APPLICATION OF UNSATURATED SHEAR STRENGTH PROPERTIES IN SLOPE STABILITY ANALYSIS

Master of Engineering

M T Champa Priyadarshani Hapangama

Department of Civil Engineering
University of Moratuwa
Sri Lanka

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DECLARATION

The work included in this thesis in part or whole has not been submitted for any other academic qualification at any institution.

Signature of the Candidate

Certified

Signature of the Supervisor

ABSTRACT

It is very important to study applications of unsaturated soil properties in slope stability analysis due to the additional shear strength an unsaturated soil possesses. Shear strength of an unsaturated soil is strongly related to the amount of water in the voids of the soil, and therefore to the matric suction. It is postulated that the shear strength of an unsaturated soil should also bear a relationship to the soil-water characteristic curve.

In this thesis, the effect of unsaturated shear strength properties on stability of slopes is investigated by analysing for the stability of hypothetical cut slopes.

The effect of the position of water table below the failure surface of hypothetical cut slopes were analysed using Slope/w software for different water table positions for three different cut slope angles.

For this work, analyses were done by replacing the cohesion by the apparent cohesion values. Apparent cohesion values were increased by increasing the depth of water table and increasing the effect of negative pore water pressure. Different apparent cohesion values corresponding to the different percentage of negative hydrostatic pressures were utilized.

Spreadsheets prepared by a previous research were used to analyse the hypothetical cut slopes by the Modified Janbu's Method of slices for unsaturated soils. The negative pore water pressure could be directly taken into account in this method, and the Factors of Safety (FOS) derived by this method are compared with the results from SLOPE/W software.

Variation of FOS with slope angle and position of water table are investigated. The parametric study done here gives an insight into the problem of landslides. Lowering of the Water Table is been to increase the FOS against sliding failure, as expected.

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CHAPTER 1

1.0 INTRODUCTION

1.1 Emergence of unsaturated soil mechanics

Most of the theories available to solve geotechnical engineering problems are founded on the basis of pore water pressure being positive, or by considering soil as saturated. Consequently, current laboratory and field testing procedures have been developed to obtain design parameters for saturated soils.

Even though main attention has been focused on saturated soils, a large portion of soil surface cover exists in nature in an unsaturated state and the water table is deep. For example, most of the building foundations are shallow the foundations and are located above the ground water table. In addition to that, retaining walls and cut slopes mostly occur above the ground water table.

But there are a number of reasons why attention has been focussed on saturated soils and not on unsaturated soils. One reason is that unlike for saturated soils, there has been a lack of an appropriate science with a theoretical base for unsaturated soils. On the other hand, changes in the water table and water content in soil may increase additional risk to the designer, because critical situations may occur during rainy season. But in practical situations most of the slope failures occur in unsaturated soils and before the soil get saturated. So it is very important to study behaviour of unsaturated soil for slope stability analysis.

Although shear strength theories of an unsaturated soil have been formulated and found to be consistent with observed experimental behaviour, the experimental studies on unsaturated soils are generally costly, time consuming and difficult to conduct.

Shear strength data from the research literature suggest that there is a nonlinear increase in shear strength of unsaturated soil, as a result of an increase in matric suction. Since the shear strength of an unsaturated soil is strongly related to the amount of water in the voids of the soil, and to the matric suction, it is postulated that the shear strength of an unsaturated soil should also bear a relationship to the soil-water characteristic curve.

1.2 Unsaturated soil and stability of slopes

An unsaturated soil is characterized by negative pore water pressure and consequent matric suction, which is defined as the difference between pore air pressure and pore water pressure. This matric suction result in increasing the shear strength of the soil in the unsaturated state compared to that in the saturated state.

Laboratory studies have shown that there is a relationship between the soil-water characteristic curve and unsaturated soil properties (Fredland and Raharjo 1993). Several models have been proposed to empirically predict the permeability function for an unsaturated soil using the saturated coefficient of permeability as the starting value (Fredland et al 1994)

A value for the shear strength of soil is required to investigate the stability of slopes and embankments, the bearing capacity of foundations and pressure against earth retaining structures. The Mohr-Coulomb theory, using the effective stress state, is commonly used for predicting the shear strength of saturated soils. Even though soils encountered in engineering practice are often unsaturated, slope stability is usually based on the saturated shear strength parameters.

Similar design approaches have been developed for retaining structures, pavements and other earth structures. These approaches are conservative to varying degrees in that the influence of soil suction is ignored. However, even low suction can be responsible for maintaining the stability of slopes (Walle and Hachich, 1989)

In tropical countries such as Sri Lanka, a large portion of soil cover consist of the soil formed in place due to weathering of underlying rock owing to the specific climatic conditions. These soils which are known as residual soils, exist in a partially saturated state, mostly during dry seasons. Thus, natural slopes formed by such soils posses high factors of safety values against failure during dry season. This is due to high shear strength that they posses under unsaturated state arising out of soil suction.

During rainy seasons the wetting front can saturate to considerable depths of the residual soil cover, reducing the shear strength of such soils. The apparent cohesion of such soils, which contributes to additional shear strength of soil under unsaturated conditions, disappears upon saturation. Most of the landslides which occur in Sri Lanka have their failure surface passing through residual soils and colluvium deposits (Tennakoon, 1994).

Inhabited areas with steep slopes consisting of residual soils are sometimes the sites of catastrophic response to rainfall and experience generated landslides that claim many lives. Globally, landslides cause billions of dollars in damage and thousands of deaths and injuries each year. In the tropical regions, the soils involved are often residual soils and have deep water tables. The surface soils have negative pore water pressures that play a significant role in the stability of the slope. However, heavy, continuous rainfall can result in a decreased matric suction and even an increased pore-water pressure to a significant depth, induce a cycle of wetting and drying and result in the instability of the slope.

Standard approaches to stability analysis usually simplify consideration of the hydrological condition to that of a static, fixed ground water level. Stability analysis procedures are then used to determine the factor of safety for the slope, given the distribution of positive pressure along the slip surface. Soil suction is generally ignored in such analysis, being assumed zero. However many slope failures in tropical residual soils are attributed to complex dynamic hydrological conditions.

It is common engineering practice to ignore negative pore water pressure above the ground water table in slope stability analysis, and disregard the contribution from the negative pore water pressure on shear strength. The unsaturated soil region is assumed to be saturated with zero pore water pressure. This is a reasonable assumption for many situations where the major portion of the slip surface is below the ground water table. However this assumption may not be realistic and can affect both the computed factor of safety and the location of the critical slip surface when the ground water table is deep or where the concern is over the possibility of a shallow failure surface (Fredland, 1995b)

Unsaturated soil behaviour can have a significant effect on the computed results particularly when the slope is steep and the water table is deep. In-situ measurements of suction with depth have shown that except in the region very close to the water table, the suction increases as the elevation from the water table in the unsaturated zone increases (Sweeny, 1982).

It has long been known that pore suctions in unsaturated soils can play an important role in the stability of geotechnical structures, at least temporarily, and that these suctions are highly dependent on soil type and infiltration conditions. The suction stress formula requires four parameters, three for the soil type and one for the steady infiltration (or evaporation) due to environmental effects.

Suction stress formulation is based firmly within the context of Terzaghi's classical effective stress theory as modified for unsaturated soils by Bishop (1960) in the form:

$$\sigma' = (\sigma - Ua) + \chi\,(Ua - Uw)$$

In which σ' and σ are respectively, the effective and total stress, Ua is the air pressure in the voids, and Uw is the suction pore pressure within the unsaturated soil matrix. The term (Ua-Uw) is called the matric suction, and χ is the matric suction coefficient, generally determined experimentally, which is related primarily to the degree of saturation of the soil. The matric suction coefficient χ may be interpreted as the average proportion of the voids along any cross section through a partially saturated soil, which passes through water.

The portion of the soil profile above the ground water table, called the vadose zone, can be readily subdivided into two portions. The portion immediately above the ground water table is known as the capillary fringe. When the soil structure at a particular location within the capillary fringe is considered, it remains essentially saturated while pore water pressures are slightly negative. The portion above the capillary fringe is unsaturated. As the distance above the ground water table increases, the pore water pressure become increasingly negative as the degree of saturation of the soil decreases. The pore water pressure can sometimes become highly negative. Difficulties associated with measurement of suction values have become one of the primary reasons to ignore the additional shear strength in the saturated zone. Due to this negligence, the assumption made regarding the zone above the ground water table can be highly conservative and sometimes unreasonable.

Inclusion of unsaturated soil strength has the effect of increasing the cohesion of the soil and results in the deepening of critical slip surface (Ching et at.1999). Therefore, when the ground water table is deep there is more possibility for shallow surface failure above the ground water table, where the zone has negative pore water pressure.

Regardless of the degree of saturation of the soil, the pore- water pressure profile in Figure 1.1 will come to equilibrium at hydrostatic condition when there is zero flux from ground surface. If moisture is extracted from the ground surface (e.g., evaporation), the pore-water pressure line will be drawn to the left. If moisture enters at the ground water surface (e.g., infiltration), the pore-water profile will be drawn to the right.

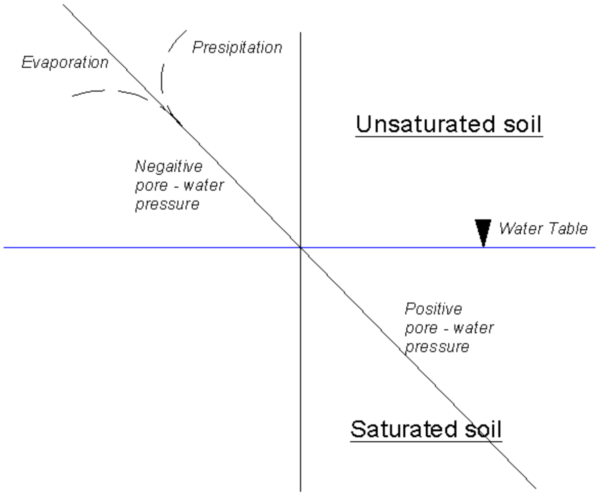

FIGURE - 1

Figure 1.1: Pore pressure variation in soil

1.3 The scope of work and objective

There are a number of experiments and studies carried out in Sri Lanka to investigate the relationship between occurrences of landslides and rainfall but there have not been studied in much detail. Most of these landslide analyses were done considering the saturated soil parameters.

Analysis of slopes with saturated soil strength properties is the common practice available for slope stability analysis. If the landslide occurs at the time water table is deep or before becoming fully saturated, use of saturated soil parameters to analyse stability of slopes and to calculate factor of safety is not reasonable. Also a question arises why these landslides happen when the soil gets partially saturated.

Saturated analysis may give factor of safety values less than one even for stable slopes, since the slope may actually be unsaturated even though it is assumed to be saturated in analysis. The analysis of slopes under unsaturated condition yield higher factor of safety values than at saturated conditions.

So it is very important to study stability of slopes under various degrees of saturation, by using unsaturated soil parameters, and it is essential to understand the behaviour of unsaturated soils.

Objectives of the current research are:

1. To investigate the effect of use of unsaturated shear strength properties in the slope stability analysis, and

2. To conduct a parametric study on the variation of the Factor of Safety against sliding failure of cut soil slopes with the slope angle and position of the water table

1.4 Organization of the research and thesis

This work is an expansion of the research carried out by Rathnasiri (2002). Analyses were done to find stability of slopes under various degrees of saturation. For these analyses, soil properties in the location of Pussallawa land slide were used. The same soil properties are used for the current work, and analyses were done by considering various angles of cut slopes with varying water table, by using both saturated and unsaturated states.

Chapter 1

- Presents the introduction

Chapter 2

- Presents theories on unsaturated soil mechanics that are useful in slope stability analysis

Chapter 3

- Derivation of the factor of safety equation for slope stability analysis for unsaturated soils.

Chapter 4

- Presents the results of analysis done for hypothetical cut slopes with varying cut slope angle and varying water table

- Variation of factor of safety against failure of slopes as the water table changes are discussed in detail. The negative pore water pressure is increased from 0% to 50% of negative hydrostatic pressure.

Chapter 5

- Presents the conclusions of the study.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Shear Strength of soil

The shear strength of a soil is required for numerous analysis, such as the prediction of the stability of slopes, the design of foundations, and design of earth retaining structures. The effective stress variable proposed by Terzaghy (1936) has been used in the Mohr-Coulomb theory for predicting the shear strength of saturated soils. The shear strength equation for saturated soils is expressed as a linear function of effective stress and is given as follows:

$$\tau = c' + (\sigma_n - u_w) \tan \phi'$$

where

τ is the shear strength;
c' is the effective cohesion;
ϕ' is the effective angle of internal friction;
σ_n is the total normal stress on the plane of failure;
u_w is the pore water pressure;
$(\sigma_n - u_w)$ is the effective normal stress on the plane of failure.

Many practical problems involve assessment of the shear strength of unsaturated soils. Fredlund and Morgenstern (1977) showed that the shear strength of unsaturated soils can be described by any two of three stress variables, namely $(\sigma - u_a)$, $(\sigma - u_w)$, and $(\sigma_a - u_w)$ where u_a is the pore-air pressure. Fredlund et al. (1978) proposed the following equation for the shear strength of unsaturated soils:

$$\tau = c' + (\sigma_n - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b$$

where

ϕ^b is the angle describing the rate of increase in shear strength relative to a change in matric suction, $(u_a - u_w)$, when $(\sigma_n - u_a)$ and $(u_a - u_w)$ are used as the two state variables;

and

ϕ' is the angle describing the rate of increase in shear strength with respect to net normal stress, $(\sigma_n - u_w)$, when $(\sigma_n - u_w)$ and $(u_a - u_w)$ are used as the two state variables.

The influence of the matric suction can be considered as an increase of the cohesion of the soil (Fredlund, 1979). This procedure makes it unnecessary to reformulate the equation for the factor of safety in cases like slope stability analyses. The total cohesion is therefore equal to the sum of the effective cohesion, c' and the increase in cohesion due to matric suction.

i.e

$$c = c' + (u_a - u_w) \tan \phi^b$$

2.2 Methodologies for the determination of Unsaturated Soil Property Functions

Several approaches can be taken to determine unsaturated soil property functions. Laboratory tests can be used as a direct measure of the required unsaturated soil properties. For example, a modified shear test can be used to measure the relationship between soil suction and shear strength. These tests can be costly and the necessary equipment may not be available.

Measurement of the soil-water characteristic curve for a soil can be used as an indirect laboratory test to compute unsaturated soil property functions. The soil- water characteristic curve can then be used in conjunction with the saturated shear strength properties of the soil, to predict the relationship between shear strength and soil suction. Some accuracy will likely de lost in reverting to this approach, but the trade-off between accuracy and cost may be acceptable for many engineering projects (Fredlund, 1998).

2.3 Soil-water characteristic curve

The soil- water characteristic curve for a soil is defined as the relationship between water content and suction. The water content variable (i.e., volumetric water content,θ, gravimetric water content, **w** or degree of saturation, **S**) defines the amount of water contained in the pores of the soil. The variable has often been used in a dimensionless form where the water content is referenced to residual or zero water content.

Total suction, ψ, is comprised of both matric suction ($u_a - u_w$) and osmotic suction, π. It is primarily the matric suction component that is of interest with regards to the engineering behaviour of unsaturated soils. Laboratory data have indicated that a change in total suction is essentially equivalent to a change in the matric suction for many unsaturated soil situations. The high suction range of the soil-water characteristic curve is required primarily when studying evaporative processes near the ground surface. Typical features of the drying and wetting portions of the soil-water characteristic curves are defined in Figure 2.1.

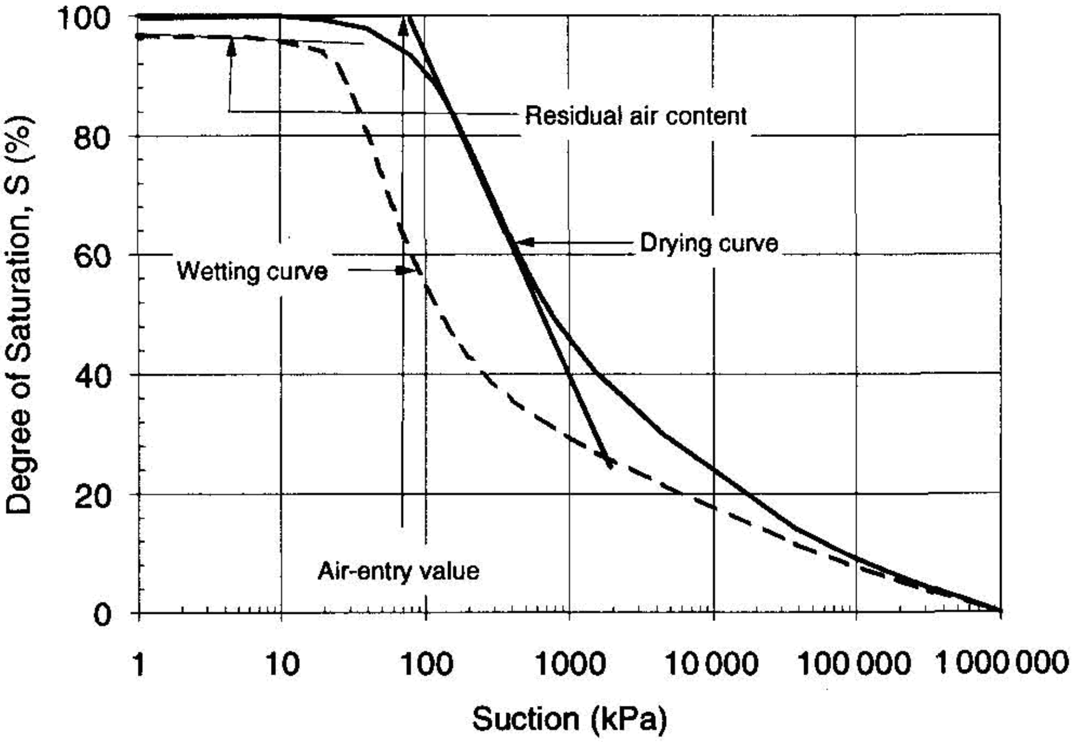

Figure 2.1 Definition of variables associated with the soil-water characteristic curve. (After Fredlund ,1994)

2.4 Nature, characterization and theory of the soil-water characteristic curve

The soil-water characteristic curve has played a role in understanding the behaviour of unsaturated soil near the ground surface in disciplines such as soil science, soil physics, agronomy and agriculture. The soil-water characteristic curve is now recognised as one part of the water phase constitutive relationship in geotechnical engineering. This curve is of value for the important role it plays in predicting unsaturated soil property functions.

Volumetric water content, θ is defined as the ratio of the volume of water to the total volume of soil. The relationship between the various volume–mass designations for water content and other variable can be written as follows: (Fredlund, 1998)

$$\theta = \frac{S\,e}{1+e} = S\,n$$

where:

θ = volumetric water content,
S = degree of saturation,
e = void ratio, and
n = porosity.

The relationship between volumetric water content, θ, and gravimetric water content, w, can be written,

$$\theta = w\,\rho_d/\rho_w$$

where:

ρ_d = dry density of the soil,
ρ_w = density of water, and
w = gravimetric water content.

The volumetric water content is often normalized by dividing by the saturated water content, θ_s.

CHAPTER 3

3.0 FACTOR OF SAFETY IN SLOPE STABILYTY ANALYSIS

3.1 Derivation of the Factor of Safety Equation for Unsaturated Soils

The shear strength function for unsaturated soil can be written as;

$$\tau = c' + (\sigma_n - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b$$

The method proposed by Janbu (1954) to analyse stability of slopes with saturated strength parameters, can be used to derive a factor of safety equation to analyse slopes, irrespective of the fact whether the failure surface is circular or noncircular. Janbu has proposed a simplified method of analysis and a rigorous method of analysis. In the simplified method of analysis, the assumption is made that the interslice shear forces are zero and by examining overall force equilibrium, a value of the factor of safety F_o is obtained. The solution is achieved by an iteration procedure. The forces acting on a slice in the Janbu's simplified method are shown in figure 3.1

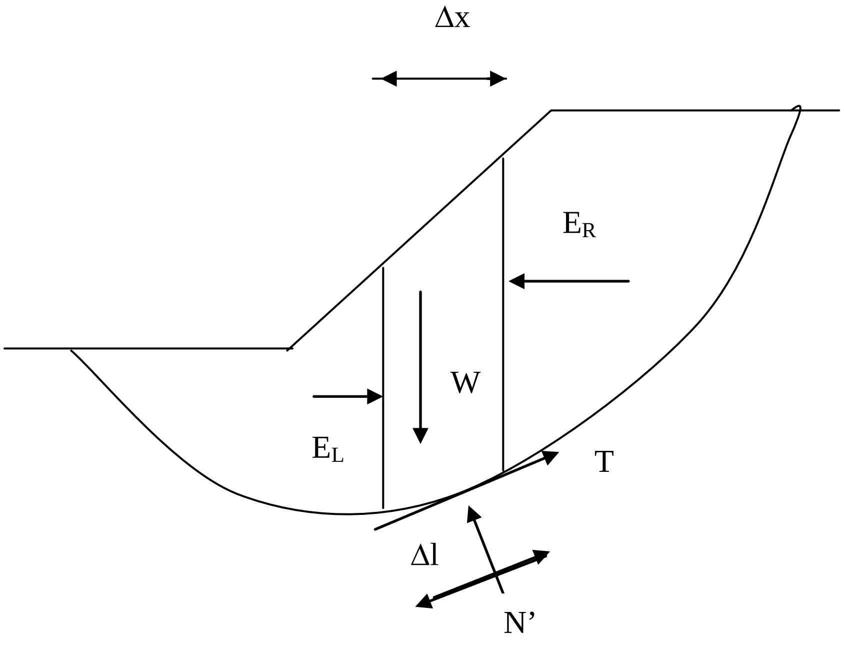

Figure 3.1: Forces acting on a slice in Janbu's simplified method

For the slice shown,

Mobilized shear strength $\tau_m = \tau_f/F$

Where, F is the factor of safety.

$N_i = \sigma \Delta l$

$T_i = 1/F\ \tau_f\ \Delta l = 1/F\ [c' + \Delta l\ (\sigma_n - u_a) \tan \phi' + \Delta l (u_a - u_w) \tan \phi^b$

$T_i = 1/F\ [Sin\ \theta_i]$---[1]

Resolving vertically,

$N_i Cos\ \theta_I + T_i Sin\ \theta_i = W_i - (X_L - X_R)$

Assuming $(X_L - X_R) = 0$ (For Janbu's simplified method)

$N_i\ Cos\ \theta_i + 1/F\ [c'\Delta l + (N_i - u_a \Delta l) \tan \phi' + \Delta l (u_a - u_w) \tan \phi^b\ ] Sin\ \theta_i = W_i$

$N_i\ Cos\ \theta_i\ [1 + 1/F \tan \phi' \tan \theta_i] = W_i - Sin\ \theta_i / F [c'\Delta l - u_a \Delta l \tan \phi' + \Delta l (u_a - u_w) \tan \phi^b]$

If $Cos\ \theta_i\ [1 + 1/F \tan \phi' \tan \theta_i] = M_\theta$

$N_i = \{W_i - 1/F[c'\Delta l\ Sin\ \theta_I - u_a \Delta l \tan \phi'\ Sin\ \theta_I + \Delta l (u_a - u_w) \tan \phi^b\ Sin\ \theta_I]\} / M_\theta$ ————————[2]

Resolving parallel to the base of the slice,

$T_i + (E_L - E_R)\ Cos\ \theta_I = [W_i - (X_L - X_R)]\ Sin\ \theta_I$

Assuming $(X_L - X_R) = 0$ and substituting for T_i

$(E_L\text{-}E_R)$ Cos θ_I = W_i Sin θ_I - 1/F [c'Δl + (N_i-u_aΔl) tan ϕ' + Δl(u_a-u_w)tan ϕ^b]

$(E_L\text{-}E_R)$ = W_i tan θ_I - 1/F [c'Δl + (N_i-u_aΔl) tan ϕ' + Δl(u_a-u_w)tan ϕ^b]Sec θ_I----------------[3]

In the absence of surface loading,

Σ $(E_L\text{-}E_R)$ = 0 --- [4]

Σ $(E_L\text{-}E_R)$ = Σ W_i tan θ_I - 1/F [c'Δl + (N_i-u_aΔl) tan ϕ' + Δl(u_a-u_w)tan ϕ^b]Sec θ_I = 0 -----[5]

$$\therefore F_0 = \frac{\sum[\mathrm{c'}\,\Delta\mathrm{l} + (\mathrm{N_i} - u_a\Delta l)\tan\phi' + (u_a - u_w)\Delta l\tan\phi^b]Sec\theta_i}{\sum W\tan\theta_i} \text{ ------------------------------[6]}$$

N_i = {W_i - 1/F[c'Δl Sin θ_i -u_aΔltan ϕ' Sin θ_i + Δl(u_a-u_w)tan ϕ^b Sin θ_i]}/ M_θ ———————[2]

Substituting for N_i in [6]

$$\mathrm{c'}\,\Delta\mathrm{l} + (\mathrm{N_i} - u_a\Delta l)\tan\phi' + (u_a - u_w)\Delta l\tan\phi^b$$
$$= c'\Delta l_i + [\{W_i - \frac{Sin\theta}{F}(c'\Delta l Sin\theta - u_a\Delta l\tan\phi' Sin\theta + (u_a - u_w)\Delta l\tan\phi^b Sin\theta\}\frac{1}{M_\theta} - u_a\Delta l]\tan\phi'$$
$$+ (u_a - u_w)\Delta l\tan\phi^b$$

$$\mathrm{c'}\,\Delta\mathrm{l} + (\mathrm{N_i} - u_a\Delta l)\tan\phi' + (u_a - u_w)\Delta l\tan\phi^b$$
$$= c'\Delta l_i + [\{W_i - \frac{1}{F_f}(c'\Delta l - u_a\Delta l\tan\phi' + (u_a - u_w)\Delta l\tan\phi^b)Sin\theta\}\frac{1}{M_\theta} - u_a\Delta l]\tan\phi' + (u_a - u_w)\Delta l\tan\phi^b$$

$$\mathrm{c'}\,\Delta\mathrm{l} + (\mathrm{N_i} - u_a\Delta l)\tan\phi' + (u_a - u_w)\Delta l\tan\phi^b$$
$$= c'\Delta l_i - \frac{c'\Delta l_i Sin\theta_i\tan\phi'}{F_f M_i(\theta)} + \frac{W_i\tan\phi'}{M_i(\theta)} - \{u_a\Delta l - \frac{u_a\Delta l\tan\phi' Sin\theta_i}{F_f M_i(\theta)}\}\tan\phi' + (u_a - u_w)\Delta l\tan\phi^b$$
$$- \frac{(u_a - u_w)\Delta l\tan\phi^b Sin\theta\tan\phi'}{F_f M\ \ (\theta)} ---------------------------------[6](a)$$

Consider

$$c'\Delta l_i - \frac{c'\Delta l_i Sin\theta_i \tan\phi'}{F_f M_i(\theta)} = c'\Delta x_i[\frac{1}{Cos\theta_i} - \frac{\tan\theta_i \tan\phi'}{F_f M_i(\theta)}] \text{-----------------------} [6](b)$$

By definition,

$$M_i(\theta) = Cos\theta[1 + \frac{\tan\theta_i \tan\phi'}{F_f}]$$

$$\frac{M_i(\theta)}{Cos\theta} = [1 + \frac{\tan\theta_i \tan\phi'}{F_f}]$$

$$\frac{M_i(\theta)}{Cos\theta} - 1 = \frac{\tan\theta_i \tan\phi'}{F_f}$$

$$\therefore \frac{1}{F_f}\frac{\tan\theta_i \tan\phi'}{M_i(\theta)} = \frac{1}{Cos\theta} - \frac{1}{M_i(\theta)} \text{-----------------------------} [6](c)$$

Substituting this in [6] (b)

$$c'\Delta l_i - \frac{c'\Delta l_i Sin\theta_i \tan\phi'}{F_f M_i(\theta)} = c'\Delta x_i[\frac{1}{Cos\theta_i} - (\frac{1}{Cos\theta_i} - \frac{1}{M_i(\theta)})]$$

$$c'\Delta l_i - \frac{c'\Delta l_i Sin\theta_i \tan\phi'}{F_f M_i(\theta)} = \frac{c'\Delta x_i}{M_i(\theta)} \text{-----------------------------------} [6](d)$$

Similarly in [6] (a),

$$[(u_a - u_w)\Delta l_i - \frac{(u_a - u_w)\Delta l \tan\phi' Sin\theta_i]\tan\phi^b}{F_f M_i(\theta)} = \frac{(u_a - u_w)\Delta x_i \tan\phi^b}{M_i(\theta)} \text{------------} [6](e)$$

Substituting [6](d) and [6](e) in [6](a),

$$\mathrm{c}'\,\Delta \mathrm{l}_{\mathrm{i}} + (\mathrm{N}_{\mathrm{i}} - u_a \Delta l)\tan\phi' + (u_a - u_w)\Delta l \tan\phi^b = \frac{c'\Delta l_i}{M_i(\theta)} - \frac{W_i \tan\phi'^b}{M_i(\theta)} + \frac{(u_a - u_w)\Delta x_i \tan\phi^b}{M\ (\theta)} - \frac{u_a \Delta x_i}{M_i(\theta)}$$

By substituting the above result in [6]

$$F_0 = \frac{\sum[\,\{\mathrm{c}' \text{-} u_a + (u_a - u_w)\tan\phi^b\}\Delta x_i + W_i \tan\phi'\,]\dfrac{1}{Cos\theta_i}\dfrac{1}{M_i(\theta)}}{\sum\{W \tan\theta_i\}}$$

$$F_0 = \frac{\sum[\,\{\mathrm{c}' \text{-} u_a \tan\phi' + (u_a - u_w)\tan\phi^b\}\Delta x_i + W_i \tan\phi'\,]\dfrac{1}{n\ (\ \theta_i)}}{\sum\{W_i \tan\theta_i\}}$$

$$F_0 = \frac{\sum[\,\{\mathrm{c}'\Delta x_i + (\mathrm{w}_{\mathrm{i}}\ \text{-}\, u_a \Delta x_i)\tan\phi' + (u_a - u_w)\Delta x_i \tan\phi^b\} / n_\theta}{\sum\{W_i \tan\theta_i\}}$$

Where, $n_\theta = Cos^2\theta(1 + \dfrac{\tan\theta \tan\phi'}{F})$

CHAPTER 4

4.0 SLOPE STABILITY ANALISIS

4.1 With Water Table at a uniform distance below ground surface

Hypothetical cut slopes with three different slope angles were analysed by varying the water table level, with the use of Slope/w software and a spreadsheet calculation developed for saturated and unsaturated soil conditions by Ratnasiri(2002). The spreadsheet had been developed based on Janbu's simplified method.

The slope angles were selected as 48, 55 and 60 to the horizontal and the height difference between the crest and the toe of the cut slope was taken as 30m. The properties of the soil in the cut slope were assumed to be equal to the soil found at Pussallawa landslide site (Rathnasiri, 2002), (i.e. c'= 20 kPa, ϕ' =33, ϕ^b = 28.46 and γ = 17.25kN/m^3). It was assumed that the same soil exist upto the bedrock. In this analysis initially the location of water table was assumed at a depth of 5m below ground surface, and failure surfaces were found using Slope/w computer software. The three different slopes were analysed to find minimum factor of safety against failure when the water table is below the failure surface.

The failure surfaces given by the Slope/W software for different angles were drawn to the same scale with AutoCAD computer package in order to analyse the same slope with the use of spreadsheets written for Janbu's simplified method. Slices were marked along the slope and slice weights and angle of failure of each slice were measured using AutoCAD. The factors of safety of the slopes were determined assuming full saturation for the purpose of comparison. Figure 4.1 to Figure 4.10 show the rotational failure surfaces obtained from Slope/w software for various angles of hypothetical cut slopes which were analyzed by using soil parameters at Pussallawa landslide location.

In order to investigate the effect of the partial saturation, water table was lowered and heights to the base of each slice from the water table were calculated. From these heights, the negative hydrostatic pressures at the each slice were calculated. The effective portion of the negative hydrostatic pressure at the failure was taken as a certain percentage (10%, 20%, 30%, 40%, and 50%) of full negative pressure.

Analyses were done using Slope/w software by replacing the cohesion with the apparent cohesion values according to the section 2.1. Apparent cohesion values were increased by increasing the depth of water table and increasing the negative pore water pressure.

(Different apparent cohesion values corresponding to the different percentage of negative hydrostatic pressures were used).

When the apparent cohesion is changed, a change of failure surface is also possible. To check the variation of the failure surface as the apparent cohesion is increased, the failure surfaces given by the Slope /W software at different percentages of negative hydrostatic pressures were plotted on an AutoCAD drawing to same scale. It was observed that there are no considerable changes in the failure surfaces; (Figures 4.8 - 4.10).

In this work analysis were done for 0% to 50% of negative hydrostatic pressure in steps of 10% for each angle of cut slopes, while varying the water table. (See Tables 4.1 to Table 4.12 and corresponding charts).

Furthermore the factor of safety against failure of the slope along the selected failure surface were calculated using spreadsheets when the negative pore water pressures are increased from 0% to 50% of negative hydrostatic pressure (Appendix A).

Table 4.13 to Table 4.18, and corresponding charts, show that the factor of safety values given by Slope/w software when the cohesion values are replaced with apparent cohesion values to account for the effect of partial saturation, increase with the increase of percentage of negative hydrostatic pressure. For the slope angle of 48 the values obtained from Slope/w software are higher than the values obtained from spreadsheets. But for higher angles of cut slopes the factor of safety values obtained from spreadsheets (which had been developed based on Janbu's simplified method) are higher.

Table 4.19 to Table 4.21 shows the variation of the factor of safety as the angle of cut slopes is varied for different percentage of negative hydrostatic pressures, obtained by spreadsheets prepared for Janbu's simplify method.

4.2 With Water Table at a non-uniform distance below ground surface

To reflect a more realistic profile, the water table was considered to exist at a shallow depth as given in Figure 4.11 and Figure 4.13 and at a relatively deeper depth as given in Figure 4.12 and Figure 4.14.

Then the effect of negative pore pressure would vary with height above water table. To represent this effect in the SLOPE/W software, the soil above water table was considered as three layers with different apparent cohesion values, although the soil may actually be only one type.

In this work analysis were done for 0% to 50% of negative hydrostatic pressure in steps of 10% for 48 and 55 angle of cut slopes, while varying the water table. (See Tables 4.22 to Table 4.24 and corresponding charts).

When this problem was analysed with the spread sheets (Appendix A), the negative pore pressure continued to increase with the elevation above water table and therefore yielded a FOS that continued to increase with elevation above Water Table. This is evident in Table 4.25 and the corresponding chart. However this behaviour will not exist exactly in the real set up, as the effect of negative pore pressure will have a diminishing overall effect on the apparent cohesion of the soil with increasing height above water table because the volume of retained water will become increasingly insignificant at greater elevations above the water table.

Table 4.26 to Table 4.28 shows the variation of the factor of safety as the angle of cut slopes is varied for different percentage of negative hydrostatic pressures, obtained by Slope/w software.

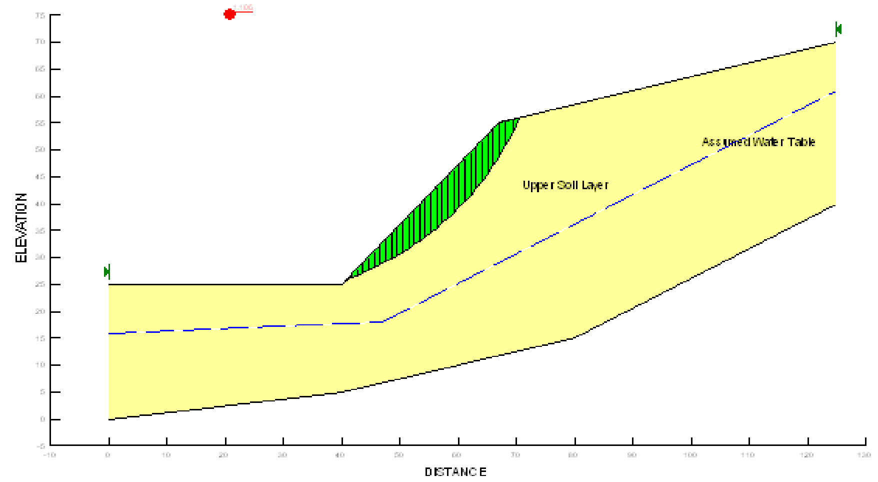

Figure 4.1 -48^{o} cut slope with water table below the failure surface

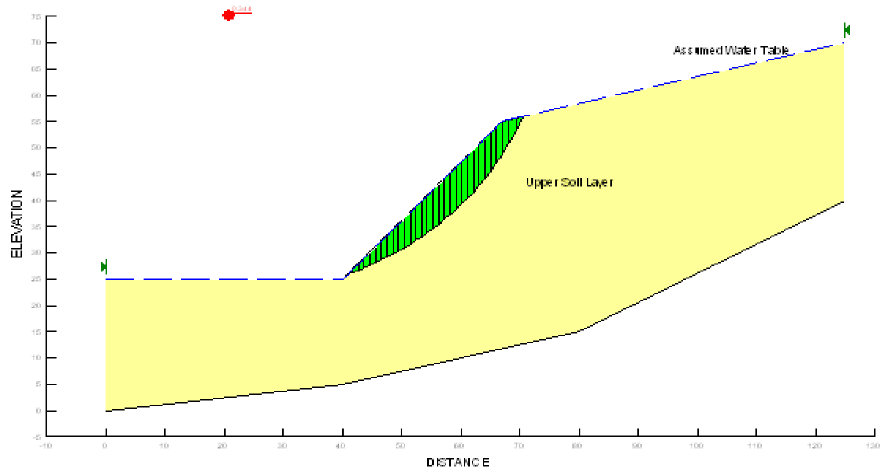

Figure 4.2 -48^{o} cut slope with water table at the ground surface

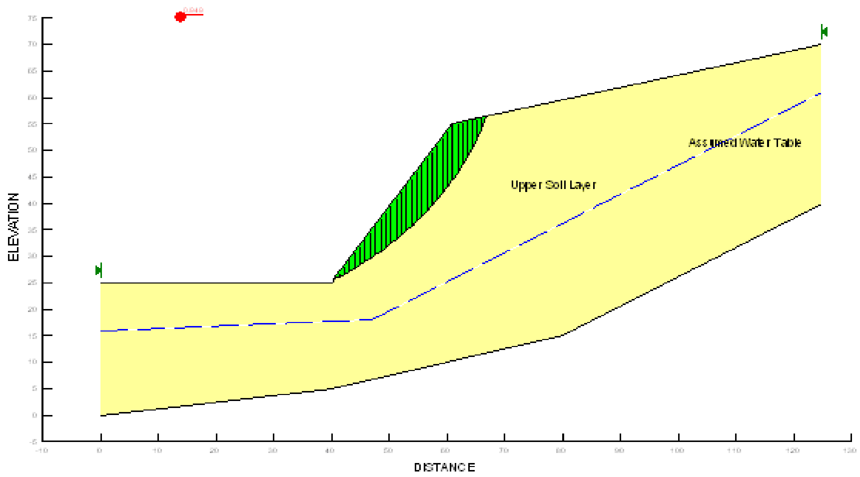

Figure 4.3 -55° cut slope with water table below the failure surface

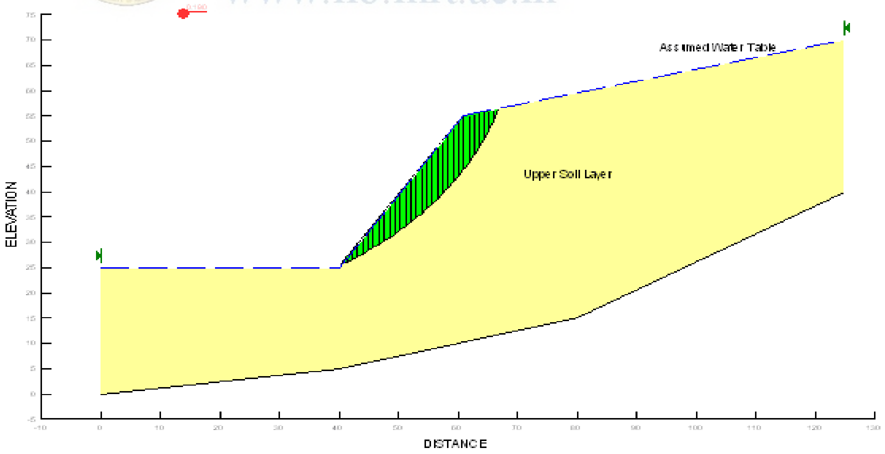

Figure 4.4 -55° cut slope with water table at the ground surface

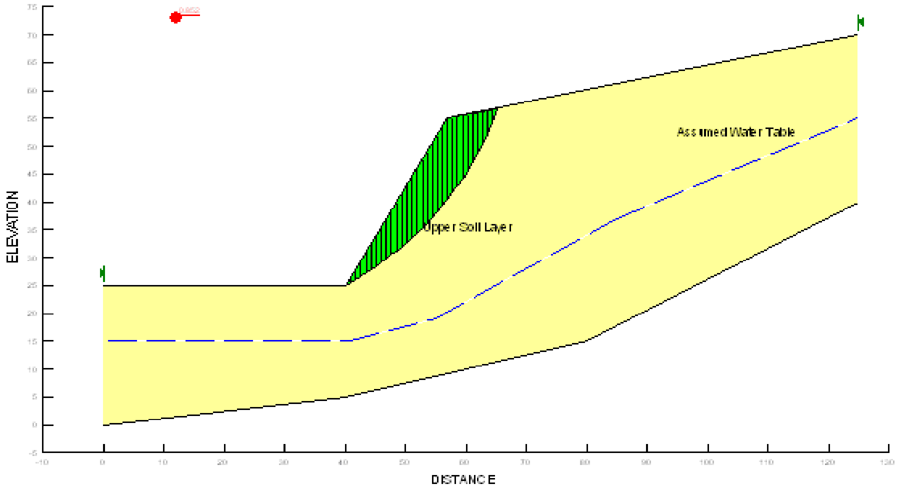

Figure 4.5 -60^{o} cut slope with water table below the failure surface

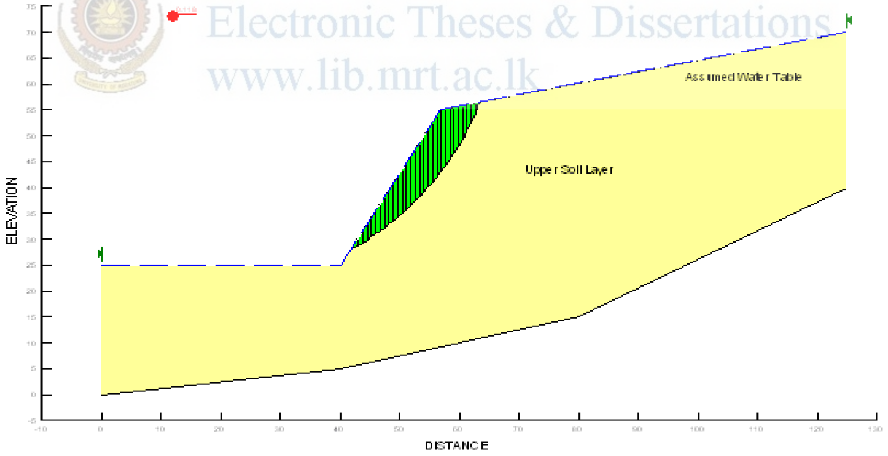

Figure 4.6 -60^{o} cut slope with water table at the ground surface

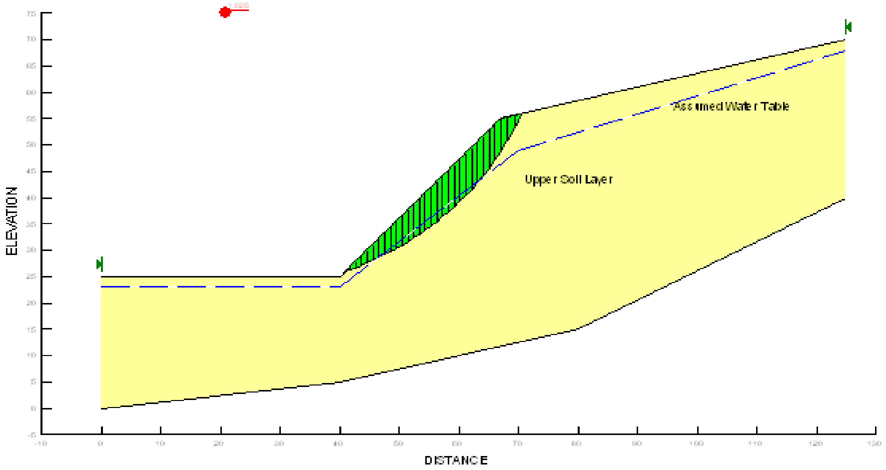

Figure 4.7 -48^{o} cut slope with water table above the failure surface

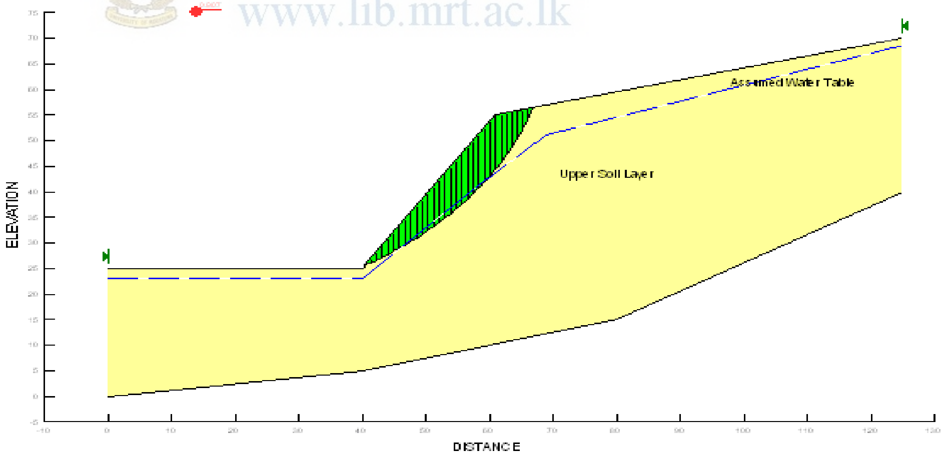

Figure 4.8 -55^{o} cut slope with water table above the failure surface

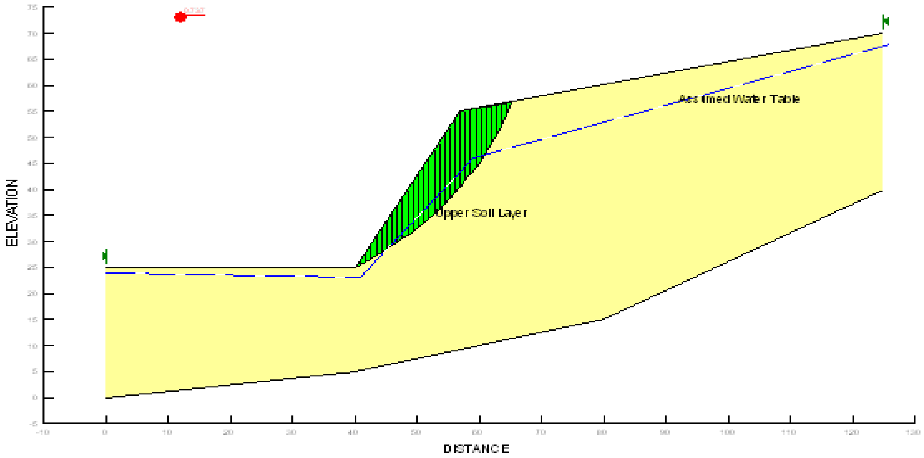

Figure 4.9 -60^{o} cut slope with water table above the failure surface

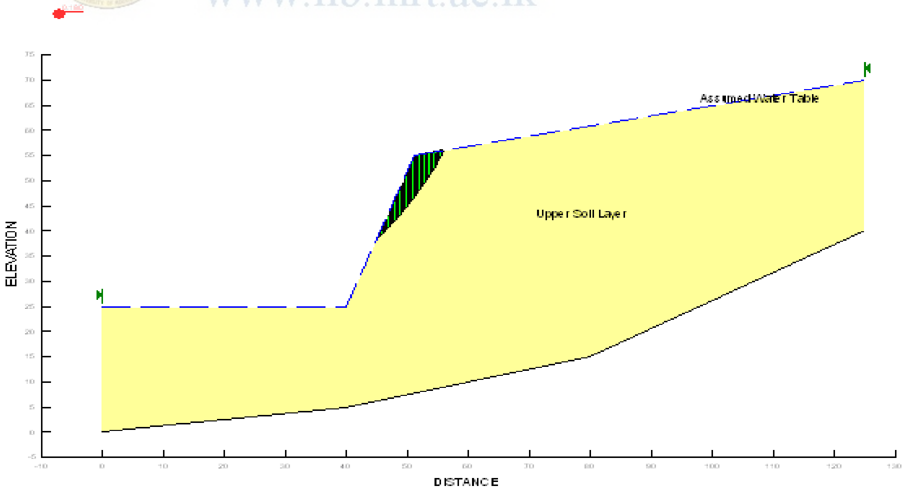

Figure 4.10 -70^{o} cut slope with water table at the ground surface

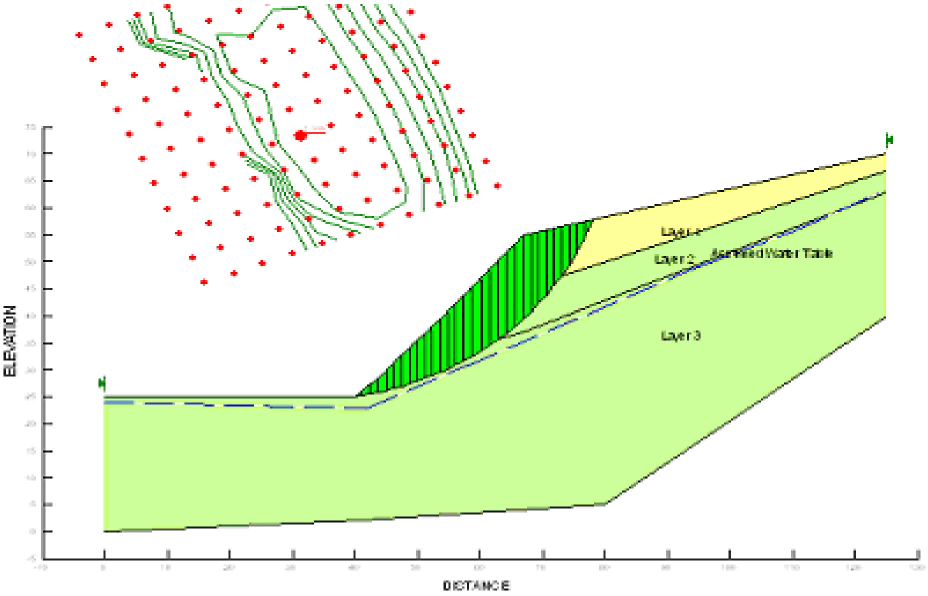

Figure 4.11- 48^{o} cut slope considering the soil to be of layers with different soil parameters, with water table at an upper level

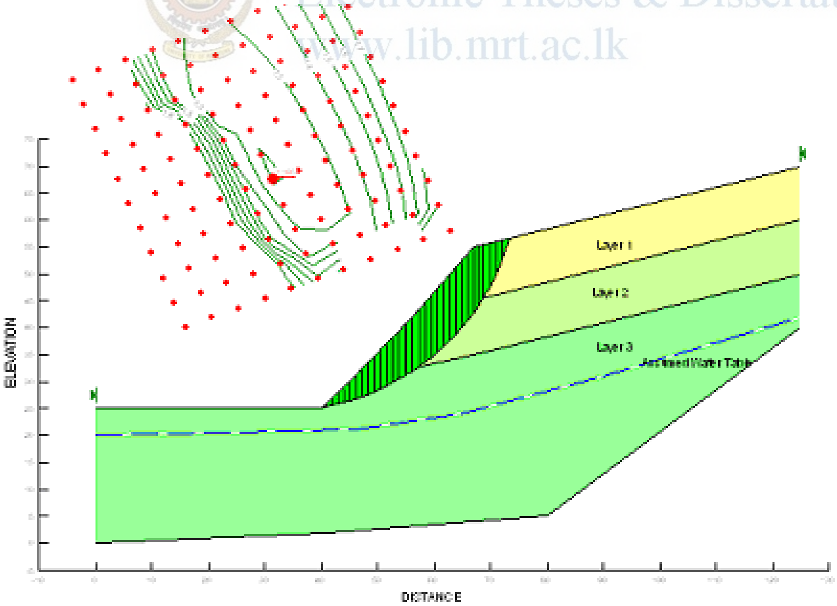

Figure 4.12- - 48^{o} cut slope considering the soil to be of layers with different soil parameters, with water table at a lower level

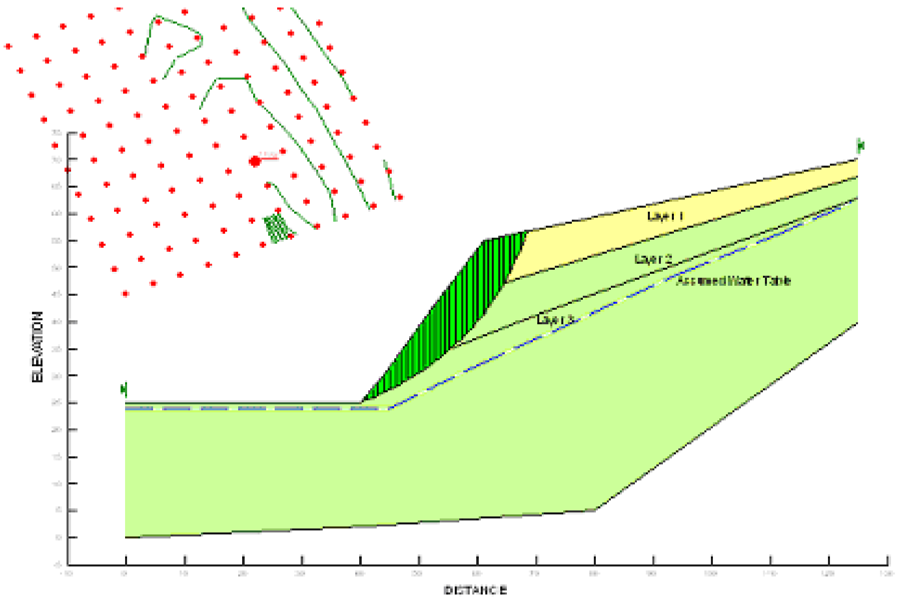

Figure 4.13- - 55^{o} cut slope considering the soil to be of layers with different soil parameters, with water table at an upper level

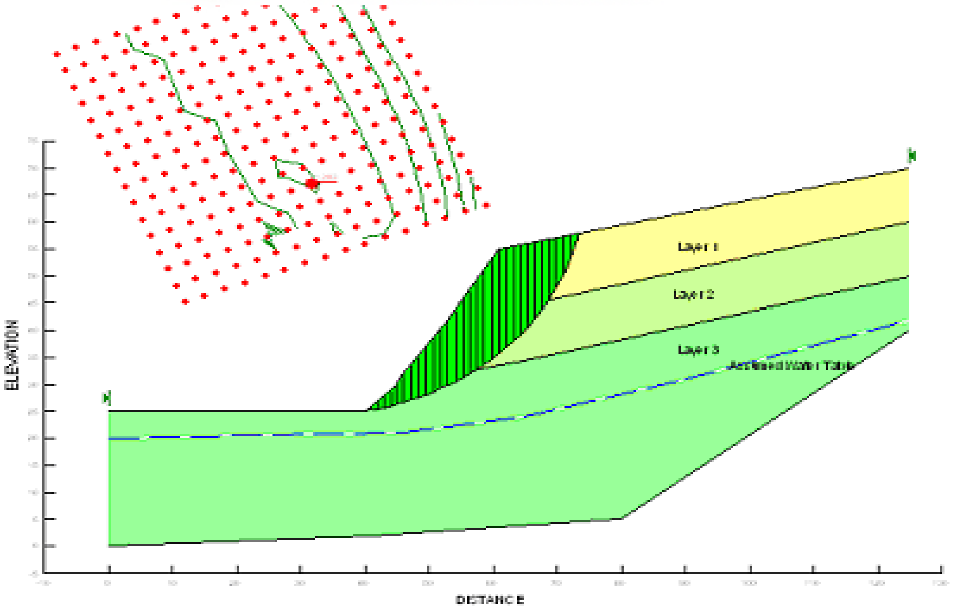

Figure 4.14- 55^{o} cut slope considering the soil to be of layers with different soil parameters, with water table at a lower level

CHAPTER 5

CONCLUSIONS

The slope stability analysis carried out using unsaturated soil properties show that the factor of safety of the slope is increased considerably when the water table is lower.

Results obtained from modified Janbu's simplified method for unsaturated soils by using spreadsheets are approximately equal to the factor of safety values given by Slope/w software for 48 and 55 angles of slopes. But when the cut slope angle gets increased to 60 degrees the factor of safety values obtained from spreadsheets are slightly higher. Since the unsaturated analysis is not accommodated specifically by Slope/w software, the cohesion values are replaced with apparent cohesion values. Apparent cohesion values account for the effect of partial saturation which change with the percentage of negative hydrostatic pressure. That can be given as:

$c = c' + (u_a - u_w) \tan \phi^b$

The influence of the matric suction can be considered as an increase of the cohesion of the soil. This procedure makes it unnecessary to reformulate the equation for the factor of safety. The total cohesion is therefore equal to the sum of the effective cohesion, c' and the increase in cohesion due to matric suction.

The analysis shows that increase in shear strength due to matric suction in unsaturated soil can be incorporated in the software available for slope stability analysis by replacing the input cohesion values with apparent cohesion values. The change in the apparent cohesion with location of water table can be incorporated in the analysis by calculating average apparent cohesion values for different zones of the soil body and considering areas with different calculated cohesion values as different layers.

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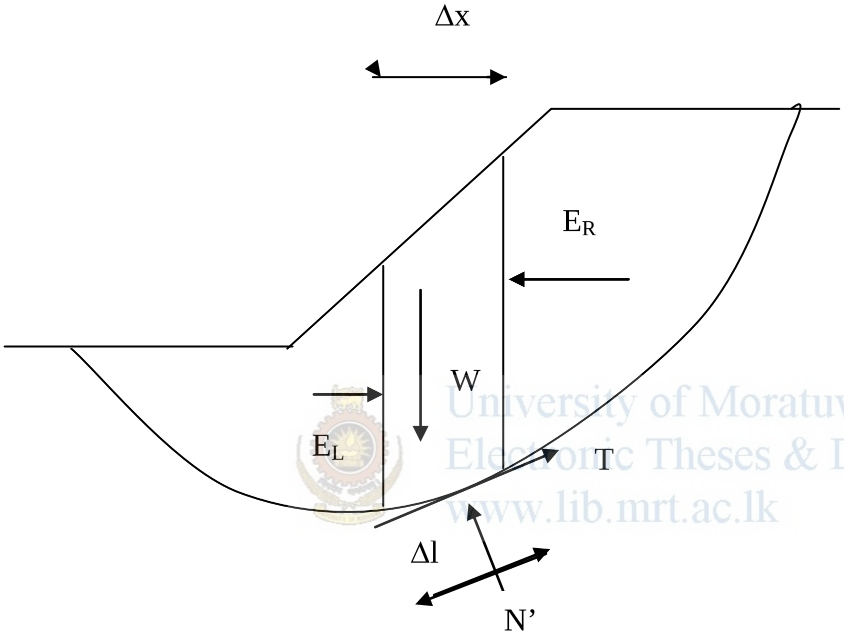
Derivation of the Factor of Safety Equation for Unsaturated Soils

The shear strength function for unsaturated soil can be written as;

$\tau = c' + (\sigma_n - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b$



For the slice shown,

Mobilized shear strength $\tau_m = \tau_f / F$

Where, F is the factor of safety.

$N_i = \sigma \Delta l$

$T_i = 1/F \ \tau_f \ \Delta l = 1/F \ [c' + \Delta l \ (\sigma_n - u_a) \tan \phi' + \Delta l (u_a - u_w) \tan \phi^b$

$T_i = 1/F \ [\mathrm{Sin} \ \theta_i]$---[1]

Resolving vertically,

$N_i \mathrm{Cos} \ \theta_I + T_i \mathrm{Sin} \ \theta_i = W_i - (X_L - X_R)$

Assuming $(X_L-X_R)=0$ (For Janbu's simplified method)

$N_i \, \mathrm{Cos}\, \theta_i + 1/F\, [c'\Delta l + (N_i-u_a\Delta l) \tan \phi' + \Delta l(u_a-u_w)\tan \phi^b\,]\mathrm{Sin}\, \theta_i = W_i$

$N_i \, \mathrm{Cos}\, \theta_i\, [1+1/F \tan \phi' \tan \theta_i] = W_i - \mathrm{Sin}\, \theta_i/F[c'\Delta l - u_a\Delta l \tan \phi' + \Delta l(u_a-u_w)\tan \phi^b]$

If $\mathrm{Cos}\, \theta_i\, [1+1/F \tan \phi' \tan \theta_i] = M_\theta$

$N_i = \{W_i - 1/F[c'\Delta l\, \mathrm{Sin}\, \theta_I - u_a\Delta l \tan \phi'\, \mathrm{Sin}\, \theta_I + \Delta l(u_a-u_w)\tan \phi^b\, \mathrm{Sin}\, \theta_I]\}/ M_\theta$ —————————— [2]

Resolving parallel to the base of the slice,

$T_i + (E_L-E_R)\, \mathrm{Cos}\, \theta_I = [W_i - (X_L-X_R)]\, \mathrm{Sin}\, \theta_I$

Assuming $(X_L-X_R)=0$ and substituting for T_i

$(E_L-E_R)\, \mathrm{Cos}\, \theta_I = W_i\, \mathrm{Sin}\, \theta_I - 1/F\, [c'\Delta l + (N_i-u_a\Delta l) \tan \phi' + \Delta l(u_a-u_w)\tan \phi^b\,]$

$(E_L-E_R) = W_i \tan \theta_I - 1/F\, [c'\Delta l + (N_i-u_a\Delta l) \tan \phi' + \Delta l(u_a-u_w)\tan \phi^b\,]\mathrm{Sec}\, \theta_I$------------------- [3]

In the absence of surface loading,

$\Sigma\, (E_L-E_R) = 0$ --- [4]

$\Sigma\, (E_L-E_R) = \Sigma\, W_i \tan \theta_I - 1/F\, [c'\Delta l + (N_i-u_a\Delta l) \tan \phi' + \Delta l(u_a-u_w)\tan \phi^b\,]\mathrm{Sec}\, \theta_I = 0$ ---------[5]

$$\therefore F_0 = \frac{\sum[\, c'\Delta l + (N_i - u_a \Delta l)\tan\phi' + (u_a - u_w)\Delta l \tan\phi^b\,]Sec\theta_i}{\sum W \tan\theta_i}$$ --------------------------------- [6]

$N_i = \{W_i - 1/F[c'\Delta l\, \mathrm{Sin}\, \theta_i - u_a\Delta l \tan \phi'\, \mathrm{Sin}\, \theta_i + \Delta l(u_a-u_w)\tan \phi^b\, \mathrm{Sin}\, \theta_i]\}/ M_\theta$ —————————— [2]

Substituting for N_i in [6]

$$c'\Delta l + (N_i - u_a\Delta l)\tan\phi' + (u_a - u_w)\Delta l\tan\phi^b$$
$$= c'\Delta l_i + [\{W_i - \frac{Sin\theta}{F}(c'\Delta l Sin\theta - u_a\Delta l\tan\phi' Sin\theta + (u_a - u_w)\Delta l\tan\phi^b Sin\theta\}\frac{1}{M_\theta} - u_a\Delta l]\tan\phi'$$
$$+ (u_a - u_w)\Delta l\tan\phi^b$$

$$c'\Delta l + (N_i - u_a\Delta l)\tan\phi' + (u_a - u_w)\Delta l\tan\phi^b$$
$$= c'\Delta l_i + [\{W_i - \frac{1}{F_f}(c'\Delta l - u_a\Delta l\tan\phi' + (u_a - u_w)\Delta l\tan\phi^b)Sin\theta\}\frac{1}{M_\theta} - u_a\Delta l]\tan\phi' + (u_a - u_w)\Delta l\tan\phi^b$$

$$c'\Delta l + (N_i - u_a\Delta l)\tan\phi' + (u_a - u_w)\Delta l\tan\phi^b$$
$$= c'\Delta l_i - \frac{c'\Delta l_i Sin\theta_i\tan\phi'}{F_f M_i(\theta)} + \frac{W_i\tan\phi'}{M_i(\theta)} - \{u_a\Delta l - \frac{u_a\Delta l\tan\phi' Sin\theta_i}{F_f M_i(\theta)}\}\tan\phi' + (u_a - u_w)\Delta l\tan\phi^b$$
$$- \frac{(u_a - u_w)\Delta l\tan\phi^b Sin\theta\tan\phi'}{F_f M\ (\theta)} \text{-------------------------------------}[6](a)$$

Consider

$$c'\Delta l_i - \frac{c'\Delta l_i Sin\theta_i\tan\phi'}{F_f M_i(\theta)} = c'\Delta x_i[\frac{1}{Cos\theta_i}\frac{\tan\theta_i\tan\phi'}{F_f M_i(\theta)}] \text{-------------------------}[6](b)$$

By definition,

$$M_i(\theta) = Cos\theta[1 + \frac{\tan\theta_i\tan\phi'}{F_f}]$$

$$\frac{M_i(\theta)}{Cos\theta} = [1 + \frac{\tan\theta_i\tan\phi'}{F_f}]$$

$$\frac{M_i(\theta)}{Cos\theta} - 1 = \frac{\tan\theta_i\tan\phi'}{F_f}$$

$$\therefore \frac{1}{F_f}\frac{\tan\theta_i\tan\phi'}{M_i(\theta)} = \frac{1}{Cos\theta} - \frac{1}{M_i(\theta)} \text{-------------------------------------}[6](c)$$

Substituting this in [6] (b)

$$c'\Delta l_i - \frac{c'\Delta l_i Sin\theta_i\tan\phi'}{F_f M_i(\theta)} = c'\Delta x_i[\frac{1}{Cos\theta_i} - (\frac{1}{Cos\theta_i} - \frac{1}{M_i(\theta)})]$$

$$c'\Delta l_i - \frac{c'\Delta l_i Sin\theta_i \tan\phi'}{F_f M_i(\theta)} = \frac{c'\Delta x_i}{M_i(\theta)} ---------------------------------------[6](d)$$

Similarly in [6] (a),

$$[(u_a - u_w)\Delta l_i - \frac{(u_a - u_w)\Delta l \tan\phi' Sin\theta_i]\tan\phi^b}{F_f M_i(\theta)} = \frac{(u_a - u_w)\Delta x_i \tan\phi^b}{M_i(\theta)} -------------[6](e)$$

Substituting [6](d) and [6](e) in [6](a),

$$\mathrm{c'}\,\Delta \mathrm{l_i} + (\mathrm{N_i} - u_a\Delta l)\tan\phi' + (u_a - u_w)\Delta l \tan\phi^b = \frac{c'\Delta l_i}{M_i(\theta)} - \frac{W_i \tan\phi'^b}{M_i(\theta)} + \frac{(u_a - u_w)\Delta x_i \tan\phi^b}{M\ \ (\theta)} - \frac{u_a\Delta x_i}{M_i(\theta)}$$

By substituting the above result in [6]

$$F_0 = \frac{\sum[\{\mathrm{c'}\text{-}u_a + (u_a - u_w)\tan\phi^b\}\Delta x_i + W_i \tan\phi']\frac{1}{Cos\theta_i}\frac{1}{M_i(\theta)}}{\sum\{W \tan\theta_i\}}$$

$$F_0 = \frac{\sum[\{\mathrm{c'}\text{-}u_a \tan\phi' + (u_a - u_w)\tan\phi^b\}\Delta x_i + W_i \tan\phi']\frac{1}{n\ (\ \theta_i)}}{\sum\{W_i \tan\theta_i\}}$$

$$F_0 = \frac{\sum[\{\mathrm{c'}\Delta x_i + (\mathrm{w_i}\ \text{-}\ u_a\Delta x_i)\tan\phi' + (u_a - u_w)\Delta x_i \tan\phi^b\}/n_\theta}{\sum\{W_i \tan\theta_i\}}$$

Where, $n_\theta = Cos^2\theta(1 + \frac{\tan\theta\tan\phi'}{F})$

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