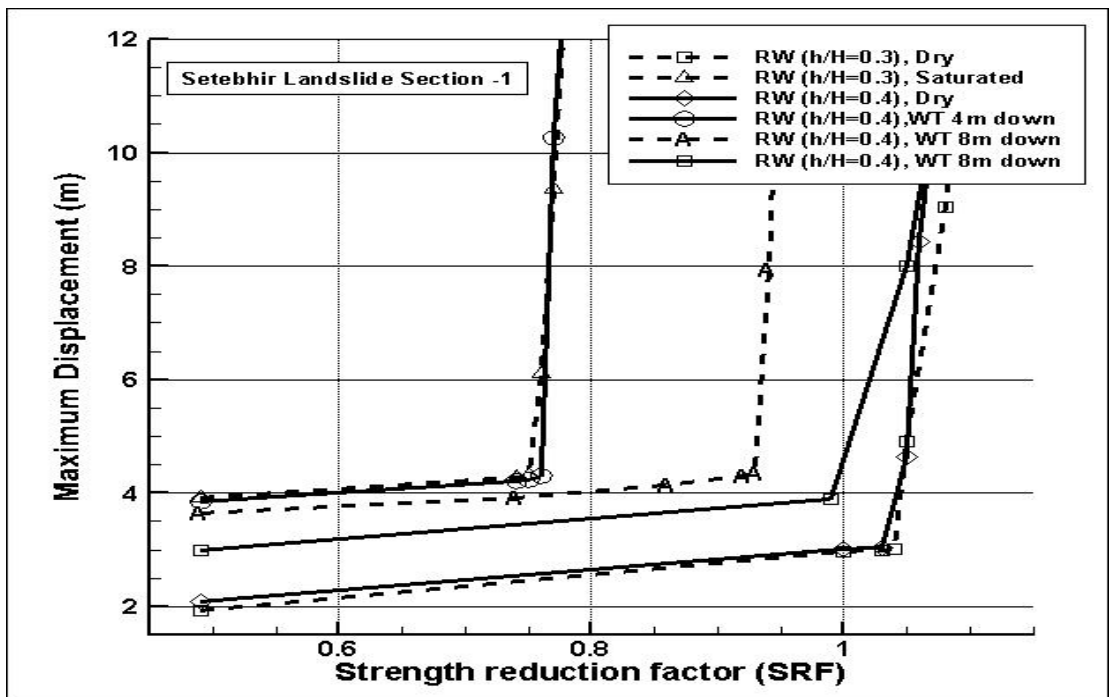
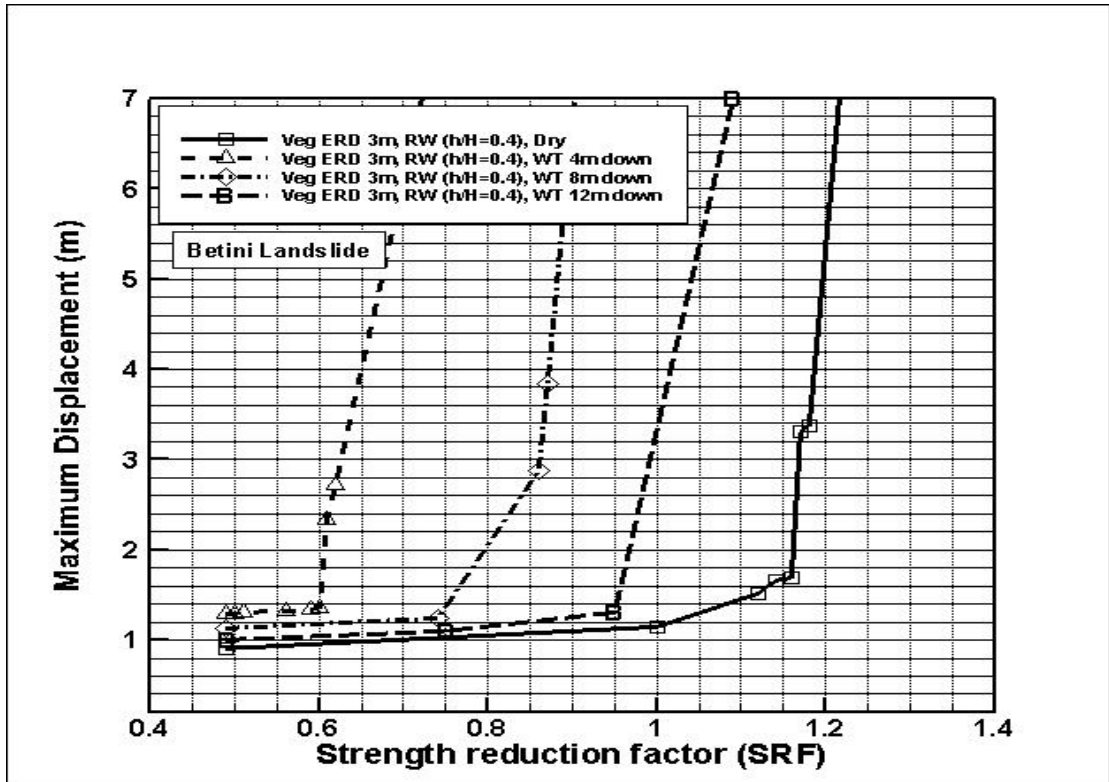


Figure 6.10 SRF vs Displacement plots of site specific results

**ANNEX III**

**GENERAL MITIGATION ANALYSIS DETAILS**

## General Mitigation FOS Value

Table 6.5 FOS value from the general mitigation model

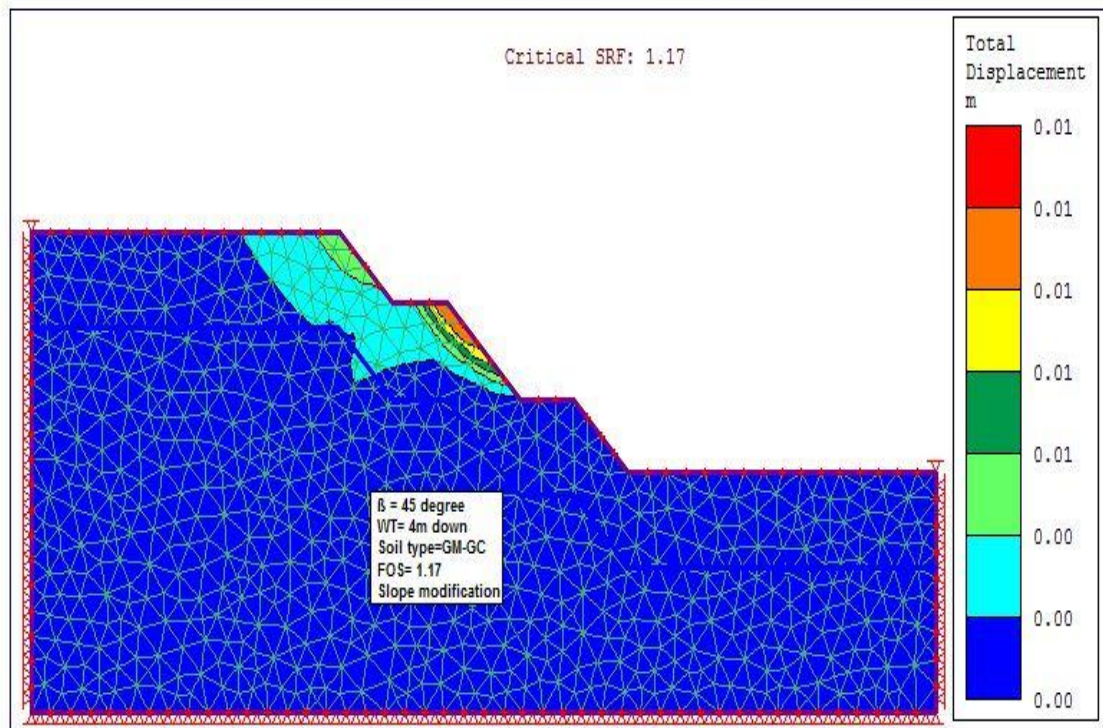
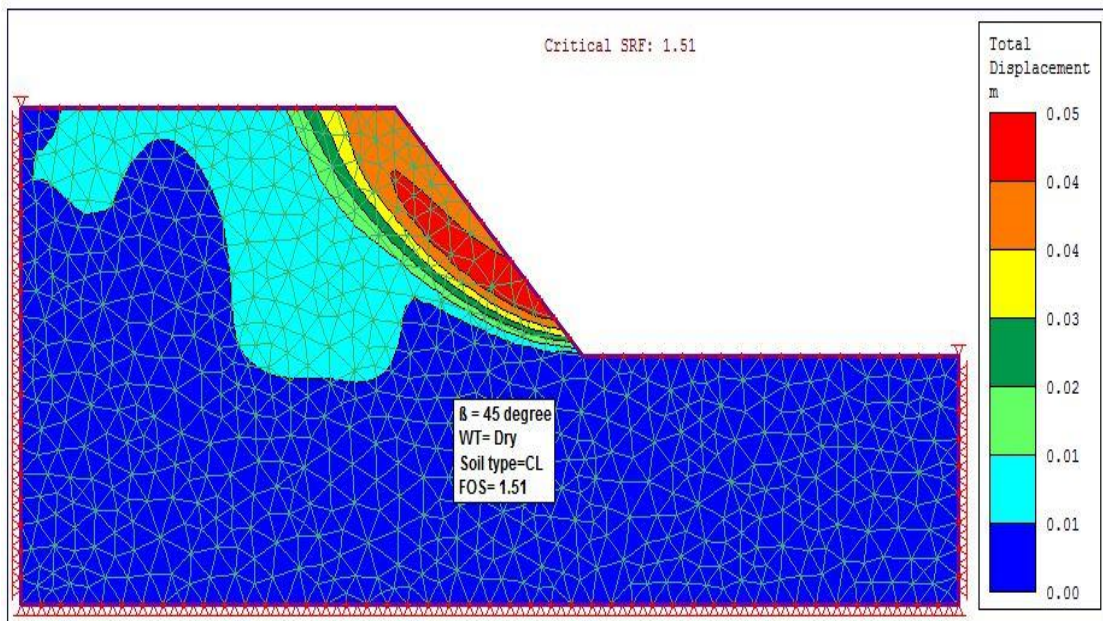
| <b>Landslide Mitigation Table</b>            |             |       |      |      |       |       |      |      |      |
|--|-------------|-------|------|------|-------|-------|------|------|------|
| <b>Mitigation measures</b>                   | Slope Angle | 30    |      |      |       |       |      |      |      |
|  | Soil type   | SM-SC | SP   | CL   | CL-ML | GM-GC | SC   | SM   | ML   |
| <b>Ground Water Table Reduction</b>          | Dry         | 1.47  | 1.28 | 2    | 1.91  | 1.35  | 1.1  | 1.19 | 1.14 |
|  | Sat         | 0.75  | 0.36 | 1.2  | 1.12  | 0.63  | 0.36 | 0.4  | 0.35 |
|  | 2m          | 1.22  | 1.17 | 1.61 | 1.55  | 1.19  | 1.02 | 1.11 | 1.05 |
|  | 4m          | 1.47  | 1.28 | 1.86 | 1.82  | 1.35  | 1.11 | 1.19 | 1.14 |
| <b>Vegetation ERD 1m</b>                     | Dry         | 1.59  | 1.59 | 2.06 | 1.98  | 1.53  | 1.38 | 1.48 | 1.43 |
|  | Sat         | 0.87  | 0.62 | 1.27 | 1.21  | 0.79  | 0.61 | 0.67 | 0.6  |
|  | 2m          | 1.29  | 1.27 | 1.66 | 1.6   | 1.27  | 1.12 | 1.21 | 1.15 |
|  | 4m          | 1.57  | 1.59 | 1.91 | 1.98  | 1.53  | 1.48 | 1.48 | 1.43 |
| <b>Slope Modification</b>                    | Dry         | 1.93  | 1.45 | 2.48 | 2.42  | 1.67  | 1.27 | 1.37 | 1.31 |
|  | Sat         | 1.05  | 0.45 | 1.55 | 1.48  | 0.89  | 0.42 | 0.47 | 0.41 |
|  | 2m          | 1.57  | 1.49 | 1.95 | 1.92  | 1.56  | 1.18 | 1.38 | 1.3  |
|  | 4m          | 1.91  | 1.48 | 2.24 | 2.24  | 1.67  | 1.25 | 1.37 | 1.31 |
| <b>Retaining wall at toe (h/H=0.3)</b>       | Dry         | 1.56  | 1.32 | 2.23 | 2.09  | 1.43  | 1.15 | 1.23 | 1.18 |
|  | Sat         | 0.81  | 0.39 | 1.4  | 1.26  | 0.66  | 0.38 | 0.41 | 0.36 |
|  | 2m          | 1.39  | 1.32 | 1.87 | 1.8   | 1.32  | 1.14 | 1.24 | 1.19 |
|  | 4m          | 1.56  | 1.32 | 2.12 | 2.07  | 1.41  | 1.15 | 1.23 | 1.19 |
| <b>Retaining wall at toe (h/H=0.2)</b>       | Dry         | 1.46  | 1.24 | 1.95 | 1.9   | 1.31  | 1.08 | 1.15 | 1.12 |
| <b>Retaining wall at toe (h/H=0.4)</b>       | Dry         | 1.62  | 1.36 | 2    | 1.95  | 1.47  | 1.17 | 1.24 | 1.18 |
| <b>Vegetation ERD 1m +Slope Modification</b> | Dry         | 2.04  | 2.05 | 2.52 | 2.49  | 1.97  | 1.77 | 1.9  | 1.84 |
|  | Sat         | 1.14  | 0.82 | 1.61 | 1.54  | 1.07  | 0.78 | 0.87 | 0.77 |
|  | 2m          | 1.63  | 1.63 | 2    | 1.97  | 1.63  | 1.44 | 1.56 | 1.48 |
|  | 4m          | 1.98  | 2.05 | 2.28 | 2.29  | 1.97  | 1.78 | 1.91 | 1.84 |
| <b>Vegetation +Retaining wall (h/H=0.3)</b>  | Dry         | 1.72  | 1.7  | 2.31 | 2.18  | 1.61  | 1.46 | 1.55 | 1.51 |
|  | Sat         | 0.97  | 0.73 | 1.47 | 1.38  | 0.87  | 0.68 | 0.74 | 0.68 |
|  | 2m          | 1.47  | 1.44 | 1.95 | 1.86  | 1.43  | 1.27 | 1.36 | 1.31 |
|  | 4m          | 1.72  | 1.68 | 2.21 | 2.16  | 1.62  | 1.46 | 1.55 | 1.51 |
| <b>Mitigation measures</b>                   | Slope Angle | 35    |      |      |       |       |      |      |      |
|  | Soil type   | SM-SC | SP   | CL   | CL-ML | GM-GC | SC   | SM   | ML   |
| <b>Ground Water Table Reduction</b>          | Dry         | 1.27  | 1.04 | 1.79 | 1.7   | 1.15  | 0.9  | 0.97 | 0.93 |
|  | Sat         | 0.6   | 0.23 | 1.02 | 0.95  | 0.5   | 0.24 | 0.27 | 0.21 |

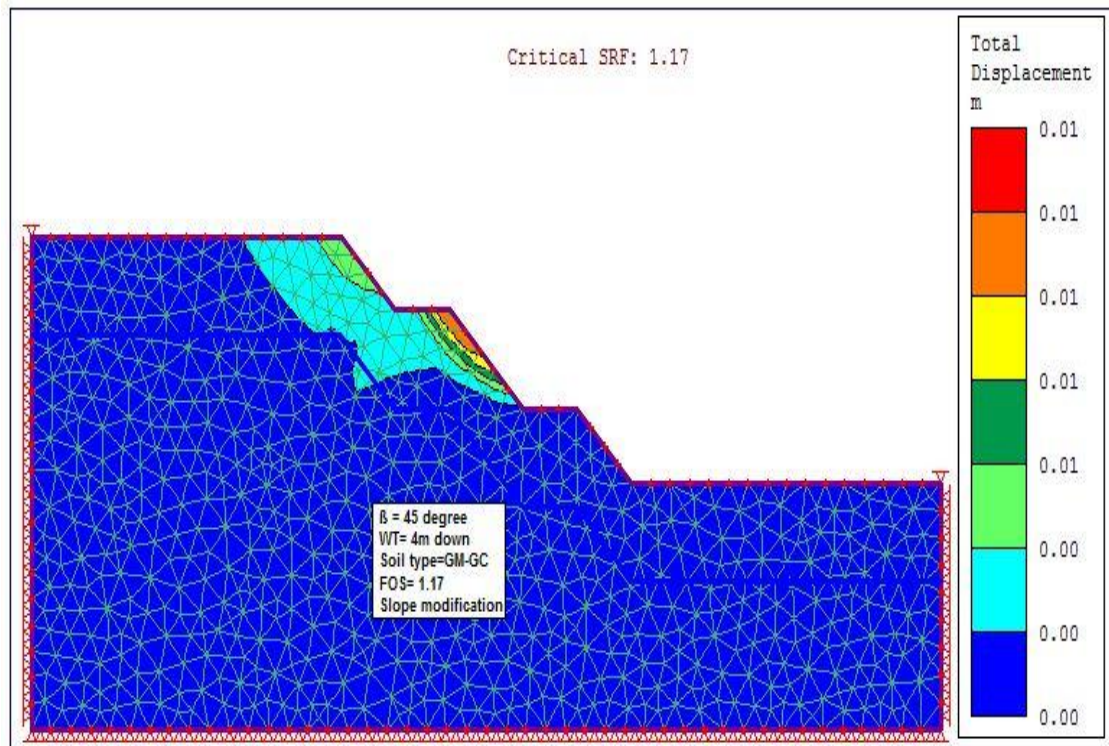
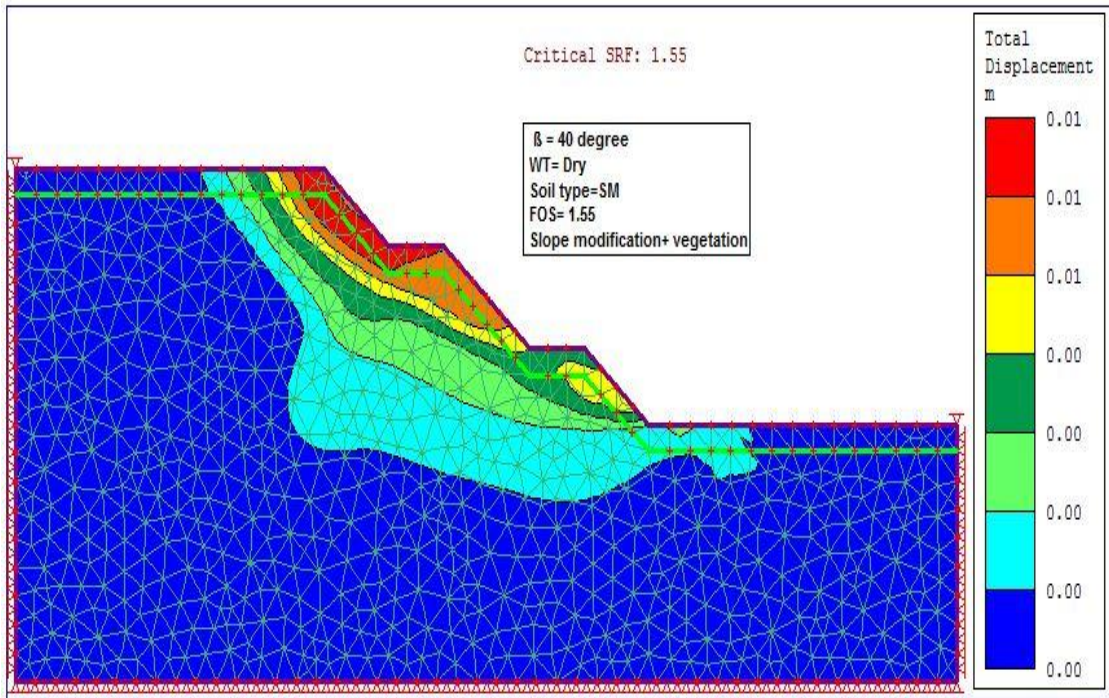
|  |             |       |      |      |       |       |      |      |      |
|--|-------------|-------|------|------|-------|-------|------|------|------|
|  | 2m          | 1.06  | 0.99 | 1.44 | 1.38  | 1.02  | 0.87 | 0.94 | 0.89 |
|  | 4m          | 1.27  | 1.04 | 1.68 | 1.63  | 1.14  | 0.9  | 0.97 | 0.93 |
| <b>Vegetation ERD 1m</b>                     | Dry         | 1.39  | 1.35 | 1.85 | 1.76  | 1.31  | 1.17 | 1.25 | 1.22 |
|  | Sat         | 0.71  | 0.47 | 1.1  | 1.04  | 0.61  | 0.48 | 0.53 | 0.41 |
|  | 2m          | 1.13  | 1.09 | 1.5  | 1.44  | 1.1   | 0.97 | 1.04 | 0.99 |
|  | 4m          | 1.38  | 1.35 | 1.74 | 1.69  | 1.31  | 1.18 | 1.26 | 1.22 |
| <b>Slope Modification</b>                    | Dry         | 1.71  | 1.29 | 2.29 | 2.21  | 1.46  | 1.06 | 1.17 | 1.12 |
|  | Sat         | 0.93  | 0.28 | 1.42 | 1.34  | 0.73  | 0.26 | 0.33 | 0.26 |
|  | 2m          | 1.43  | 1.16 | 1.82 | 1.77  | 1.4   | 1.09 | 1.18 | 1.12 |
|  | 4m          | 1.71  | 1.24 | 2.09 | 2.08  | 1.46  | 1.08 | 1.14 | 1.12 |
| <b>Retaining wall at toe (h/H=0.3)</b>       | Dry         | 1.35  | 1.09 | 2    | 1.86  | 1.19  | 0.94 | 1.01 | 0.99 |
|  | Sat         | 0.66  | 0.3  | 1.18 | 1.06  | 0.58  | 0.3  | 0.36 | 0.28 |
|  | 2m          | 1.19  | 1.01 | 1.57 | 1.46  | 1.06  | 0.89 | 0.96 | 0.92 |
|  | 4m          | 1.32  | 1.06 | 1.97 | 1.86  | 1.16  | 0.94 | 1.01 | 0.99 |
| <b>Retaining wall at toe (h/H=0.2)</b>       | Dry         | 1.3   | 1.07 | 1.9  | 1.79  | 1.17  | 0.92 | 0.98 | 0.94 |
| <b>Retaining wall at toe (h/H=0.4)</b>       | Dry         | 1.41  | 1.1  | 2.12 | 1.95  | 1.25  | 0.95 | 1.02 | 1.02 |
| <b>Vegetation ERD 1m +Slope Modification</b> | Dry         | 1.85  | 1.85 | 2.35 | 2.28  | 1.78  | 1.6  | 1.72 | 1.66 |
|  | Sat         | 1.02  | 0.68 | 1.48 | 1.41  | 0.94  | 0.65 | 0.72 | 0.64 |
|  | 2m          | 1.49  | 1.48 | 1.87 | 1.83  | 1.48  | 1.31 | 1.42 | 1.34 |
|  | 4m          | 1.82  | 1.85 | 2.15 | 2.14  | 1.78  | 1.6  | 1.72 | 1.67 |
| <b>Vegetation +Retaining wall (h/H=0.3)</b>  | Dry         | 1.53  | 1.48 | 2.1  | 1.97  | 1.43  | 1.29 | 1.37 | 1.34 |
|  | Sat         | 0.87  | 0.63 | 1.32 | 1.22  | 0.78  | 0.6  | 0.63 | 0.6  |
|  | 2m          | 1.31  | 1.28 | 2.1  | 1.96  | 1.43  | 1.29 | 1.37 | 1.34 |
|  | 4m          | 1.53  | 1.48 | 2.06 | 1.96  | 1.43  | 1.29 | 1.37 | 1.34 |
| <b>Mitigation measures</b>                   | Slope Angle | 40    |      |      |       |       |      |      |      |
|  | Soil type   | SM-SC | SP   | CL   | CL-MI | GM-GC | SC   | SM   | ML   |
| <b>Ground Water Table Reduction</b>          | Dry         | 1.11  | 0.88 | 1.62 | 1.52  | 0.99  | 0.76 | 0.82 | 0.79 |
|  | Sat         | 0.47  | 0.02 | 0.83 | 0.77  | 0.38  | 0.05 | 0.05 | 0.02 |
|  | 2m          | 0.92  | 0.83 | 1.31 | 1.23  | 0.87  | 0.72 | 0.79 | 0.75 |
|  | 4m          | 1.11  | 0.88 | 1.53 | 1.46  | 0.99  | 0.76 | 0.82 | 0.79 |
| <b>Vegetation ERD 1m</b>                     | Dry         | 1.23  | 1.17 | 1.68 | 1.59  | 1.16  | 1.02 | 1.08 | 1.06 |
|  | Sat         | 0.55  | -    | 0.93 | 0.87  | 0.46  | 0.01 | 0.01 | 0.02 |
|  | 2m          | 1     | 0.92 | 1.36 | 1.29  | 0.95  | 0.82 | 0.89 | 0.84 |
|  | 4m          | 1.22  | 1.17 | 1.57 | 1.52  | 1.16  | 1.02 | 1.08 | 1.06 |
| <b>Slope Modification</b>                    | Dry         | 1.56  | 0.98 | 2.13 | 2.04  | 1.29  | 0.84 | 0.9  | 0.87 |
|  | Sat         | 0.77  | 0.21 | 1.29 | 1.29  | 0.58  | 0.2  | 0.22 | 0.19 |
|  | 2m          | 1.3   | 0.9  | 1.7  | 1.65  | 1.27  | 0.85 | 0.92 | 0.89 |

|  |                |       |      |      |       |       |      |      |      |
|--|----------------|-------|------|------|-------|-------|------|------|------|
|  | 4m             | 1.56  | 0.98 | 1.97 | 1.94  | 1.29  | 0.84 | 0.91 | 0.88 |
| <b>Retaining wall at toe<br/>(h/H=0.3)</b>       | Dry            | 1.16  | 0.85 | 1.79 | 1.65  | 0.98  | 0.74 | 0.79 | 0.78 |
|  | Sat            | 0.47  | -    | 0.93 | 0.85  | 0.32  | -    | -    | -    |
|  | 2m             | 1.01  | 0.88 | 1.53 | 1.41  | 0.94  | 0.76 | 0.82 | 0.69 |
|  | 4m             | 1.16  | 0.85 | 1.77 | 1.65  | 1.01  | 0.74 | 0.79 | 0.76 |
| <b>Retaining wall at toe<br/>(h/H=0.2)</b>       | Dry            | 1.13  | 0.88 | 1.65 | 1.6   | 0.99  | 0.76 | 0.82 | 0.78 |
| <b>Retaining wall at toe<br/>(h/H=0.4)</b>       | Dry            | 1.18  | 0.9  | 1.82 | 1.7   | 1     | 0.77 | 0.84 | 0.8  |
| <b>Vegetation ERD 1m<br/>+Slope Modification</b> | Dry            | 1.69  | 1.67 | 2.19 | 2.11  | 1.61  | 1.44 | 1.55 | 1.5  |
|  | Sat            | 0.91  | 0.52 | 1.35 | 1.3   | 0.8   | 0.52 | 0.59 | 0.5  |
|  | 2m             | 1.37  | 1.35 | 1.76 | 1.7   | 1.36  | 1.19 | 1.29 | 1.22 |
|  | 4m             | 1.68  | 1.67 | 2.03 | 2     | 1.61  | 1.44 | 1.55 | 1.5  |
| <b>Vegetation +Retaining<br/>wall (h/H=0.3)</b>  | Dry            | 1.16  | 1.21 | 1.86 | 1.73  | 1.2   | 1.06 | 1.13 | 1.1  |
|  | Sat            | 0.65  | 0.15 | 1.07 | 0.995 | 0.55  | 0.25 | 0.29 | 0.18 |
|  | 2m             | 1.12  | 1.04 | 1.61 | 1.49  | 1.05  | 0.92 | 0.99 | 0.59 |
|  | 4m             | 1.16  | 1.21 | 1.84 | 1.73  | 1.2   | 1.06 | 1.13 | 1.1  |
| <b>Mitigation measures</b>                       | Slope<br>Angle | 45    |      |      |       |       |      |      |      |
|  | Soil<br>type   | SM-SC | SP   | CL   | CL-ML | GM-GC | SC   | SM   | ML   |
| <b>Ground Water Table<br/>Reduction</b>          | Dry            | 0.99  | 0.79 | 1.51 | 1.38  | 0.87  | 0.68 | 0.73 | 0.71 |
|  | Sat            | 0.38  | -    | 0.67 | 0.64  | 0.25  | -    | -    | -    |
|  | 2m             | 0.79  | 0.71 | 1.2  | 1.12  | 0.7   | 0.62 | 0.69 | 0.65 |
|  | 4m             | 1.06  | 0.99 | 1.44 | 1.36  | 0.93  | 0.86 | 0.92 | 0.89 |
| <b>Vegetation ERD 1m</b>                         | Dry            | 1.1   | 1.03 | 1.57 | 1.45  | 1.02  | 0.9  | 0.96 | 0.94 |
|  | Sat            | 0.47  | -    | 0.81 | 0.74  | 0.44  | -    | -    | -    |
|  | 2m             | 0.89  | 0.92 | 1.27 | 1.29  | 0.83  | 0.79 | 0.82 | 0.81 |
|  | 4m             | 1.15  | 1.24 | 1.5  | 1.42  | 1.1   | 1.07 | 1.14 | 1.11 |
| <b>Slope Modification</b>                        | Dry            | 1.42  | 0.89 | 2    | 1.91  | 1.16  | 0.77 | 0.83 | 0.8  |
|  | Sat            | 0.69  | 0.19 | 1.17 | 1.09  | 0.52  | 0.16 | 0.17 | 0.14 |
|  | 2m             | 1.21  | 0.91 | 1.61 | 1.55  | 1.17  | 0.78 | 0.84 | 0.82 |
|  | 4m             | 1.42  | 0.89 | 1.87 | 1.83  | 1.14  | 0.77 | 0.83 | 0.8  |
| <b>Retaining wall at toe<br/>(h/H=0.3)</b>       | Dry            | 1.04  | 0.79 | 1.68 | 1.53  | 0.87  | 0.68 | 0.74 | 0.7  |
|  | Sat            | 0.41  | -    | 0.68 | 0.69  | 0.32  | -    | -    | -    |
|  | 2m             | 0.91  | 0.76 | 1.43 | 1.31  | 0.81  | 0.67 | 0.72 | 0.69 |
|  | 4m             | 1.04  | 0.79 | 1.66 | 1.53  | 0.87  | 0.68 | 0.74 | 0.71 |
| <b>Retaining wall at toe<br/>(h/H=0.2)</b>       | Dry            | 1.02  | 0.78 | 1.6  | 1.45  | 0.86  | 0.67 | 0.73 | 0.69 |
| <b>Retaining wall at toe<br/>(h/H=0.4)</b>       | Dry            | 1.06  | 0.8  | 1.72 | 1.6   | 0.88  | 0.69 | 0.75 | 0.71 |
| <b>Vegetation ERD 1m</b>                         | Dry            | 1.56  | 1.53 | 2.06 | 1.97  | 1.49  | 1.33 | 1.42 | 1.38 |

|  |             |       |      |      |       |       |      |      |      |
|--|-------------|-------|------|------|-------|-------|------|------|------|
| <b>+Slope Modification</b>                   | Sat         | 0.8   | 0.36 | 1.24 | 1.17  | 0.7   | 0.38 | 0.43 | 0.36 |
|  | 2m          | 1.36  | 1.25 | 1.66 | 1.6   | 1.26  | 1.1  | 1.19 | 1.13 |
|  | 4m          | 1.56  | 1.53 | 1.92 | 1.88  | 1.48  | 1.33 | 1.42 | 1.32 |
| <b>Vegetation +Retaining wall (h/H=0.3)</b>  | Dry         | 1.21  | 1.12 | 1.75 | 1.62  | 1.11  | 0.98 | 1.04 | 1.01 |
|  | Sat         | 0.56  | -    | 0.95 | 0.89  | 0.5   | -    | 0.01 | -    |
|  | 2m          | 1.04  | 0.97 | 1.49 | 1.4   | 0.98  | 0.86 | 0.92 | 0.88 |
|  | 4m          | 1.21  | 1.12 | 1.72 | 1.61  | 1.11  | 0.98 | 1.04 | 1.01 |
| <b>Mitigation measures</b>                   | Slope Angle | 50    |      |      |       |       |      |      |      |
|  | Soil type   | SM-SC | SP   | CL   | CL-ML | GM-GC | SC   | SM   | ML   |
| <b>Ground Water Table Reduction</b>          | Dry         | 0.88  | 0.61 | 1.28 | 1.25  | 0.73  | 0.52 | 0.58 | 0.54 |
|  | Sat         | -     | -    | -    | -     | -     | -    | -    | -    |
|  | 2m          | 0.69  | 0.55 | 1.04 | 0.99  | 0.64  | 0.48 | 0.52 | 0.49 |
|  | 4m          | 0.88  | 0.61 | 1.28 | 1.21  | 0.73  | 0.52 | 0.56 | 0.55 |
| <b>Vegetation ERD 1m</b>                     | Dry         | 0.99  | 0.93 | 1.43 | 1.34  | 0.9   | 0.81 | 0.86 | 0.84 |
|  | Sat         | -     | -    | -    | -     | -     | -    | -    | -    |
|  | 2m          | 0.78  | 0.67 | 1.1  | 1.06  | 0.72  | 0.6  | 0.65 | 0.61 |
|  | 4m          | 1     | 0.93 | 1.35 | 1.28  | 0.93  | 0.81 | 0.86 | 0.84 |
| <b>Slope Modification</b>                    | Dry         | 1.26  | 0.69 | 1.89 | 1.79  | 0.98  | 0.59 | 0.64 | 0.62 |
|  | Sat         | 0.45  | -    | 0.79 | 0.81  | 0.34  | -    | -    | -    |
|  | 2m          | 1.13  | 0.73 | 1.53 | 1.46  | 1     | 0.64 | 0.68 | 0.64 |
|  | 4m          | 1.26  | 0.69 | 1.82 | 1.72  | 0.99  | 0.59 | 0.64 | 0.62 |
| <b>Retaining wall at toe (h/H=0.3)</b>       | Dry         | 0.93  | 0.67 | 1.54 | 1.4   | 0.78  | 0.47 | 0.59 | 0.49 |
|  | Sat         | -     | -    | -    | -     | -     | -    | -    | -    |
|  | 2m          | 0.8   | 0.65 | 0.64 | 1.17  | 0.72  | 0.56 | 0.59 | 0.57 |
|  | 4m          | 0.92  | 0.64 | 1.51 | 1.39  | 0.78  | 0.47 | 0.51 | 0.49 |
| <b>Retaining wall at toe (h/H=0.2)</b>       | Dry         | 0.9   | 0.64 | 1.4  | 1.3   | 0.77  | 0.52 | 0.58 | 0.53 |
| <b>Retaining wall at toe (h/H=0.4)</b>       | Dry         | 0.95  | 0.7  | 1.6  | 1.36  | 0.79  | 0.54 | 0.6  | 0.55 |
| <b>Vegetation ERD 1m +Slope Modification</b> | Dry         | 1.46  | 1.42 | 1.96 | 1.87  | 1.37  | 1.23 | 1.32 | 1.28 |
|  | Sat         | 0.7   | 0.01 | 1.09 | 1.06  | 0.57  | 0.25 | 0.31 | 0.17 |
|  | 2m          | 1.2   | 1.15 | 1.58 | 1.52  | 1.17  | 1.02 | 1.1  | 1.04 |
|  | 4m          | 1.46  | 1.42 | 1.83 | 1.78  | 1.38  | 1.23 | 1.32 | 1.28 |
| <b>Vegetation +Retaining wall (h/H=0.3)</b>  | Dry         | 1.11  | 1.02 | 1.65 | 1.52  | 1.01  | 0.89 | 0.95 | 0.93 |
|  | Sat         | 0.26  | -    | -    | 0.47  | 0.25  | -    | -    | -    |
|  | 2m          | 0.93  | 0.84 | 1.4  | 1.27  | 0.86  | 0.75 | 0.8  | 0.77 |
|  | 4m          | 1.11  | 1.02 | 1.61 | 1.51  | 1.02  | 0.89 | 0.95 | 0.93 |

## Displacement Contour





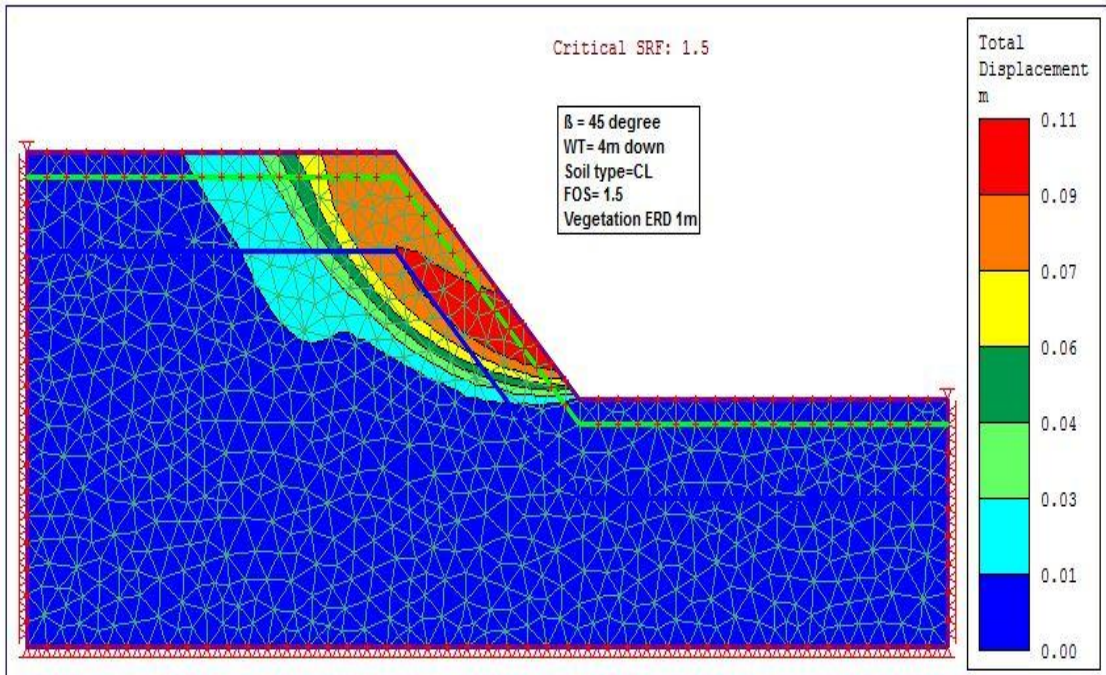


Figure 6.11 Displacement contour results from general mitigation analysis

**ANNEX IV**

**MODELING PROCEDURE ON PHASE2**

## Modeling Procedure and Steps on Phase2

### Step 1: Project setting

#### General Settings

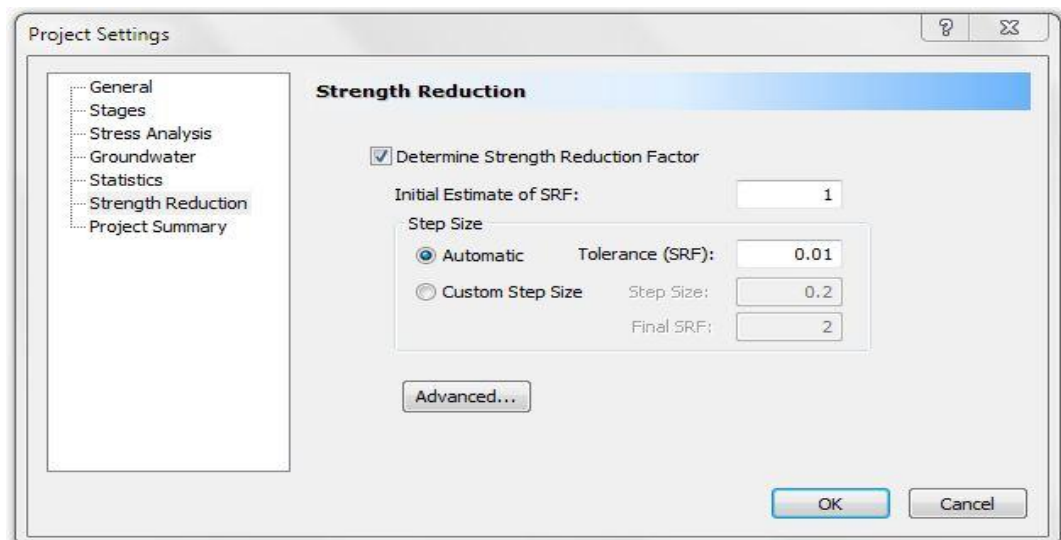
- Single stage model
- Analysis Type: Plane Strain
- Solver Type: Gaussian Elimination
- Units: Metric, stress as kPa

#### Analysis Options

- Maximum Number of Iterations: 3000
- Tolerance: 0.001
- Number of Load Steps: Automatic
- Convergence Type: Absolute Energy
- Tensile Failure: Reduces Shear Strength
- Joint tension reduces joint stiffness by a factor of 0.01

#### Strength Reduction Settings

- Initial Estimate of SRF: 1
- Step Size: Automatic
- Tolerance (SRF): 0.01
- Limit SSR Search Area: No
- Apply SSR to Mohr-Coulomb Tensile Strength: Yes
- Convergence Parameters: Automatic



## Step 2: Groundwater Analysis

### *Groundwater Analysis*

- Method: Piezometric Lines
- Pore Fluid Unit Weight: 9.81 kN/m<sup>3</sup>
- Probability: None

## Step 3: Loading Options

### *Field Stress*

- Field stress: gravity
- Using actual ground surface
- Total stress ratio (horizontal/vertical in-plane): 1
- Total stress ratio (horizontal/vertical out-of-plane): 1

Field Stress Properties

Field Stress Type: Gravity

Use actual ground surface  Use effective stress ratio  Use variable stress ratio

Ground Surface Elevation (m): 0

Unit Weight of Overburden (kN/m<sup>3</sup>): 27

Total Stress Ratio (horiz/vert in plane): 1

Total Stress Ratio (horiz/vert out-of-plane): 1

Locked-in horizontal stress (in plane) (kPa, Comp. +): 0

Locked-in horizontal stress (out-of-plane) (kPa, Comp. +): 0

OK

Cancel

Statistics...

Advanced >>

## Step 4: Mesh Setup

### *Mesh*

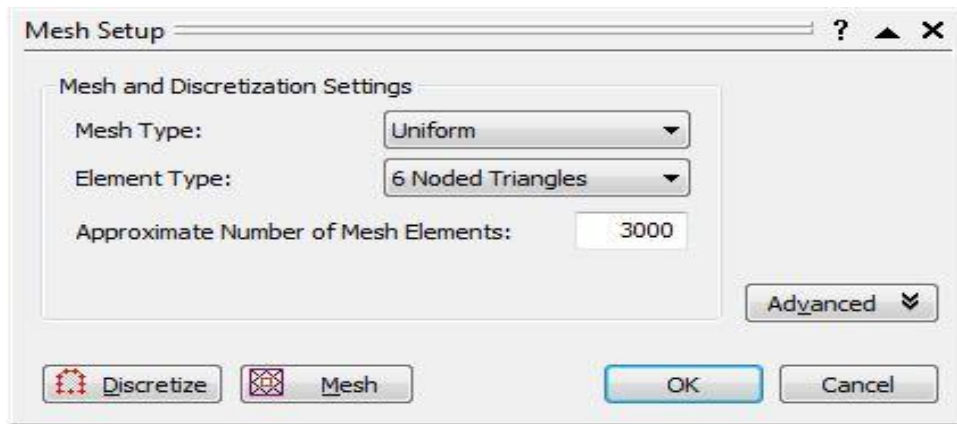
- Mesh type: uniform
- Element type: 6 noded triangles
- Number of elements: 2959
- Number of nodes: 6140

### *Mesh Quality*

- All elements are of good quality

### **Poor quality elements defined as:**


- Side length ratio (maximum / minimum) > 30.00
- Minimum interior angle < 2.0 degrees
- Maximum interior angle > 175.0 degrees



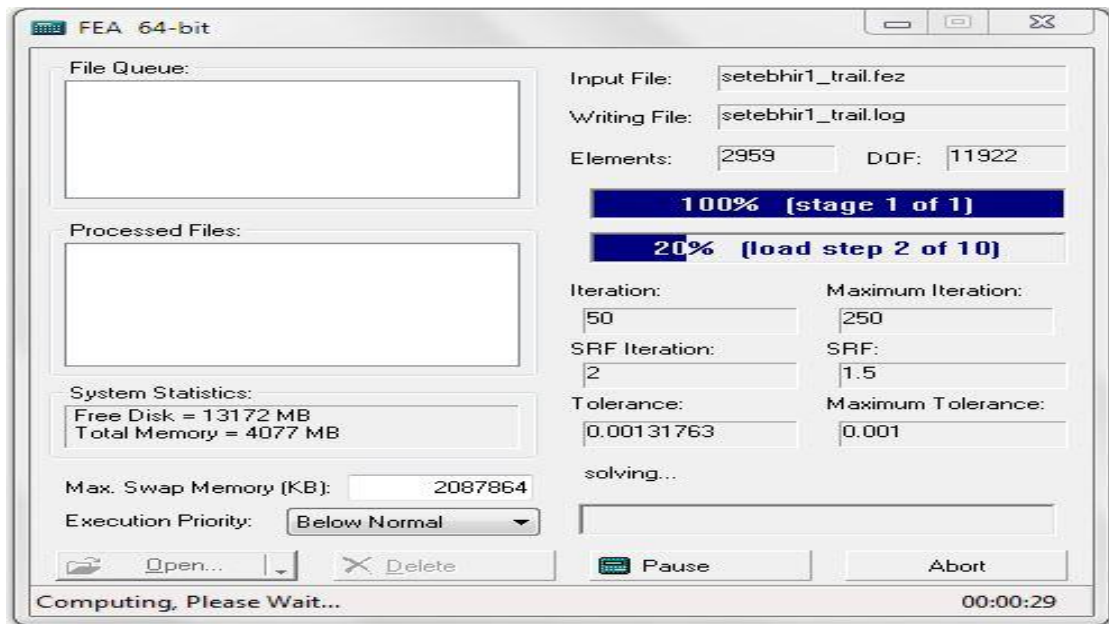
Step 5: Material Property Input

***Material Properties***

**Material: silt to clayey sand**

|                           |   |
|---------------------------|---|
| Color                     |  |
| Initial element loading   | field stress & body force   |
| Unit weight               | 21 kN/m <sup>3</sup>  |
| Elastic type              | isotropic   |
| Young's modulus           | 50000 kPa   |
| Poisson's ratio           | 0.3   |
| Failure criterion         | Mohr-Coulomb  |
| Peak tensile strength     | 0 kPa   |
| Residual tensile strength | 0 kPa   |
| Peak friction angle       | 36 degrees  |
| Peak cohesion             | 8.5 kPa   |
| Material type             | Plastic   |
| Dilation Angle            | 0 degrees   |
| Residual Friction Angle   | 36 degrees  |
| Residual Cohesion         | 8.5 kPa   |
| Piezo to use              | None  |
| Ru value                  | 0   |

Step 6: Computation



### Step 7: Interpretation