ASSESSMENT OF SLOPE STABILITY AND STABILIZATION TECHNIQUES THROUGH PROBABILISTIC APPROACH

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ABSTRACT

Uncertainty and randomness of data is a major issue associated in geotechnical engineering. It is therefore desirable to use methods and concepts in engineering planning and design that can facilitate the evaluation and analysis of uncertainty. Formal probabilistic approach provides a useful framework to incorporate these uncertainties in slope instability problems. Under the research described in this thesis, number of probabilistic models have been developed to evaluate the stability of slopes and their use in the evaluation of stability of slopes and the evaluation of effectiveness of various stabilization techniques have been discussed.

Two probabilistic analytical models that can be used to evaluate the stability of slopes that can fail either along circular failure surfaces or non-circular failure surfaces have been developed. These models formally recognize the uncertainties associated with various geotechnical parameters and provide means to quantify their effects on the stability. The result is given in the form of probability of unsatisfactory performance of the slope. Each model developed was facilitated to perform computations in five different ways ranging from theoretically sound methods to some approximate methods, and the results obtained were compared with each other. In addition, the results were compared with the results obtained by a commercial software, wherever applicable. In addition, two other probabilistic analytical models were developed to analyze the slopes stabilized by soil nailing.

It is seen that the behavior of the probabilistic models developed under this research perform satisfactorily, and it can be recommended to use these models in routine problems of slope instability to provide more realistic results incorporating the uncertainties associated with

various geotechnical parameters. Analyses of a number of examples and case histories discuss the uses of the probability of failure in decision making to evaluate the stability of slopes as well as the effectiveness of various stabilization techniques. It also emphasizes the importance of the appropriate failure mechanism and the appropriate deterministic model in the probabilistic analysis. Analysis of case histories provides an important discussion showing the inadequacy of the conventional factor of safety alone in evaluating the stability of slopes.

DECLARATION

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

23/08/2002

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UOM Verified Signature

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LIST OF SYMBOLS

$\overline{F}$	- Mean Factor of Safety
$\bar{x}_i$	- Mean Value of "i"th Random Variable
α	- Angle of the Nail to the Horizontal
ϕ	- Angle of Internal Friction
γ	- Bulk Density
σ	- Standard Deviation
β	- Reliability Index
ϕ'	- Effective Angle of Internal Friction
$\sigma_{\phi'}$	- Standard Deviation of Effective Angle of Internal Friction
$\sigma_{c'}$	- Standard Deviation of Effective Cohesion
σ_F	- Standard Deviation of Factor of Safety
σ_{F0}	- Standard Deviation of Uncorrected Factor of Safety
θ_i	- Slice Angle of "i"th Slice
β_{LN}	- Lognormal Reliability Index
ϕ_u	- Undrained Angle of Internal Friction
σ_u	- Standard Deviation of Pore Pressure
δ_{xi}	- Small Increment applicable ti "i"th Random Variable
σ_{xi}	- Standard Deviation of "i"th Random Variable
Δx_i	- Width of "i"th Slice
c	- Cohesion
c'	- Effective Cohesion
COV	- Coefficient of Variation
COV (F)	- Coefficient of Variation of Factor of Safety
COV(ϕ)	- Coefficient of Variation of Angle of Internal Friction
COV(c)	- Coefficient of Variation of Cohesion
COV(u)	- Coefficient of Variation of Pore Pressure
c_u	- Undrained Cohesion
d	- Diameter of a Nail
$E_{L,i}$	- Side Normal Force acting on "i"th Slice (Left Boundary)
$E_{R,i}$	- Side Normal Force acting on "i"th Slice (Right Boundary)
F	- Factor of Safety
F_0	- Uncorrected Factor of Safety for Janbu's Simplified Method
f_0	- Janbu's Correction Factor for Factor of Safety
f_b	- Bond Coefficient
f_y	- Yield Strength of Nail Material

HCV - Highest Conceivable Value

h_i - Average Height of the "i"th Slice

l - Effective Length of a Nail

LCV - Lowest Conceivable Value

n - Total number of Nails passing through a particular Slice

N - Total number of samples

N_i' - Effective Normal Force on "i"th Slice

P_f - Probability of Failure

$P_f(LN)$ - Probability of Failure assuming Lognormal Distribution for FOS

$P_f(N)$ - Probability of Failure assuming Normal Distribution for FOS

Q_i - Surcharge acting on "i"th Slice

SM - Safety Margin

$T_{m,i}$ - Shear Force acting along the Failure Surface on the "i"th Slicce

T_N - Force Mobilized in Nails

$T_{N,i}$ - Nail Force acting on the "i"th Slice

U_i - Pore Pressure Force on "i"th Slice

u_i - Pore Pressure acting on "i"th Slice

V_F - Variance of Factor of Safety

W_i - Weight of "i"th Slice

x_i - "i" th random variable

Note:

Symbols used in the flowcharts are described in the same flowcharts

Chapter 1

INTRODUCTION

1.1 Introduction

Uncertainty and randomness of data is a major issue associated in geotechnical engineering. In many occasions, data are incomplete, yet decisions have to be made. It is therefore desirable to use methods and concepts in engineering planning and design that can facilitate the evaluation and analysis of uncertainty. Statistics and probability provides an important tool to handle these situations, and currently, the role of statistics had been extended to cover many aspects of engineering, which were earlier based entirely on deterministic concepts and judgment.

Probability theory can be used for a systematic and logical analysis of problems considering significant uncertainties. The probabilistic analysis may, however, be made on the basis of a conventional (deterministic) model in which attention is given to randomness or uncertainties of the significant parameters. Probability theory provides a solid framework for assessment of risk and for decision-making under uncertainty.

In spite of it's potential value, probabilistic approach has not been much used in routine geotechnical practice as it is commonly perceived that it would require more data, time and effort than that are available in most circumstances.

1.2 Deterministic vs. Probabilistic Approaches

1.2.1 Deterministic Approach

Traditionally, all the engineering problems were solved based on deterministic concepts, where, there is a unique solution to a particular set of parameters. No particular attention is given to the uncertainties associated with the input parameters.

The parameter used in conventional geotechnical engineering is the "Factor of Safety", and there are many ways in which this can be defined when applicable to various aspects of geotechnical engineering. According to the common accepted definition in the evaluation of the stability of slopes, the factor of safety is the ratio of the shear strength to the shear stress mobilized for equilibrium.

When there is an uncertainty involved in the parameters, most widely used approach is to perform a "sensitivity analysis" or a "parametric study", in which different sets of parameters are used as inputs to find the influence on factor of safety. However, this cannot be considered as an explicit way of considering uncertainty formally.

Chowdhury (1992) commented that "factor of safety" can be referred to as "factor of ignorance", because it is a number arrived at without giving due consideration to the various uncertainties associated with it.

1.2.2 Probabilistic Approach

This is based on the concept that many or varied outcomes of a situation are possible, and the uncertainty is recognized formally. The aim of the probabilistic approach is to determine the probability of an outcome, which is the failure of the slope in our discussion. The term failure here does not only mean the catastrophic failure, but the "unsatisfactory performance", which can either be the catastrophic failure or some occurrence of significant movements. Therefore the probability of failure quantifies the probability where an unsatisfactory performance of the geotechnical structure may occur. This probability can be any percentage between 0% and 100%. The converse of the probability of failure is the probability of success, and it is also defined in probabilistic terms as the "Reliability" of the structure. Hence:

Reliability = 1 – Probability of Failure .... (1.1)

Generally, the probability of failure or reliability is estimated based on a suitable deterministic model. There are two ways of defining the probability of failure. One approach is to define it based on the "Factor of Safety", and the accepted definition is probability that the factor of safety being less than one. i.e.:

$$P_f = P(F < 1) \text{ ....(1.2)}$$

Other approach of defining the probability of failure is based on the safety margin, which is the difference between the resisting forces and disturbing forces. Then, the probability of failure is the probability of safety margin being less than zero. i.e.:

$$P_f = P(SM < 0) \text{ ....(1.3)}$$

1.3 Current State of the Art of Probabilistic Evaluation of Slope Stability

1.3.1 Introduction

Over the past two decades, probabilistic approach has created a remarkable interest amongst researchers worldwide. The interest has further increased within the last 10 years and number of publications can be found describing the use of probabilistic approach in geotechnical engineering.

As far back in 1983, Lee et. al. have discussed the effects of soil variability in geotechnical engineering. They discussed the reasons for the uncertainties associated and propose methods to quantify uncertainty.

Then Kulhawy (1992) presented a strategy for evaluation of soil properties considering various uncertainties associated with them. According to him, his approach is built on the practices existed at that time and it purports to achieve a more rational, reliability based procedure in future.

In 1994, Christian et.al. came up with methods of deriving probabilistic descriptions of soil parameters from field and laboratory test data and applying them in stability analysis. They incorporate the First Order Second Moment method in the design of a dam and illustrated the relative contributions of uncertainties of different parameters to the reliability of an embankment, through an example. Thereafter a relative simple example has presented regarding probabilistic assessment for a landslide by Chowdhury and Flentje (1998).

In addition, number of authors including Chowdhury and Flentje (1998), Flentje and Chowdhury (1999), AGS (2000) and Ho et.al. (2000) have discussed the possibilities and the importance of using the probabilistic analysis in landslide risk assessment. Yet the application of probabilistic approach in practice is very slow, hence, Duncan (2000) has published a paper reiterating the merits of reliability approach in geotechnical engineering. In his paper he has proposed some simple models to evaluate the probability of failure and also some proposals for the use of reliability methods without using a large amount of data.

In the following sections, the basic concepts applicable to the development of probabilistic analytical models are presented.

1.3.2 Uncertainties of Geotechnical Parameters

1.3.2.1 Types of Uncertainties

According to Chowdhury and Flentje (2001), in most cases of slope stability analysis, uncertainty is associated with (a) geotechnical parameters, and (b) geotechnical models. The range and importance of different uncertainties depend on the size and importance of the project as well as on the scope and quality of geotechnical investigation and testing.

One major source of uncertainty concerns the spatial variability of geotechnical parameters. Even a comprehensive geotechnical investigation cannot reveal these uncertainties unless it is done at a prohibitive cost. Another source of uncertainty is the temporal variability of important parameters such as pore water pressure within a slope at different locations or depths and especially along a potential slip surface. In addition, systematic uncertainties, which are a consequence of limited number of ground investigation boreholes, a limited number of shear strength and other geotechnical tests and the fact that no measurement is perfect are added.

Modeling uncertainties may relate to minor geological details and to the assumptions inherent in concepts such as limit equilibrium.

1.3.2.2 Methods of Quantification of Uncertainty

An essential component in the probabilistic approach is the quantifications of uncertainty, by means of either the standard deviation or the coefficient of variation. Duncan(2000) proposes four methods that can be used in this respect, viz.:

1. Computation from data
2. Use of published values
3. "Three-Sigma Rule", and,
4. Graphical Three-Sigma Rule.

If sufficient data are available, the definition of standard deviation can be used directly to calculate its value as:

$$\sigma = \sqrt{\frac{\Sigma[(x_i - \bar{x})^2]}{N-1}} \quad \text{................(1.4)}$$

An approach that can be used to estimate the values of standard deviations when sufficient data are not available is to use estimates based on published values, which are most conveniently expressed in terms of coefficient of variation. Duncan (2000) paper itself presents coefficient of variation values for number of geotechnical engineering parameters. In addition, it lists a number of publications from where one can get those parameters including Harr (1984), Kulhawy (1992) and Lacasse and Nadim (1997). In addition author find another set of coefficient of variation values in Lee et. al. (1983). However Christian and Baecher (2001) warn against the use of published values by suggesting that many of the published values of variances in geotechnical properties are too large.

In the "Three-Sigma Rule" proposed by Duncan (2000), he uses the fact that 99.73% of all values of a normally distributed parameter fall within three standard deviations from the average. Hence, the value is given as:

$$\sigma = \frac{HCV - LCV}{6} \quad \text{..............(1.5)}$$

But after the discussion given by Christian and Baecher (2001), Duncan (2001) proposed that "Two-Sigma Rule" would be an improvement on the "Three-Sigma Rule" and the corresponding equation is given as:

$$\sigma = \frac{HCV - LCV}{4} \quad \text{..............(1.6)}$$

The same concept has extended to a graphical representation, to be applicable to many situations in geotechnical engineering, especially where the parameter of interest varies with depth. Some examples are presented in Duncan (2000).

1.3.3 Application of Probabilistic Concepts to Slope Stability Analysis

1.3.3.1 Suitable Probability Distributions

The probabilistic approach involves considering the Factor of Safety, F as a random variable. Therefore, one has to assume a suitable distribution for F. The candidates for a suitable distribution are:

1. Normal Distribution, and,
2. Lognormal Distribution

The normal distribution is the most widely used probability distribution in engineering, and it has a probability density function as shown in figure 1.1.

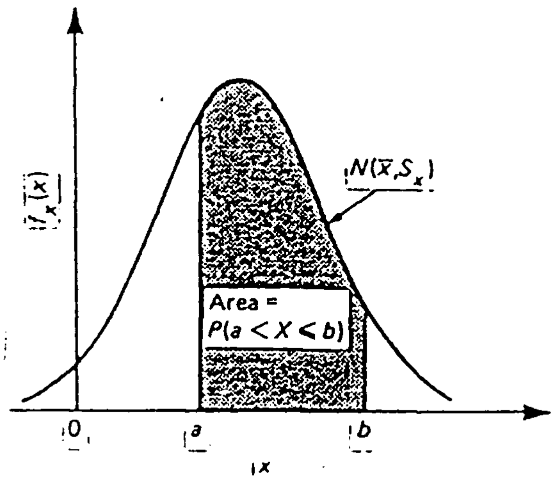


Figure 1.1: Normal Distribution

Lee et. al. (1983) proposed that when the number of additive variables in the uncertainty becomes large, the distribution of their sum approach the normal distribution, and for the same reason they proposed that the normal distribution is suitable for the factor of safety. When the normal distribution is assumed for factor of safety, the reliability index is given as:

$$\beta = \frac{\overline{F} - 1}{\sigma_F} \quad \text{..............(1.7)}$$

Using this reliability index, the reliability or the probability of failure can be directly estimated using published standard normal distribution tables. The graphical representation of reliability and probability of failure is given in figure 1.2.

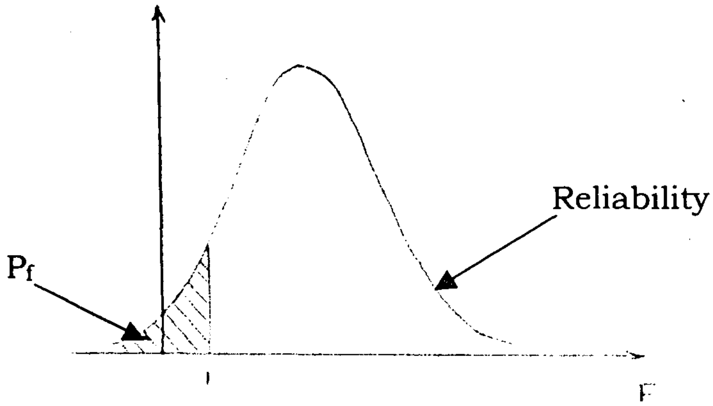


Figure 1.2: Graphical Representation of Reliability and Probability of Failure

Lognormal distribution results when the natural logarithm of a parameter is normally distributed. The graphical representation of the probability density function for lognormal distribution is given in figure 1.3.

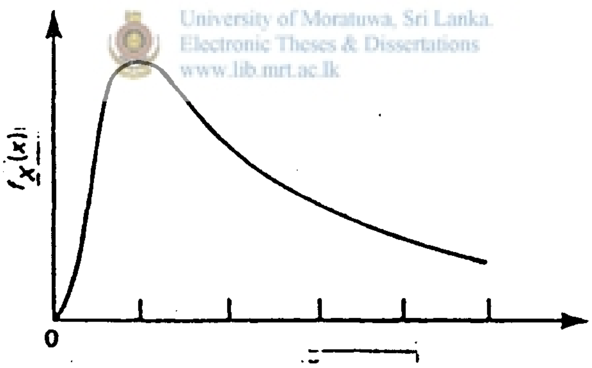


Figure 1.3: Lognormal distribution

When the factor of safety is assumed to have a lognormal distribution, the definition of reliability index is given by (Duncan, 2000):

$$\beta_{LN} = \frac{\ln\left(\frac{\overline{F}}{\sqrt{1+\mathrm{cov}(F)^2}}\right)}{\sqrt{\ln\{1+\mathrm{cov}(F)^2\}}} \quad \text{...............(1.8)}$$

This reliability index can also be used in standard normal distribution tables to estimate the reliability or the probability of failure.

Some researchers prefer lognormal distribution to be the most suitable for Factor of Safety due to various reasons. Lee et. al. (1983) reported that this distribution results from variables in the uncertainty being multiplicative instead of additive. Chowdhury (1992) reported that lognormal distribution is the preferred distribution for a random variable, which must have a positive value. Therefore he recommends the use of lognormal distribution for FOS, which, by definition, should have a positive value. Duncan (2000) reported that there is no proof to say that the FOS is lognormally distributed, but he believes it as a reasonable approximation. But in a discussion to Duncan (2000) paper, Christian and Baecher (2001) gave reasons for the preference of lognormal distribution as:

1. it avoids negative values, and
2. the equation has many multiplications and divisions.

However, they have counter argued saying that the equation also has number of additions and subtractions. Hence, in the absence of any other information they indicated their preference for the normal distribution assumption. After their views, Duncan (2001) has concluded the discussion by suggesting that it may be useful to compute probability of failure using both normal and lognormal distributions.

1.3.3.2 Different Approaches of Probabilistic Analysis

Two approaches available for probabilistic analysis can be listed as:

1. First Order Second Moment method (FOSM), and
2. Monte-Carlo simulation method

In addition Christian and Baecher (2001) has indicated their preference on some other methods, viz., Hasofer and Lind (1974) approach and Point estimate method (Rosenblueth, 1975), but they are not discussed in this thesis.

First Order Second Moment method

The basic properties associated with a function of several random variables are considered in quantification of factor of safety, since FOS itself is a function of several random variables.

If $F = f(x_1, x_2, ..., x_n)$, where $x_1, x_2, ..., x_n$ are uncorrelated and statistically independent random variables, then mean value of F and the variance V_F are calculated as;

$$\overline{F} = f(\overline{x}_1, \overline{x}_2, ..., \overline{x}_n) ....(1.9)$$

$$V_F = \sum_{i=1}^{n} \left(\frac{\partial F}{\partial x_i} \right)^2 \cdot V_{x_i} ......(1.10)$$

[Chowdhury (1992), Christian et.al. (1994), Smith (1986)].

Since this is the first order approximation of Taylor series expansion and since it involve second moment (i.e. variance) of FOS, this method is called the "First Order Second Moment (FOSM)" method.

As that can be seen, FOSM method involves computation of partial derivatives of F, and hence many people would feel that it is a tedious process. Hence, Duncan (2000) suggests an approximate solution that can be used to evaluate those partial derivatives. Here, Duncan assumes;

$$\frac{\partial F}{\partial x_i} \approx \frac{F(x_i + \sigma_{x_i}) - F(x_i - \sigma_{x_i})}{2 \cdot \sigma_{x_i}} = \frac{\Delta F_i}{2 \cdot \sigma_{x_i}} \quad \text{.............(1.11)}$$

where x_i represent different parameters that carry uncertainty.

After substituting in equation (1.10) Duncan's equation for variance is given as;

$$V_F = \left(\frac{\Delta F_1}{2}\right)^2 + \left(\frac{\Delta F_2}{2}\right)^2 + \ldots.. + \left(\frac{\Delta F_n}{2}\right)^2 \quad \text{......(1.12)}$$

Monte-Carlo Simulation Approach

This is another well-known approach used in probabilistic analysis. In this approach, a particular problem is analyzed using a selected deterministic model, for a large number of times by changing the geotechnical parameters over a wide range, which is determined by the standard deviations of the parameters. The resulting factor of safety values are used to establish the probability distribution of factor of safety. Probability of failure is then calculated using the p.d.f. of F.

SLOPE/W computer program (Geo Slope Office, 1998) is capable of performing Monte Carlo analysis and a brief description of the way it perform Monte Carlo analysis is given in annex 2.

1.3.4 Role of Probabilistic Analysis in Landslide Risk Assessment

With the large amount of uncertainties associated it is very difficult to accurately predict the performance of slopes. The method adopted in conventional geotechnical engineering to tackle these uncertainties is to adopt a higher factor of safety. However, because of the cost involved, it is difficult to justify a higher design safety factor even for a case where consequences of failure are quite disastrous. In addition, over designing mitigates against achieving an elegant solution. Hence, there needs to be a balance between the degree of over-convertism and the uncertainties it is to cover. A good example in this regard has been given by Ho et.al. (2000). According to them, over-convertism in the assessment of natural hillsides could prohibit new developments result in loss of land value or raise serious question about whether actions should be taken to reduce the risk posed to existing developments. On the other hand, lack of recognition of significant hazards posed by natural hillsides could result in dire consequences. Hence, alternative or supplementary approaches to conventional assessment techniques may be called for, at least in certain situations and the integrated risk management approach is one possibility.

Risk management comprises of 3 parts:

1. Estimation of the level of risk (Risk Assessment)
2. Deciding whether or not it is tolerable
3. Exercising appropriate control measures to reduce the risk where the risk level cannot be tolerated.

Risk assessment may be performed qualitatively, semi-quantitatively or quantitatively. Qualitative risk assessment has to be carried out by experienced professionals on the basis of available information and site inspections, and risk may be categorized as “very high”, “high”, “medium”, “low” and “very low”. In semi-quantitative risk assessment, each of the number of factors affecting slope stability is considered explicitly and a range of scores and settings for each factor may be used to assess the extent to which that factor is favorable or unfavorable to (a) the occurrence of instability and (b) the occurrence of loss or damage consequent to failure. Quantitative risk assessment requires identification and quantitative evaluation of the factors contributing to risk.

Quantitative risk assessment has been discussed in length recently by AGS (2000) and Ho et.al. (2000). In terms of conditional probability, the risk to a given individual may be defined as follows (Morgan et. al., 1992):

$$R\ (IN) = P(H)*P(S/H)*P(T/S)*V(L/T) \quad \ldots\ldots\ldots\ldots\ (1.13)$$

where,

R(IN) = Risk to an individual (i.e. annual probability of loss of life)

P(H) = Annual probability of the hazard occurring (e.g. landslide)

P(S/H) = Probability of the spatial impact (e.g. landslide impacting a building)

P(T/S) = Probability of temporal impact (e.g. presence of people at time of landslide impact)

V(L/T) = Vulnerability of individual given landslide impact (e.g. probability of loss of life)

Similarly, probability of damage or loss to a property can be defined (Chowdhury and Flentje, 2001).

From the above it is obvious that the assessment of hazard is a very important part of landslide risk assessment. It represents the frequency of landslide occurrence, which includes the probability of failure. In the paper sited earlier (AGS, 2000) a number of approaches are mentioned as possible alternatives, including application of formal probabilistic models, to estimate probability of landsliding. But Chowdhury (2001) in his paper discusses problems associated with many of those alternatives and highlights the importance of the use of formal probabilistic approaches in landslide hazard assessment. In this case, formal probability value can be taken as an indication of susceptibility to failure (conditional upon the assumed values of key parameters) and it can be multiplied by the conditional probabilities of the key parameters, which reflect the frequency of triggering event or agent. A relatively simple example of this approach for a landslide has been given by Chowdhury and Flentje (1999).

1.3.5 Role of Probabilistic Analysis as a tool in Decision Making

Chowdhury and Flentje (2001) have also highlighted the need to use the reliability index and the probability of failure (without considering the temporal frequency discussed in section 1.3.4) in the safety assessment of slopes in preference to the conventional factor of safety. In their paper they compared the variation of factor of safety, reliability index and the probability of failure in the presence of the same coefficient of variation of factor of safety for three different slopes (table 1.1).

F, mean	cov (F)	Reliability Index, β	Probability of Failure, P_f
1.1	0.1	0.91	$18.14 * 10^{-2}$
1.2	0.1	1.67	$4.74 * 10^{-2}$
1.4	0.1	2.86	$2.12 * 10^{-5}$

Table 1.1: Reliability Index and Probability of Failure values for Slope (Constant COV) (Chowdhury and Flentje, 2001)

According to table 1.1, reliability index changes by a factor 3, and the probability of failure changes by five orders of magnitude. But it is certain that this huge change is not revealed from factor of safety varying from 1.1 to 1.4. These probability of failure values correspond to a normal distribution of factor of safety. From this example Chowdhury and Flentje (2001) highlighted the fact that the implication of factor of safety values are not clear until one steps out from the deterministic framework to incorporate variability.

To explain this further, another example is presented. There, the coefficient of variation that should be present to give same proportion of change to both reliability index and the factor of safety have been computed. The required coefficients of variation are 8.26%, 13.88% and 20.41% respectively. The results are given in tabular form below:

β	F, mean	cov (F)
1.1	1.1	8.26%
1.2	1.2	13.66%
1.4	1.4	20.41%

Table 1.2: Coefficient of Variation of F (to have constant proportion between β and F) (Chowdhury and Flentje, 2001)

From these data, it is clear how the use of probabilistic approach improves the assessment of slope performance.

In addition, Chowdhury and Flentje (2001) have suggested values for probability of failure of natural slopes and they are reproduced below:

Slope type and location	Potential failure mode	Potential consequences	Minimum reliability index	Maximum failure probability
Wooded/forested slopes, moderate to steep inclination, colluvium or residual soil cover	Shallow sliding, limited movement or just slope deformation without overall failure	No elements at risk, no potential for debris flow formation	1	0.15 (15%) (15×10^{-2})
Slopes of low to moderate inclination in which high pore water pressures can develop, forested or cleared sloping areas	Slow-moving slides, shallow to deep-seated, relatively flat slip surfaces	No potential for catastrophic failure without warning signs. Progressive action during successive rainstorms may induce complete failure over time; no elements at risk	1.5	0.05 (5%) (5×10^{-2})
Relatively steep slopes with high relief in forested or cleared areas, slopes near natural gullies, colluvium or residual soil cover	Shallow sliding with rapid movement and potential for large travel distances	Significant potential for debris flow formation during intense storms, considerable travel distance; elements at low to moderate risk of damage	2	0.01 (1%) (1×10^{-2})
Slopes in which high pore pressure can develop; near urbanised areas	Sliding with rapid movement, shallow to deep slip surfaces with relatively steep inclination	Elements at moderate to high risk of damage or destruction from landsliding	2.5	0.005 (0.5%) (5×10^{-3})
Slopes in which high pore pressures can develop; very close to properties in urbanised areas	Sliding with rapid movement Shallow to deep slip surfaces with relatively steep inclination	Elements at high to very high risk of destruction from landsliding	3	0.001 (0.1%) (1×10^{-3})

Table 1.3: Acceptable Values of Probability of Failure for Natural Slopes (Chowdhury and Flentje, 2001)

1.4 Scope of the Project

The research was aimed at the development of analytical models to perform probabilistic slope stability analysis. It had to consider two different methods to cover circular failure surfaces and non-circular failure surfaces that would be applicable to many Sri Lankan slopes consist of residual soils. Hence the developed models are based on:

1. Bishop's simplified method, and,
2. Janbu's simplified method

Analytical models use the "First Order Second Moment" method to perform probabilistic analysis and five different approaches were considered to compute the partial derivatives associated with each of the above models. These models range from some exact theoretical methods to some approximate methods. The purpose of considering five different methods was to compare the performance of each of them and to find the best method.

In addition, probabilistic models were developed to analyse slopes stabilized by soil nailing. Again two models were developed to cover Bishop's simplified method and Janbu's simplified method.

Thereafter probabilistic slope stability analyses were performed on some hypothetical problems as well as some actual slope problems with the aim to validate the models as well as to discuss the effectiveness of various stabilization techniques in probabilistic terms to illustrate the possibility of using it in the decision making.

1.5 Outline of the Thesis

This thesis provides analytical models to perform probabilistic slope stability analysis for both circular and non-circular failure surfaces and for both normal slopes as well as for slopes stabilized by soil nailing. The thesis is divided in to four parts as follows:

Part	Chapter
• Probabilistic analytical models for normal slopes	3 and 4
• Probabilistic analytical models for slopes stabilized by soil nailing	5
• Application of probabilistic analysis to natural slopes	6
• Application of probabilistic analysis to cut slopes	7

Chapter 1 provides the general introduction, the literature review and the basic concepts associated with the probabilistic analysis in geotechnical engineering. It addresses the techniques available to incorporate the uncertainty formally, and also the methods available to quantify the variability of the parameters. Then, the attention is paid to the need for probabilistic approach in risk assessment and decision-making.

Chapter 2 discusses the background behind the selection of appropriate deterministic models and the uncertainties for the development of probabilistic models.

Chapter 3 and 4 present the probabilistic models based on Bishop's simplified method and Janbu's simplified method respectively. These chapters present the developed equations and the configurations of the spreadsheets associated with each method of computations. They also discuss results obtained after applying the probabilistic analyses to two hypothetical problems each.

Chapter 5 presents the models to analyze slopes stabilized by soil nailing. In addition it discusses the effectiveness of two stabilization techniques viz., drainage and soil nailing with respect to some hypothetical problems.

Chapter 6 applies the probabilistic analysis to natural slopes, viz. stabilized Watawala landslide and the Marangahawela slope, which has shown the signs of instability very recently. For the Marangahawela slope stabilization work is still under progress.

Chapter 7 discusses the possible use of probabilistic slope stability analysis with respect to some man-made slopes in Rathnapura Municipal Council area.

Chapter 8 gives the summary and the conclusions based on the findings of the thesis. It also presents some future improvements possible in the study area.

In addition to the main text, some additional information is given in the form of 8 annexes. Annex 1 gives a brief description of the Monte Carlo analysis performed by SLOPE/W computer program. Annex 2 comprises of additional information corresponding to the examples quoted throughout the thesis. Annex 3 provides the chart for f_0 that is used in Janbu's simplified method. Annexes 4 to 7 contain sample worksheets of all the developed models. Annex 8 contains additional details about the Watawala landslide and its rehabilitation.

Chapter 2

DEVELOPMENT OF PROBABILISTIC MODELS

2.1 Selection of a Deterministic Model

The most common approach used in the deterministic analysis of slope stability problems is based on the limit equilibrium concept. Out of the number of different limit equilibrium methods, methods of slices have become most common methods due to their ability to accommodate complex geometries and variable soil and water pressure conditions (Terzaghi and Peck, 1967). Therefore, methods of slices were used as the base for the development of probabilistic models in this research.

During the past fifty years or so, a number of different approaches had been proposed for the use of methods of slices. Each method differ in the (i) statics employed in deriving the factor of safety equation, or (ii) the assumption used to render the problem determinate (Fredlund and Krahn, 1977). Methods that are commonly used to date can be listed as:

(1) Ordinary slices method (or Fellinius method)
(2) Bishop's simplified method
(3) Bishop's rigorous method
(4) Spencer's method
(5) Janbu's simplified method
(6) Janbu's rigorous method, and,
(7) Morgenstern-Price method

Ordinary slices method is the simplest form of all the methods of slices as it is the only procedure that result in a linear equation for factor of safety (Fredlund and Krahn, 1977). But the inherent assumption that interslice forces are parallel to the base of the slice violates Newton's principle of "action equals reaction". The indiscriminate change in direction of the resultant interslice force from one slice to the next results in factor of safety error that may be as much as 60% (Whitman and Bailey, 1967). Further studies made on ordinary slices method have shown that it produces conservative results (Giam, 1989). Therefore, it was decided to rule out the ordinary method of slices from the development of probabilistic models.

Bishop's simplified method (Bishop, 1955), neglects interslice shear forces and produces a factor of safety equation that satisfies moment equilibrium. The method, which can be used to analyze circular failure surfaces, is found to be rather simple and tend to give reasonably accurate results. From a comparison made by Fredlund and Krahn (1977), it is shown that Bishop's simplified method gives very close safety factors as those are given by more rigorous methods.

Janbu's methods can be used to analyze non-circular failure surfaces as well, and it satisfies the force equilibrium. In the rigorous method, values for interslice forces have to be obtained through an iterative process. Janbu's simplified method, proposed for regular use, utilizes a correction factor f_0 to account for the effect of interslice forces.

Other two rigorous methods, viz. Spencer's method and Morgenstern-Price method satisfy both force and moment equilibrium, but involves more complex calculations than the Bishop's or Janbu's methods.

Considering the advantages, disadvantages and relative complexities of each method, Bishop's simplified method and Janbu's simplified method were selected to base the probabilistic models to cover circular and non-circular failure surfaces respectively.

2.2 Assignment of Uncertainties

Slope geometry, layering of different soil strata, their densities and shear strength characteristics and pore water pressures are the parameters used in the evaluation of the stability of a slope. Out of these parameters that can carry uncertainty into the analysis, only soil strength parameters (i.e.: c' and ϕ') and the pore water pressures are considered as probabilistic parameters. Uncertainties in the determination of other parameters are much less and they are considered to be deterministic. Number of publications (Duncan, 2000; Lee et.al., 1983) uses coefficient of variation to quantify the variable nature of soil parameters, hence it is the parameter used in these models as well. For strength parameters, coefficients of variation can be assigned on the basis of soil type and the procedures followed in their evaluation. Hence different coefficient of variation values may be entered.

Much attention has not been paid in literature regarding a suitable parameter to introduce the variable nature of pore water pressures. The only available reference is the method adopted by Geo Slope Office (1998) in developing the SLOPE/W computer program. Geo Slope Office (1998) utilizes a standard deviation of the piezometric head to introduce uncertainty. During Monte Carlo trials, it varies the piezometric line between the maximum and minimum positions (see annex 1 for more details).

However, equations used in this study requires the mean and variance of pore pressure, hence it was planned to introduce the uncertainty in terms of the coefficient of variation of pore water pressure. Two alternatives are considered to introduce the variable nature of the pore pressure. They are:

a) Pore water pressure uncertainty is dependant of the soil type – this allows user to use different coefficient of variation values for different soil layers
b) Pore pressure has a constant coefficient of variation for the entire slope

A conclusion could not be arrived at to select the best out of the above two. When the permeability of soil affects the uncertainty in the measurement of pore water pressures, the approach based on the soil type would be more suitable. It is the understanding of the author that the permeability might be a factor affecting the temporal variability (discussed in 1.3.2.1) of pore pressures at different locations and depths. However, if the permeability does not affect the uncertainties and if only the method of measurement affects it, the method of using a constant coefficient of variation for the whole slope might be suitable.

Chapter 3

DEVELOPMENT OF THE PROBABILISTIC MODEL BASED ON BISHOP'S SIMPLIFIED METHOD

3.1 Basis of the Method

The starting point of the probabilistic models is the deterministic equation of the Bishop's simplified method, and it is given as:

$$F = \frac{\sum \{(c'\Delta x_i + (W_i + Q_i - u_i \Delta x_i)\tan\phi')/M_i(\theta)\}}{\sum (W_i + Q_i)\sin\theta_i} \quad ...(3.1)$$

where,

$$M_i(\theta) = \cos\theta_i + \frac{\sin\theta_i \cdot \tan\phi'}{F} ....(3.2)$$

The terms used in equations 3.1 and 3.2 are illustrated in figure 3.1.

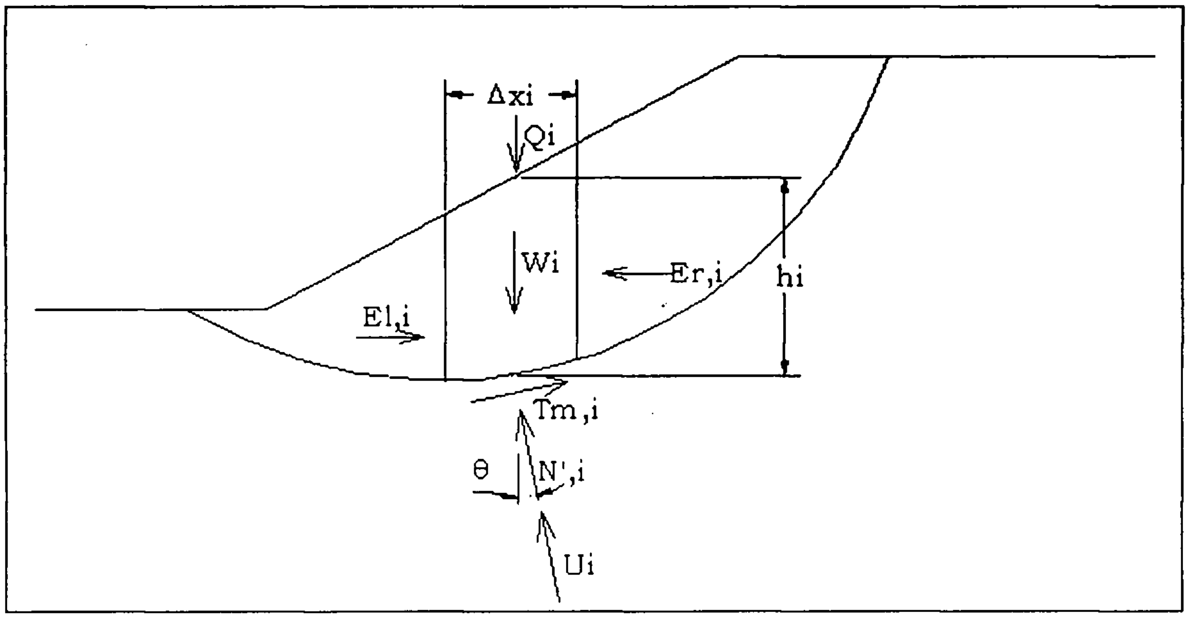


Figure 3.1: Forces acting on a Slice

The inherent assumption to neglect interslice shear forces is applicable to the probabilistic models as well. The limitation to circular failure surface is also applicable.

The first order second moment (FOSM) method is used as the basis of the development process of the probabilistic models. Once the parameters that carry uncertainties are identified, and their uncertainties are quantified, most probable value of factor of safety is calculated using the mean values of the probabilistic parameters along with the other deterministic parameters. The first order approximation of the Taylor series expansion (equation 1.10) is used to calculate variance of the factor of safety. The complete probabilistic model comprises of five different approaches to calculate variance of the factor of safety. They differ from each other in the methods of calculating the partial derivative involved in equation 1.10. The methods are:

(i) Direct differentiation of factor of safety equation assuming $M_i(\theta)$ is a deterministic quantity

(ii) Direct differentiation of factor of safety equation assuming $M_i(\theta)$ is a probabilistic parameter (as a function of angle of internal friction)

(iii) Use of approximation proposed by Duncan (2000)

(iv) Use of an approximate partial derivative assuming any small increment for Δx with central difference formula (finite differences)

(v) Use of an approximate partial derivative assuming any small increment for Δx with forward difference formula (finite differences)

The models developed allow layering of soil up to five different layers with different properties.

3.2 Assignment of Uncertainties

As discussed in section 2.2, soil strength parameters (i.e.: c' and ϕ') and the pore water pressure are treated as probabilistic parameters while all the other parameters are considered deterministic.

Uncertainties of soil strength parameters are assigned on the basis of soil layers. Therefore, for each layer, in addition to the mean values of strength parameters, their coefficients of variation are assigned. Uncertainties of pore water pressures are treated in both approaches as discussed in section 2.2. Therefore, separate spreadsheets were developed for those two cases.

3.3 Derivation of Partial Derivatives

Case 1: Direct Differentiation assuming $M_i(\theta)$ is deterministic

The assumption to treat $M_i(\theta)$ as deterministic is a reasonable simplification, since the values of $M_i(\theta)$ is almost close to 1, except in the outermost slices of a particular deep failure surface.

When the equation 3.1 is differentiated with respect to the selected probabilistic parameters, the following expressions are obtained:

$$\frac{\partial F}{\partial c'} = \frac{\sum \left(\frac{\Delta x_i}{M_i(\theta)} \right)}{\sum W_i \sin\theta_i} \quad \text{........(3.3)}$$

$$\frac{\partial F}{\partial \phi'} = \frac{\sum \left\{ (W_i + Q_i - u_i \Delta x_i) \frac{\sec^2\phi'}{M_i(\theta)} \right\}}{\sum W_i \sin\theta_i} \quad \text{........(3.4)}$$

$$\frac{\partial F}{\partial u} = \frac{\sum \left(\frac{\Delta x_i \tan\phi'}{M_i(\theta)} \right)}{\sum W_i \sin\theta_i} \quad \text{........(3.5)}$$

Case (ii): Direct Differentiation assuming $M_i(\theta)$ is Probabilistic

This assumes $M_i(\theta)$ as a function of angle of internal friction (i.e.: $M_i(\theta) = f(\phi')$). Therefore, only the partial derivative with respect to ϕ' is changed. The resulting expression can be given as:

$$\frac{\partial F}{\partial \phi'} = \frac{\sum \left[\left\{ (W_i + Q_i - u_i \Delta x_i) \frac{\sec^2\phi'}{M_i(\theta)} \right\} - \left\{ (c'\Delta x_i + (W_i + Q_i - u_i \Delta x_i)\tan\phi') \frac{\cos\theta_i \tan\theta_i \sec^2\theta_i}{F \cdot M_i^2(\theta)} \right\} \right]}{\sum W_i \sin\theta_i} \quad \text{..(3.6)}$$

Case (iii): Method proposed by Duncan (2000)

When the partial derivatives are computed according to the method proposed by Duncan (2000), equation 1.12 becomes:

$$V_F = \left(\frac{\Delta F_{c'}}{2}\right)^2 + \left(\frac{\Delta F_{\phi'}}{2}\right)^2 + \left(\frac{\Delta F_u}{2}\right)^2 \quad \text{.......(3.7)}$$

where,

$$\Delta F_{c'} = F(c' + \sigma_{c'}) - F(c' - \sigma_{c'}) \quad \text{............(3.8)}$$

$$\Delta F_{\phi'} = F(\phi' + \sigma_{\phi'}) - F(\phi' - \sigma_{\phi'}) \quad \text{............(3.9)}$$

$$\Delta F_u = F(u + \sigma_u) - F(u - \sigma_u) \quad \text{............(3.10)}$$

<u>Case (iv) and (v):</u> <u>Small Increment Methods</u>

Instead of using σ_x as the increment (in equation 1.11), these methods use much smaller increments (δ_{xi}) to calculate $\frac{\partial F}{\partial x_i}$. Both methods are based on finite difference calculus. One method uses central difference formula, while the other uses forward difference formula. Hence, for case (iv), equation 1.11 takes the form given below:

$$\frac{\partial F}{\partial x_i} \approx \frac{\Delta F_i}{\Delta x_i} = \frac{F(x_i + \delta_{x_i}) - F(x_i - \delta_{x_i})}{2 \cdot \delta_{x_i}} \quad \text{............(3.11)}$$

For case (v), it takes the following form:

$$\frac{\partial F}{\partial x_i} \approx \frac{\Delta F_i}{\Delta x_i} = \frac{F(x_i + \delta_{x_i}) - F(x_i)}{\delta_{x_i}} \quad \text{............(3.12)}$$

The variance of factor of safety is then calculated using equation 1.10.

3.4 Development of the Spreadsheets

Three different spreadsheets were developed with respect to the probabilistic model developed based on Bishop's simplified method. According to the suggestion made by Duncan (2001) (section 1.3.3.1), all the spreadsheets are equipped to compute probability of failure both with normal distribution assumption and lognormal distribution assumption.

First spreadsheet is based on the direct differentiation assuming $M_i(\theta)$ is a deterministic quantity (case (i) in 3.3). Second spreadsheet is based on the direct differentiation assuming $M_i(\theta)$ is probabilistic. The third spreadsheet covers Duncan (2000) approach and other small increment methods. A sample set of spreadsheets is given in annex 4.

Case (i): Spreadsheet for the model based on Bishop's simplified method - direct differentiation assuming $M_i(\theta)$ is deterministic (File Name: *Bishop-Prob-Direct)*

The spreadsheet consists of three worksheets viz, Deterministic Worksheet, Calculations Worksheet and Probabilistic Worksheet.

The "Deterministic" worksheet allows the user to input all the data relevant to a particular slope to perform deterministic stability analysis, performs some initial calculations, and displays the final output of the factor of safety.

The initial calculations performed in this sheet are to calculate h_{av}, W_i, Q_i, and tan ϕ'. These calculations are separated from other calculations to allow any user, if necessary, to enter the values directly into those cells. In some problems, such as a case where there are number of soil layers present, user may find it easy to calculate the weight of a particular slice separately rather than finding an average bulk density to be entered in the input data.

When displaying the final factor of safety, it shows the value of the last two trials also, so that the user can see whether the final answer has converged or not. These values are directly copied from the "Calculations" worksheet.

The "Calculations" worksheet copies all the input data from the deterministic worksheet, and performs the calculations to find out the factor of safety. Although literature reports that Bishop's simplified method converges very fast (usually in two trials) the final factor of safety is arrived only after four trials. Since the probabilistic calculations also uses this factor of safety, and the problem is automated, this seems reasonable to avoid any problems with non-converged factors of safety. Apart from that, the "Calculations" worksheet also calculates the partial derivatives of factor of safety with respect to the probabilistic parameters.

"Probabilistic" worksheet allows the input of all the data that quantifies the uncertainties of the probabilistic parameters, and finally computes two values for probability of failure one assuming normal distribution and the other assuming lognormal distribution for the probability distribution of factor of safety. However, depending on the way the variability of pore pressures is considered (section 2.2), spreadsheet program is divided in to two subsets.

Figures 3.2 to 3.5 illustrate the formulation the spreadsheet using flow diagrams.

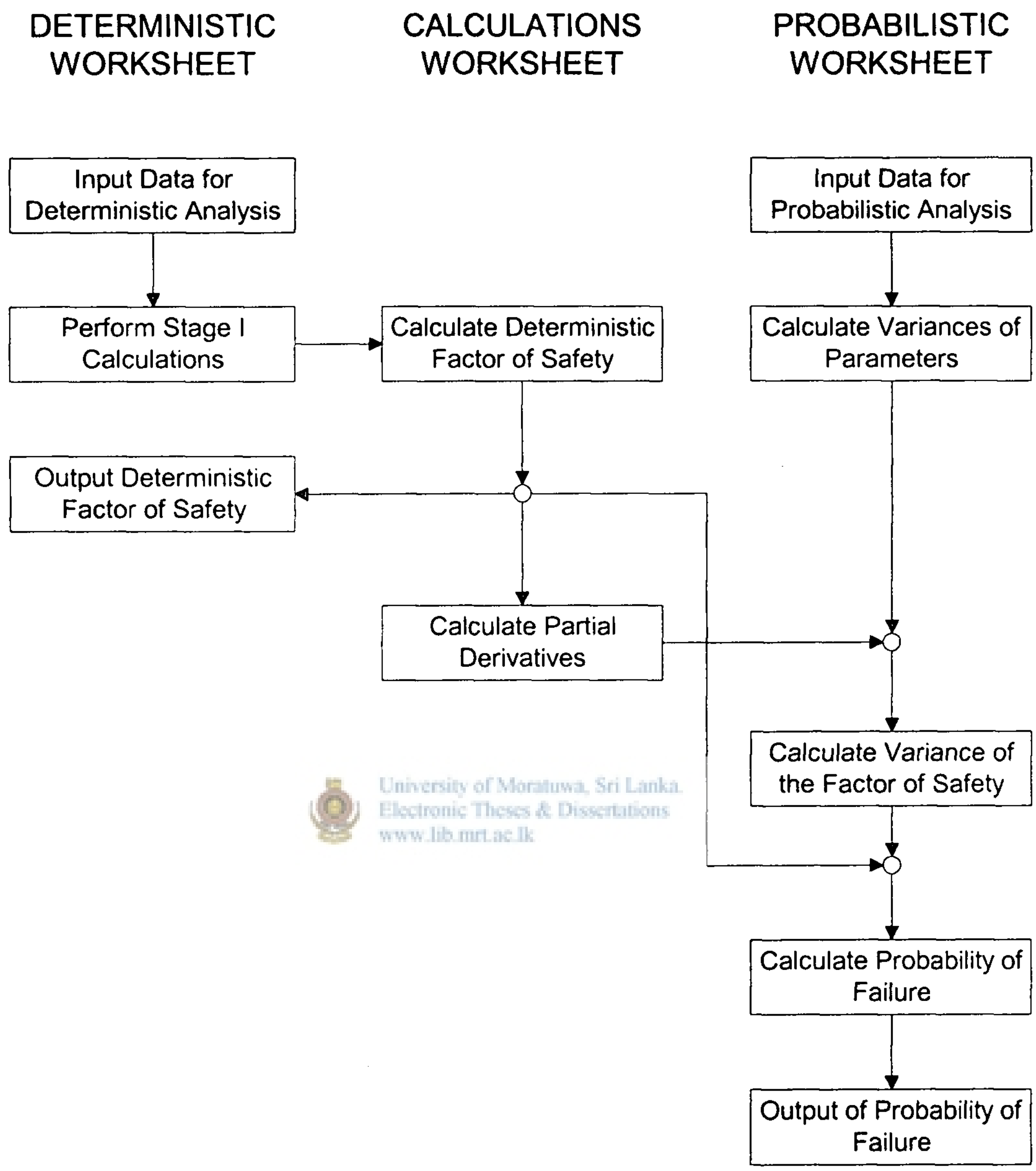


Figure 3.2: Flow chart showing the overview of the spreadsheet program (Bishop - Prob - Direct)

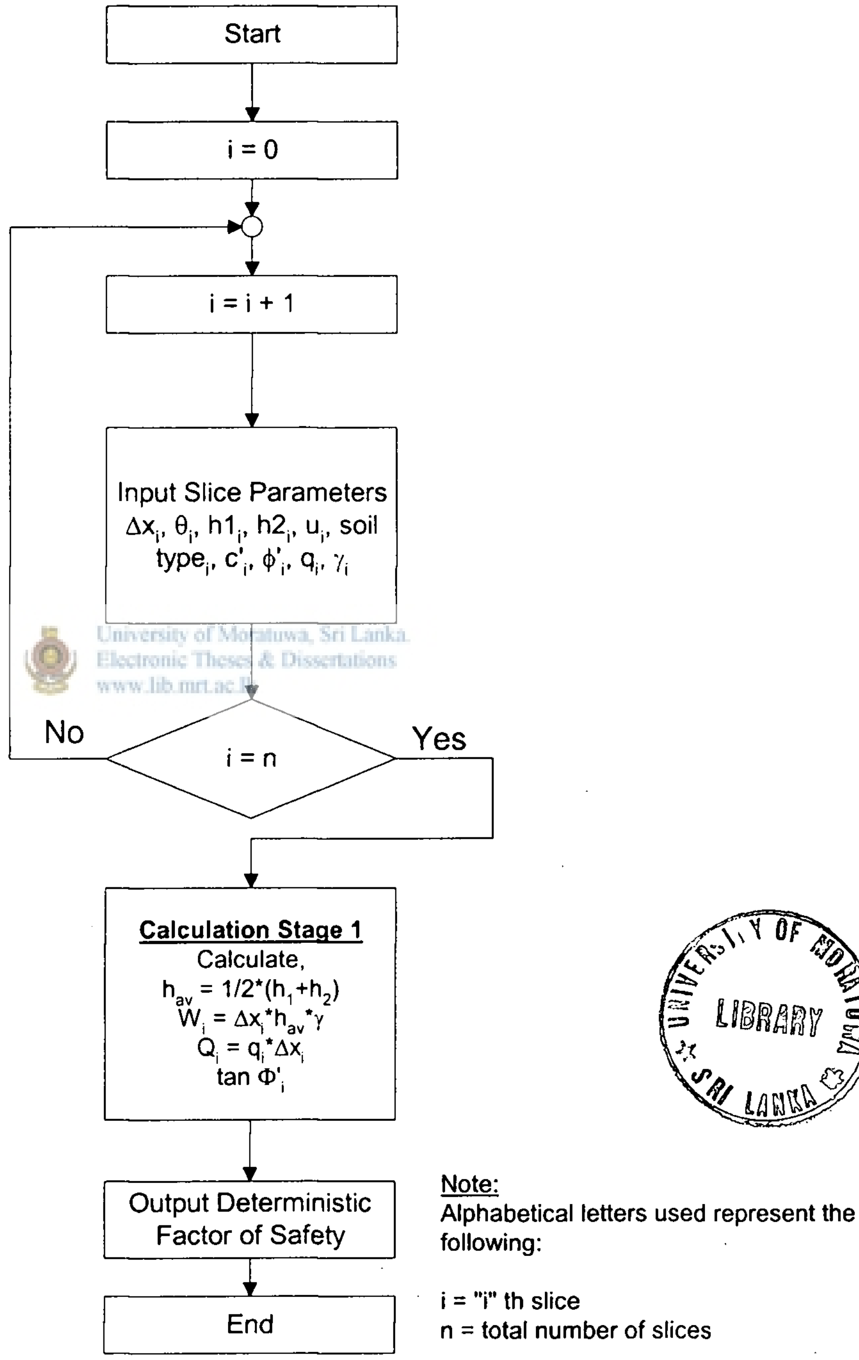
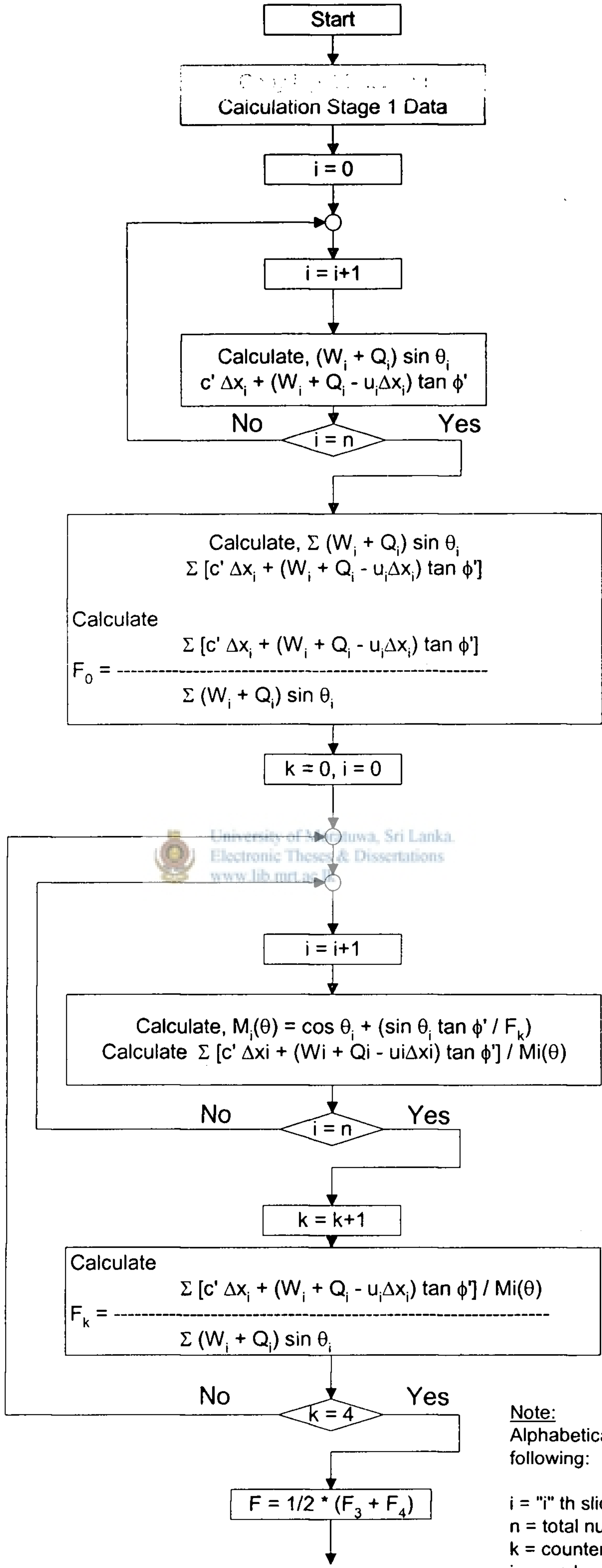


Figure 3.3: Flow chart for Deterministic worksheet (Bishop - Prob - Direct)



Note:
Alphabetical letters used represent the following:

i = "i" th slice
n = total number of slices
k = counter of the trial no. of the FOS
j = number representing soil type

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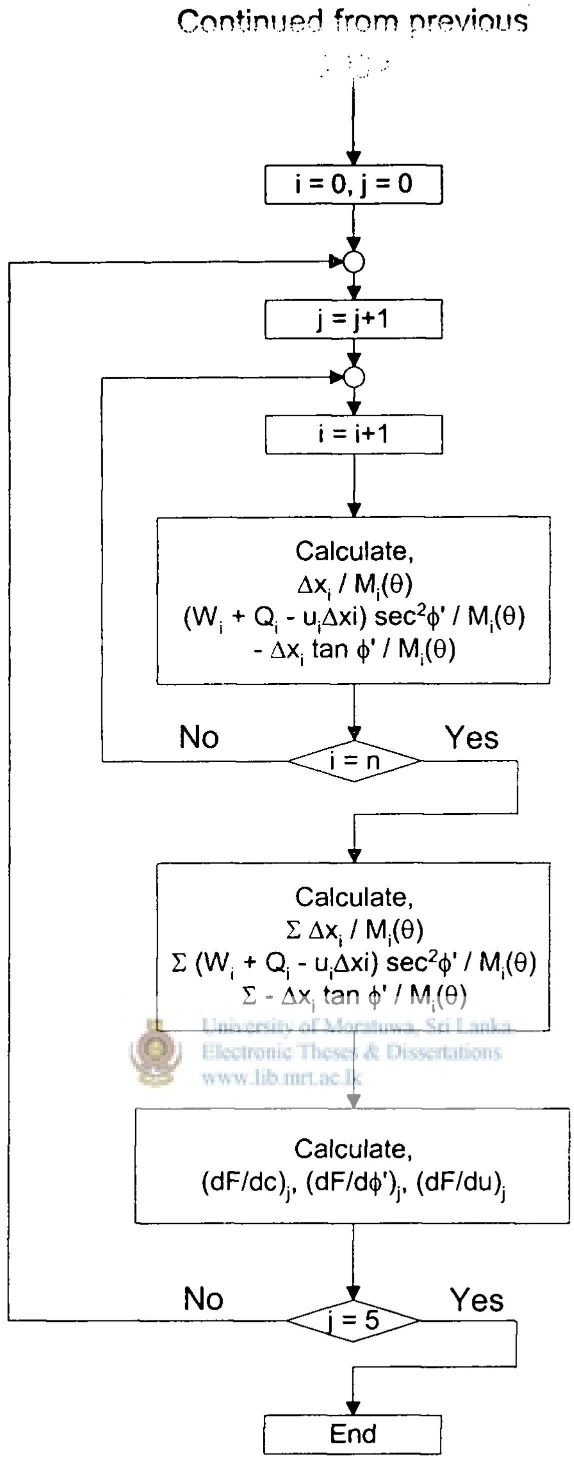
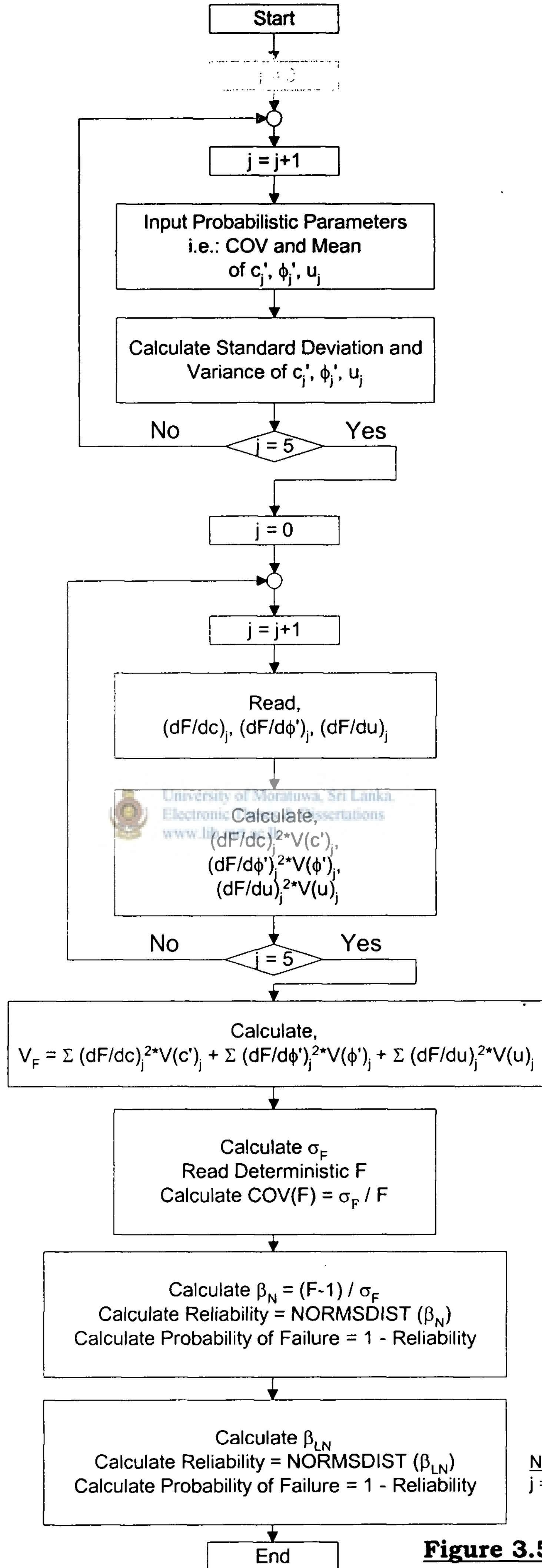
Figure 3.4: Folw diagram showing the Calculations worksheet (Bishop - Prob - Direct)



Note:
Alphabetical letters used represent the following:

i = "i" th slice
n = total number of slices
k = counter of the trial no. of the FOS
j = number representing soil type

Figure 3.4: Folw diagram showing the Calculations worksheet (Bishop - Prob - Direct)



Note:
j = number representing soil type

Figure 3.5: Flow Chart for Probabilistic Worksheet (Bishop - Prob - Direct)

Case (ii): Spreadsheet for the model based on Bishop's simplified method - direct differentiation assuming $M_i(\theta)$ is probabilistic (File Name: *Bishop-Prob-Direct-Exact)*

Only change in this model is the equation that calculates the partial derivative of factor of safety with respect to the internal angle of friction (i.e.: $\partial F/\partial \phi'$). Hence, the flowchart is the same except the equation that computes $\partial F/\partial \phi'$.

Case (iii): Spreadsheet for the model based on Bishop's simplified method – Duncan (2000) and Small Increment methods (File Name: *Bishop-Prob-Small Increment)*

This spreadsheet consists of two main worksheets to perform deterministic and probabilistic calculations, and then a set of additional worksheets to perform deterministic calculations with varied parameters.

The deterministic worksheet calculates the mean factor of safety using the mean values of the parameters.

Probabilistic worksheet allows user to enter uncertainty of probabilistic parameters in terms of their coefficient of variation. It then calculates the standard deviation and the variance, but prompt the user to enter values for increments of c', ϕ' and u.

The other set of spreadsheets are then updated appropriately to change their properties (i.e.: c' ϕ', u) and deterministic factors of safety (i.e: F_{c1}^+, F_{c1}^-, ...etc) are calculated according to new parameters. For example, in worksheet F_{c1}^+, the c' values of slices lying in soil 1 are replaced with $c'+\Delta c'$ and the factor of safety F_{c1}^+ is calculated. Similarly in F_{c1}^- worksheet, the c' values of slices lying in soil 1 are replaced with $c'-\Delta c'$ and the factor of safety F_{c1}^- is calculated. Figure 3.8 gives the flow diagram relevant to this process.

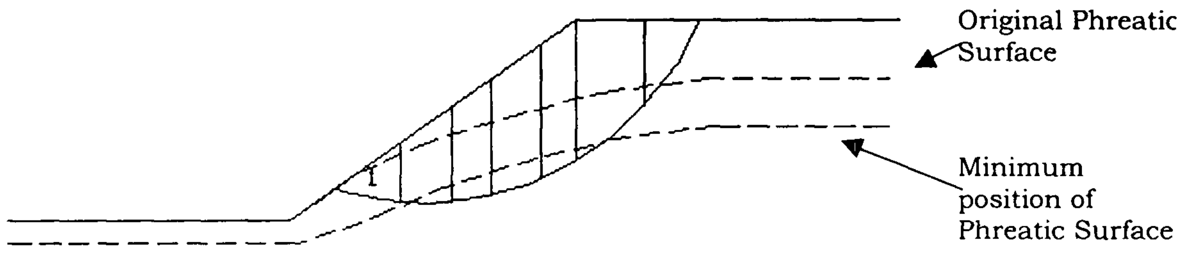
Probability of failure is calculated using finite difference calculus, and, the calculations result two values for probability of failure one using central difference formula, and the other using forward difference formula.

If the user is interested in obtaining the probability of failure according to Duncan (2000) method, the increments should be made equal to the standard deviation of each parameter, and the central difference probability of failure should be referred to. Instead, any small increment can be entered if a user requires to increase the accuracy of the approximation.

Pore water pressure variations are treated in both ways as explained in section 2.2. If the pore pressures are taken to be dependant of the soil type, user can introduce separate values of coefficient of variation for each layer. If it is taken to be independent of the soil type, the user can enter a single value for coefficient of variation, which is constant for the whole slope. These spreadsheets require mean pore pressure values to be entered either to each soil layer, or to the whole slope, and the weighted average is recommended.

Use of a fixed coefficient of variation results a fixed standard deviation, hence a fixed increment. This leads to negative values of pore pressures in some supporting worksheets that calculate F_{ul}^{-} (l represent the soil type number here such as soil 1, soil 2 etc.). The value for F_{ul}^{-} results when the pore pressure values are reduced by the increment value entered by the user (i.e.: $u = u - \Delta u$), and this corresponds to considering a lowered water table..The actual situation in such cases is that negative pore pressures may develop in some cells where there were some pore pressures initially (see figure 3.6). However, as negative pore water pressures (due to matric suction) were not considered in this study they were made zero. Hence a check is made to assign those cells with zero pore pressure.

Figures 3.7 and 3.8 illustrate the formulations of spreadsheets using flow diagrams.



Note: When the phreatic surface is lowered as shown above, the pore pressure in slice 1 becomes zero. As negative pore water pressures (due to matric suction) are not used in the formulation, it is taken to be zero.

Figure 3.6: A Slope with varying Phreatic Surfaces

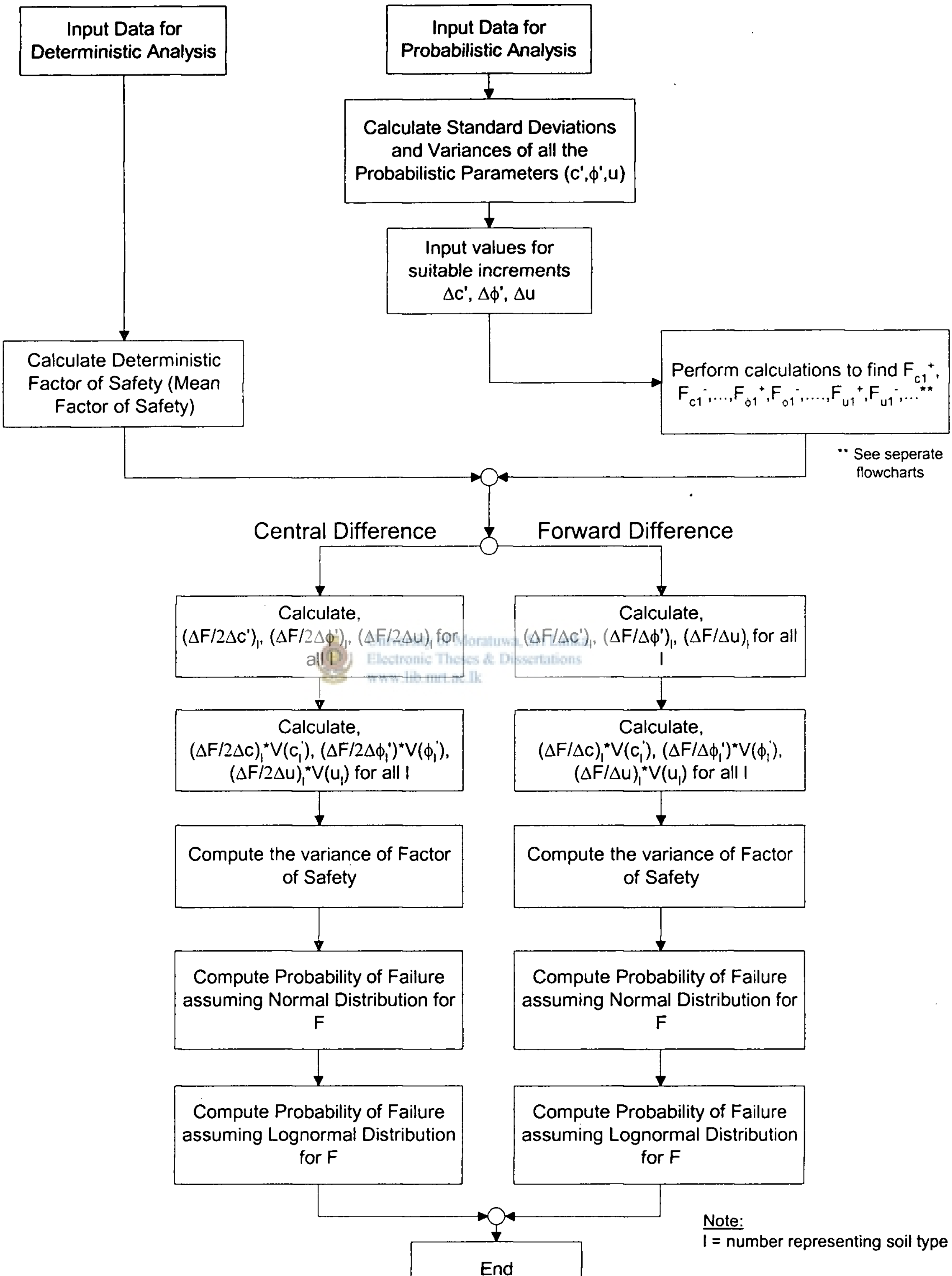
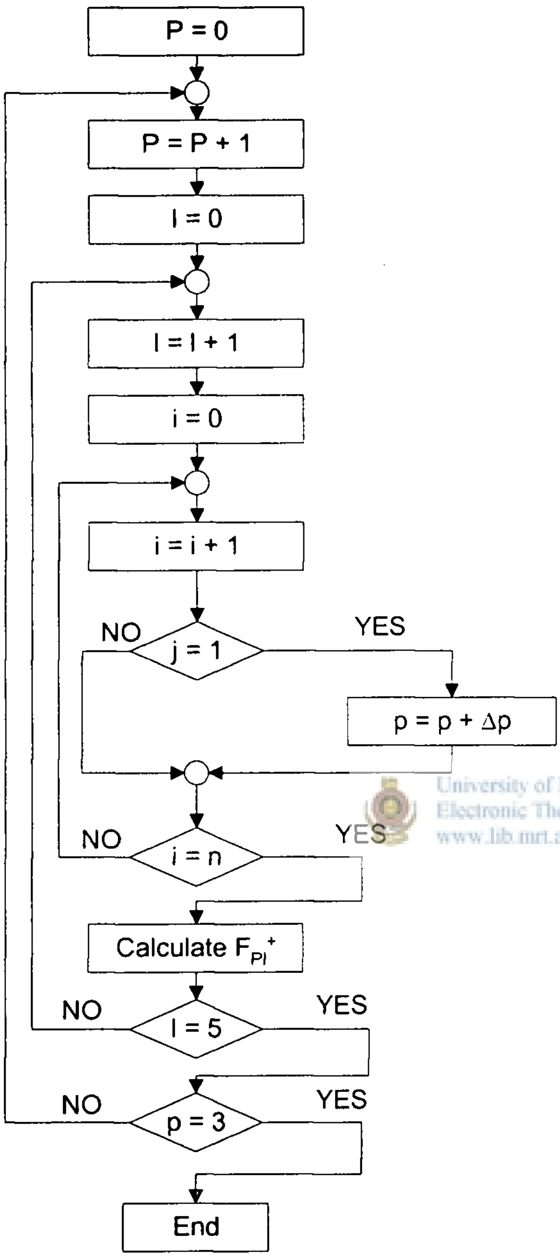
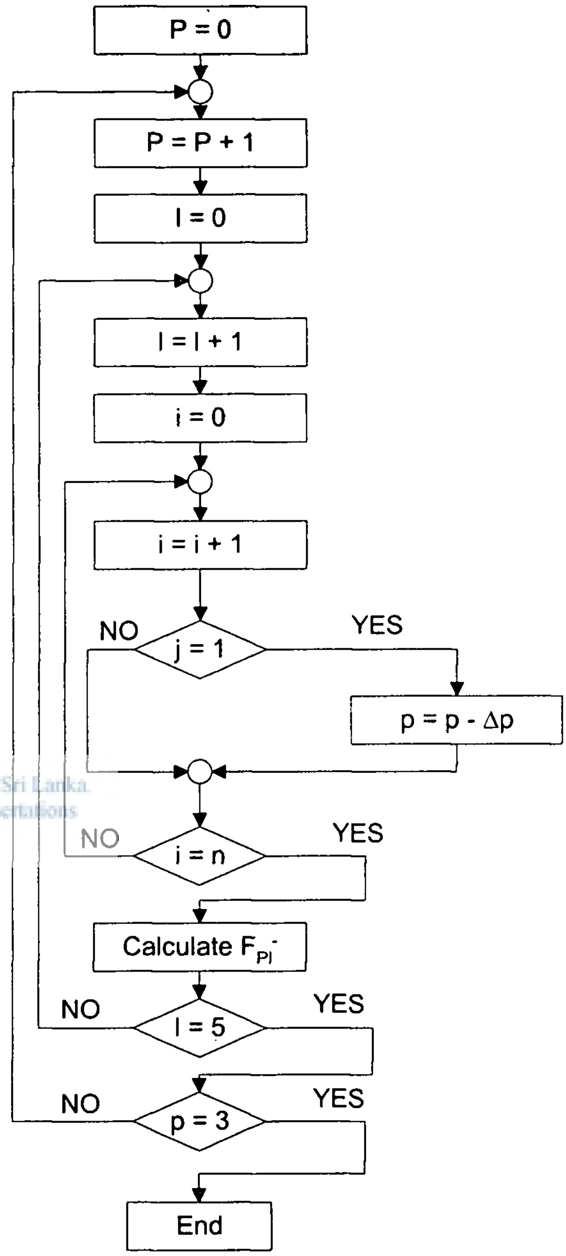


Figure 3.7: Flowchart for Small Increment Program (Bishop - Prob - Small Increment)



Flow diagram for the calculation of F_x^{+}



Flow diagram for the calculation of F_x^{-}

Note:
Alphabetical letters used represent the following:

i = "i" th slice
n = total number of slices
j = number representing soil type
I = number representing soil type
p = probabilistic parameter such as c', Φ', u
F_{pl} represent cases of F_{c1}, F_{c2}, $F_{\Phi 1}$, $F_{\Phi 2}$ etc.

Figure 3.8: Flow diagram for calculation of Fx+ and Fx- (Bishop - Prob - Small Increment)

3.5 Application of the Model

3.5.1 General

For the purpose of illustrations and comparisons of the developed probabilistic models, a number of well-analyzed problems were selected. These problems were selected from a large number of problems that were used in a survey conducted to evaluate the state of the art of the slope stability analysis techniques in Australia in 1989 (Giam, 1989). All the problems were well analyzed by a group of specialists using different programs based on limit equilibrium approach and the minimum factor of safety and critical failure surfaces were well established. Only deterministic analyses were performed. The concepts of the referee solutions are presented in detail in Giam (1989). These refereed values of factors of safety are hereafter termed as referee solutions throughout this text.

3.5.2 Test Example – 1

The example shown in figure 3.9 has a non-homogeneous soil profile by introducing three soil types of different strengths. According to the geometry, a near circular failure surface can be expected and it was the case with the referee solutions also. For the purpose of illustrations of the models, the example is divided into two parts depending on whether the phreatic surface is prevailing or not.

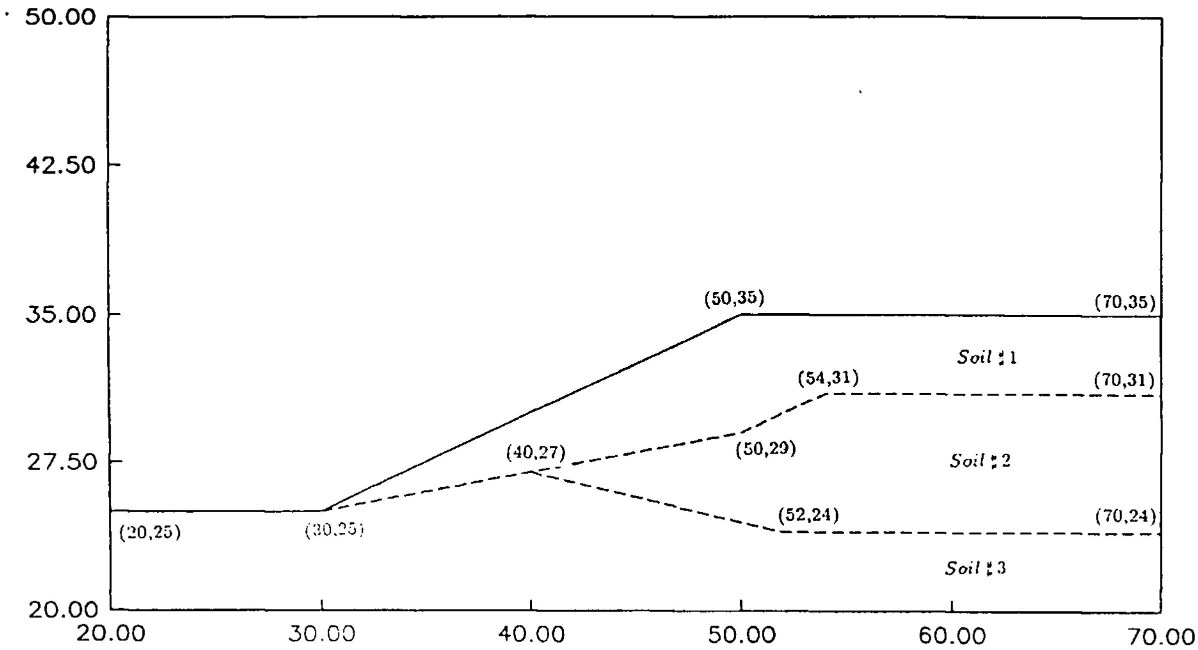


Figure 3.9: Example 1 Geometry

3.5.2.1 Example 1 (a): (Ref: ACAD1C0)

This example does not have the phreatic surface, hence only a total stress analysis is required. The deterministic parameters given are shown in table 3.1.

Soil Type	c (kN/m²)	φ (°)	γ (kN/m³)
1	0	38	19.5
2	5.3	23	19.5
3	7.2	20	19.5

Table 3.1: Deterministic Soil Parameters for Example 1(a)

Deterministic Analysis

The critical failure surface given by the referee solutions was again confirmed through SLIDE computer program that performs the analysis of circular failure surfaces based on Bishop's simplified method. Resulting circular failure surface was used for further analysis.

The slope geometry and the failure surface were drawn using AutoCAD and the failure mass was divided into 15 slices, limiting the maximum slice width to 2.05m. But the average slice width was 1.5m. The relevant dimensions of slices were extracted from AutoCAD drawing and fed manually into the spreadsheets developed.

Probabilistic Analysis

Coefficients of variation values for c and ϕ were selected based on some published values (Lee et.al., 1983, Duncan, 2000) and they are shown in table 3.2.

Soil Type	COV (c)	COV(ϕ)
1	0	0.3
2	0.3	0.4
3	0.2	0.35

Table 3.2: Coefficients of Variation values for c and ϕ

Analyses were performed using all the five methods discussed under section 3.1. For the small increment computations, the assumed increment is the 10% of the standard deviation. Monte-Carlo analysis was also performed for the same problem for 1000, 5000 and 50000 trials using the SLOPE/W computer program (GEO-SLOPE Office, 1998) to provide a comparison. For this Monte-Carlo analyses, the variability of c and ϕ were introduced in terms of their standard deviations and the values were the same as that used in the other calculations. The basic outline of the Monte-Carlo analysis performed using SLOPE/W computer program is presented in Annex 1. All other supporting documents for these examples are given in Annex 2.

Results

Results of the analyses are given in table 3.3.

	Analysis Program	Deterministic Model	Factor of Safety	Probability of Failure	
				Normal	Lognormal
1	Referee Solution		1.39	These perform only the deterministic analysis	
2	SLIDE	Bishop' s simplified	1.403		
3	Direct Differentiation (M(θ) = deterministic)	Bishop' s simplified	1.441[b]	7.43%	5.06%
4	Direct Differentiation (M(θ) = probabilistic)	Bishop' s simplified	-do-[b]	3.95%	2.14%
5	Duncan (2000) method	Bishop' s simplified	-do-[b]	7.35%	4.99%
6	Small Increment method (Central Difference)	Bishop' s simplified	-do-[b]	7.08%	4.74%
7	Small Increment (Forward Difference)	Bishop' s simplified	-do-[b]	7.15%	4.80%
8	Monte-Carlo (Det: 1.408[a])	Bishop' s simplified	1.379 to 1.407[c]	5.96% - 6.97%	SLOPE/W assumes normal distribution only
9	Monte-Carlo (Det: 1.377[a])	Spencer	1.36 to 1.385[c]	7.36% - 8.28%	

Note:

a. In SLOPE/W mean value is different from deterministic value

b. These use same deterministic model

c. Different Monte Carlo trials result in different values. Hence an approximate range is specified

Table 3.3: Results for Example 1(a)

Graphical representation of the results is given in figure 3.10. For Monte-Carlo analysis, only the average value of a particular range has been plotted.

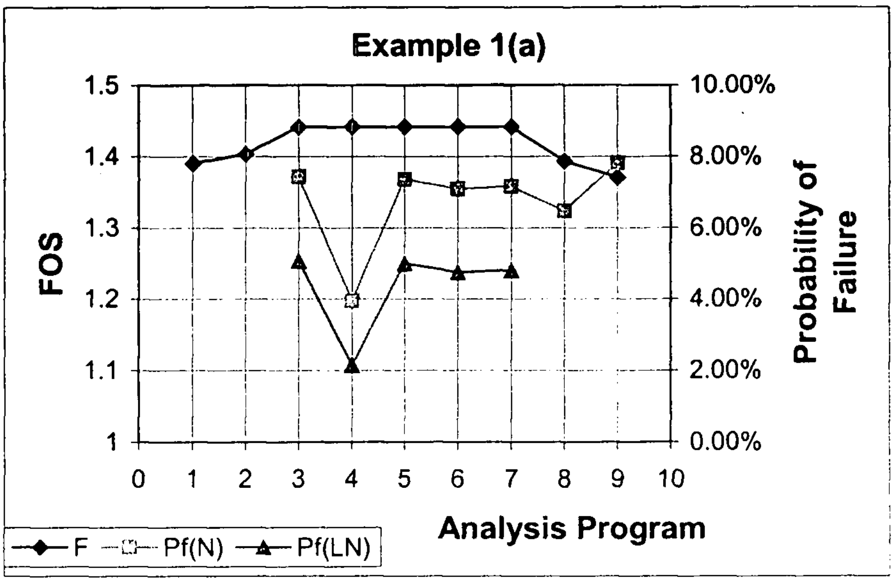


Figure 3.10: Results of Example 1(a)

Discussion of Results

The factor of safety for the selected failure surface is in close agreement with the referee solutions. This is an evidence to say that the critical failure surface had been correctly identified. The difference between author's factors of safety and those given by various computer programs (this refers to the deterministic value rather than the mean value) is only about 0.04. Author's program assumes only 16 slices, but most of these computer programs use at least 30 slices. Also, when the errors made during idealization (model errors) are considered, this difference is quite acceptable, and performances of author's programs are taken to be satisfactory in deterministic computations.

Probability of failure values, computed under the assumption of normal distribution, from author's models discussed in this chapter vary only over a narrow range from 7.08% to 7.43%, except for the case that assumes M(θ) as a probabilistic quantity. Monte Carlo analysis results, which assume Bishop's simplified method, gives probability of failure values varying over a range from 5.96% and 6.97%, while Monte Carlo results assuming Spencer's method range between 7.36% and 8.28%. It is seen that the results from author's programs lie within, if not, lie very close to the results of Monte Carlo analysis. Also, the narrow range of probability of failure values, from different assumptions of author's program, show that whether it being an approximate method or a method derived from rigorous theory, all of them perform equally well. Considering those results, any of the author's programs discussed above except for the one assuming M(θ) is probabilistic can be accepted satisfactory in computing the probability of failure.

3.5.2.2 Example 1(b): (Ref: ACAD1C1)

In this example, additional complication is introduced for the earlier example by introducing a phreatic surface (see figure 3.11) and an effective stress analysis is performed. The effective strength parameters are given in table 3.4.

Soil Type	c' (kN/m^2)	φ' (^{0})	γ (kN/m^3)
1	0	38	19.5
2	5.3	23	19.5
3	7.2	20	19.5

Table 3.4: Deterministic Soil Parameters for Example 1(b)

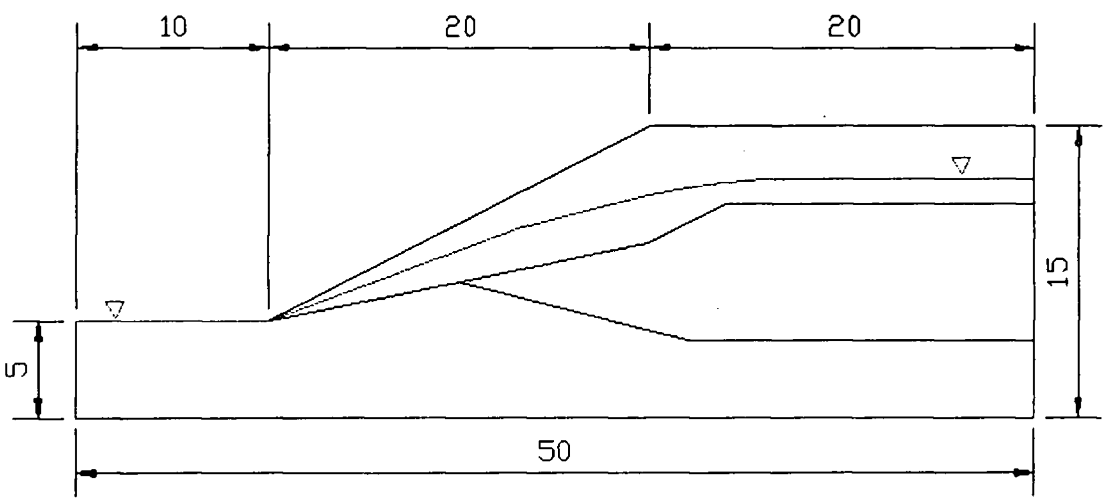


Figure 3.11: Geometry of Example 1(b)

Deterministic Analysis

As performed in example 1(a), the critical failure surface given by the referee programs and confirmed by the program SLIDE was used for further analysis. Failure mass was again divided into 15 slices limiting the maximum slice width to 1.93m. Average slice width is 1.5m. As in the example 1(a), slice dimensions were obtained by drawing the slope in AUTOCAD. Data were fed to spreadsheets manually.

Pore water pressures were estimated by constructing a flow net (annex 2). Pore pressure distribution between some critical points was obtained through the flow net, and the values corresponding to each slice were interpolated.

Probabilistic Analysis

Analyses were performed by all five methods developed by the author. Pore pressures are treated in both ways as discussed in section 2.2. In addition, Monte-Carlo analysis was performed for 1000, 5000 and 50000 trials using SLOPE/W computer program.

Coefficient of variation values for c′ and ϕ′, selected based on some published values (Duncan, 2000; Lee et.al., 1983) are given in table 3.5.

Soil Type	**COV (c′)**	**COV(ϕ′)**
1	0	0.3
2	0.3	0.4
3	0.2	0.35

Table 3.5: Coefficients of Variation values for c′ and ϕ′

Pore pressures were treated in both ways that were discussed in section 2.2. Coefficient of variation values and the mean values of pore water pressures for the case where they are treated on the basis of soil layers are given in table 3.6. The mean pore pressures for each soil layer were selected to be the weighted average.

Soil Type	**Mean u (kN/m²)**	**COV (u)**
1	6.47	0.25
2	27.64	0.3
3	23.33	0.35

Table 3.6: Mean and Coefficients of Variation of u

For the case where the pore pressure variability is defined for the whole slope, the mean value was again the weighted average. But, to find out a coefficient of variation, weighted average of maximum pore pressure and the minimum pore pressure were calculated and the coefficient of variation is calculated based on them. Hence, the mean pore water pressure was 20.09 kN/m^2 and the coefficient of variation was 0.33.

When the Monte-Carlo analysis was performed, an equivalent standard deviation for the piezometric head had to be estimated. There was no exact way to relate this to the standard deviation of the pore pressures. Hence, the standard deviation of the head was selected to be the value corresponding to the standard deviation of the mean pore pressure used in other analyses. Therefore the value of the standard deviation of head was 0.675m. All the supporting documents for this example are given in Annex 2.

Results:

Results of the analysis are given in table 3.7.

	Analysis Program	Pore Pressure COV	Deterministic Model	Factor of Safety	Probability of Failure	
					Normal	Lognormal
1	SLIDE	Not Applicable	Bishop's simplified	0.9995	Performs only the deterministic analysis	
2	Direct Differentiation (M(θ) = deterministic)	Based on soil layers	Bishop's simplified	1.028	44.69%	48.56%
3		Constant for the slope	Bishop's simplified	-do-[b]	45.19%	49.47%
4	Direct Differentiation (M(θ) = probabilistic)	Based on soil layers	Bishop's simplified	-do-[b]	43.63%	46.32%
5		Constant for the slope	Bishop's simplified	-do-[b]	44.21%	47.74%
6	Duncan (2000) method	Based on soil layers	Bishop's simplified	-do-[b]	44.98%	49.08%
7		Constant for the slope	Bishop's simplified	-do-[b]	45.24%	49.68%
8	Small Increment method (Central Difference)	Based on soil layers	Bishop's simplified	-do-[b]	44.94%	49.02%
9		Constant for the slope	Bishop's simplified	-do-[b]	45.33%	49.74%
10	Small Increment method (Forward Difference)	Based on soil layers	Bishop's simplified	-do-[b]	44.95%	49.03%
11		Constant for the slope	Bishop's simplified	-do-[b]	44.42%	48.10%
12	Monte-Carlo Det. (B): 0.987[a] (S): 0.976[a]	Based on Piezometric Head	Bishop's simplified / Spencer	0.976 – 0.985[c]	52.65% - 54.61%[c]	SLOPE/W assumes normal distribution only

Note:

a. In SLOPE/W, deterministic value is slightly different from mean value

b. These use the same deterministic model

c. Different Monte-Carlo trials result in different values. Hence a range is specified here for mean values

Table 3.7: Results of Example 1(b)

Results are shown in graphical form in figure 3.12. For Monte Carlo analysis, average values of the particular range have been plotted.

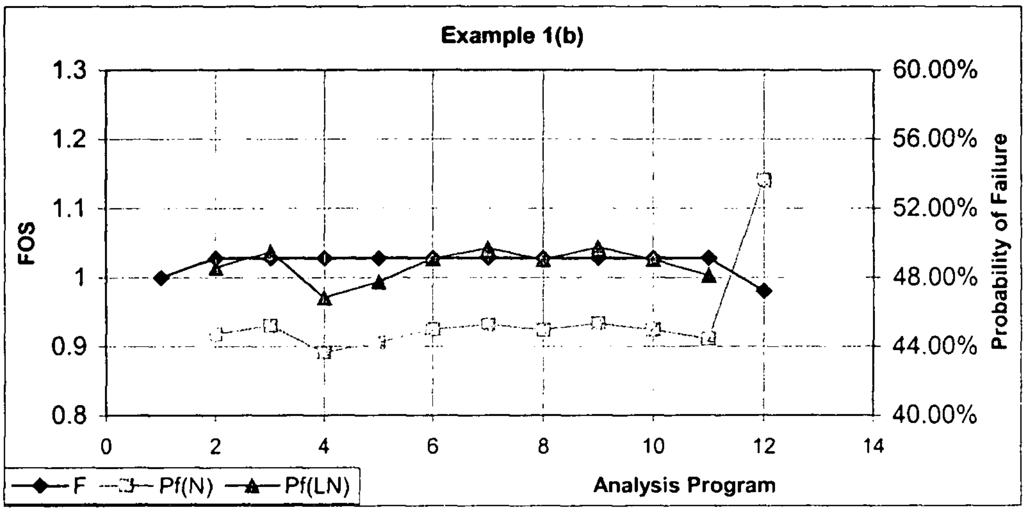


Figure 3.12: Results of Example 1(b)

Discussion of Results

The factor of safety values from author's programs and the computer programs are very close. The difference is only in the order of 0.04-0.05. As discussed in example 1(a), this difference can be allowed for the differences in manual selection and computer selection of geometrical parameters.

Probability of failure from author's models when the factor of safety is assumed to have normal distribution shows a range between 44.42% and 45.33%. However, the results of Monte Carlo analyses are a bit high with values varying between 52.65% and 54.61%. But, the method of considering pore pressure variability is different and an exact similarity cannot be expected. The narrow range of values resulted due to the author's different assumptions again show that any of these models can perform equally well.

3.6 Concluding Remarks

Some simple methods as well as some other methods based on rigorous theory, to compute the probability of failure have been presented. These methods are applicable to slopes that can have circular failure surfaces. Complicated situations where there is stratified soil with different strength parameters can be accommodated in these models.

Performance of the program was validated using the Monte Carlo analysis for two examples. Few more examples will be discussed in latter chapters in relation to the effectiveness of various stabilization techniques.

The computation of probability of failure formally recognizes the uncertainties of various geotechnical parameters. Hence, these models can be expected to have a role in developing new design guidelines for geotechnical structures based on the probability of failure.

Chapter 4

DEVELOPMENT OF THE PROBABILISTIC MODEL BASED ON JANBU'S SIMPLIFIED METHOD

4.1 Basis of the Method

The deterministic equation of Janbu's simplified method provides the basis for the probabilistic model. In this method, the correction factor *fo* is needed to account for the effect of inter slice shear forces (Fredlund and Krahn, 1977). The correction factor *fo* is related to cohesion, angle of internal friction and the shape of the failure surface (Janbu et.al. 1956).

Considering only the force equilibrium, the uncorrected factor of safety is given as:

$$F_0 = \frac{\sum \{(c'\Delta x_i + (W_i + Q_i - u_i \Delta x_i)\tan\phi')/n_i(\theta)\}}{\sum W_i \tan\theta_i} \quad \ldots\ldots(4.1)$$

where,

$$n_i(\theta) = \cos\theta_i \cdot \left(\cos\theta_i + \frac{\sin\theta_i \tan\phi'}{F}\right) ....(4.2)$$

The corrected factor of safety is given by:

$$F = f_0 F_0 \quad ....(4.3)$$

The terms used in equations (4.1) and (4.2) are illustrated in figure 4.1. The chart to get the correction factor f_0 is given in annex 3.

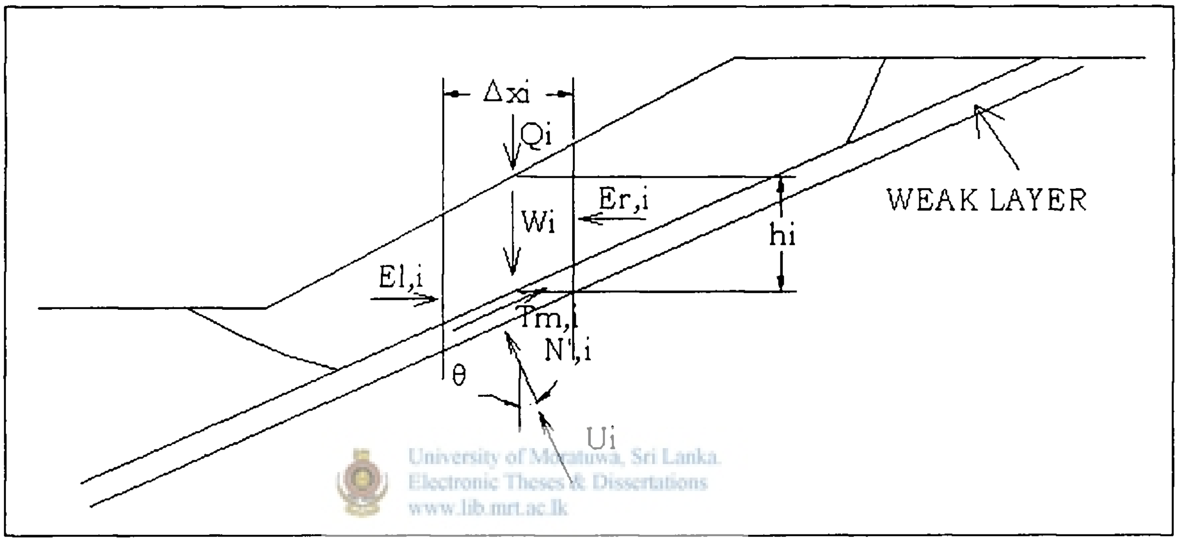


Figure 4.1: Forces acting on a Slice

The model can be used to analyze non-circular failure surfaces.

The first order second moment (FOSM) method was used to develop the probabilistic models. Once the parameters that carry uncertainty are identified and their variability are quantified, the most probable values for F_0 and F are calculated using mean values of probabilistic parameters and other deterministic parameters. The first order approximation of the Taylor series expansion (equation 1.10) is used to calculate the variance of uncorrected factor of safety F_0. Variance of the corrected factor of safety is then computed from basic statistics theory, as shown in equation 4.4 assuming the correction factor f_0 is deterministic.

$$\sigma_F^2 = f_0^2 \sigma_{F0}^2 \text{ ....(4.4)}$$

As for the models discussed in chapter 3, the complete probabilistic model comprises of five different approaches to calculate variance of the factor of safety. They differ from each other in the methods of calculating the partial derivative involved in equation (1.10). The methods are:

(i) Direct differentiation of factor of safety equation assuming $n_i(\theta)$ is a deterministic quantity
(ii) Direct differentiation of factor of safety equation assuming $n_i(\theta)$ is a probabilistic parameter (as a function of angle of internal friction)
(iii) Use of approximation proposed by Duncan (2000)
(iv) Use of an approximate partial derivative assuming any small increment for Δx with central difference formula (finite differences)
(v) Use of an approximate partial derivative assuming any small increment for Δx with forward difference formula (finite differences)

The models developed allow layering of soil up to five different layers with different properties.

4.2 Assignment of Uncertainties

As discussed in section 2.2, soil strength parameters (i.e.: c' and ϕ') and the pore water pressure are treated as probabilistic parameters while all the other parameters including correction factor f_0 are considered deterministic.

Uncertainties of soil strength parameters are assigned on the basis of soil layers. Therefore, for each layer, in addition to the mean values of strength parameters, their coefficients of variation are assigned. Uncertainties of pore water pressures are treated in both approaches as discussed in section 2.2. Therefore, separate spreadsheets have been developed for those two cases.

4.3 Derivation of Partial Derivatives

Case 1: Direct Differentiation assuming $n_i(\theta)$ is deterministic

As for $M_i(\theta)$ in Bishop's models, the assumption to treat $n_i(\theta)$ as deterministic is also a reasonable simplification, since the values of $n_i(\theta)$ is almost close to 1, except in the outermost slices of a particular deep failure surface.

When the equation 4.1 is differentiated with respect to each particular parameter, following expressions are obtained:

$$\frac{\partial F_0}{\partial c'} = \frac{\sum\left(\frac{\Delta x_i}{n_i(\theta)}\right)}{\sum W_i \tan\theta_i} \quad \text{........(4.5)}$$

$$\frac{\partial F_0}{\partial \phi'} = \frac{\sum\left\{(W_i + Q_i - u_i\Delta x_i)\frac{\sec^2\phi'}{n_i(\theta)}\right\}}{\sum W_i \tan\theta_i} \quad \text{........(4.6)}$$

$$\frac{\partial F_0}{\partial u} = \frac{\sum\left(-\frac{\Delta x_i \tan\phi'}{n_i(\theta)}\right)}{\sum W_i \tan\theta_i} \quad \text{........(4.7)}$$

Case (ii): Direct Differentiation assuming $n_i(\theta)$ is Probabilistic

This assumes $n_i(\theta)$ as a function of angle of internal friction (i.e.: $n_i(\theta) = f(\phi')$). Therefore, only the partial derivative with respect to ϕ' is changed. The resulting expression can be given as:

$$\frac{\partial F_0}{\partial \phi'} = \frac{\sum\left[\left\{(W_i + Q_i - u_i\Delta x_i)\frac{\sec^2\phi'}{n_i(\theta)}\right\} - \left\{(c'\Delta x_i + (W_i + Q_i - u_i\Delta x_i)\tan\phi')\frac{\cos^2\theta_i \tan\theta_i \sec^2\theta_i}{F \cdot n_i^2(\theta)}\right\}\right]}{\sum W_i \tan\theta_i} \quad \text{........(4.8)}$$

Case (iii): Method proposed by Duncan (2000)

When the partial derivatives are computed according to the method proposed by Duncan (2000), equation 1.12 becomes:

$$V_{F0} = \left(\frac{\Delta F_{0,c'}}{2}\right)^2 + \left(\frac{\Delta F_{0,\phi'}}{2}\right)^2 + \left(\frac{\Delta F_{0,u}}{2}\right)^2 \quad \text{.......(4.9)}$$

where,

$$\Delta F_{0,c'} = F_0(c' + \sigma_{c'}) - F_0(c' - \sigma_{c'}) \quad \text{............(4.10)}$$

$$\Delta F_{0,\phi'} = F_0(\phi' + \sigma_{\phi'}) - F_0(\phi' - \sigma_{\phi'}) \quad \text{............(4.11)}$$

$$\Delta F_{0,u} = F_0(u + \sigma_u) - F_0(u - \sigma_u) \quad \text{............(4.12)}$$

Case (iv) and (v): Small Increment Methods

Instead of using σ_x as the increment (in equation 1.11), these methods use much smaller increments (δ_{xi}) to calculate $\frac{\partial F_0}{\partial x_i}$. Both methods are based on finite difference calculus. One method uses central difference formula, while the other uses forward difference formula. Hence, for case (iv), equation 1.11 takes the form given below:

$$\frac{\partial F_0}{\partial x_i} \approx \frac{\Delta F_{0,i}}{\Delta x_i} = \frac{F_0(x_i + \delta_{x_i}) - F_0(x_i - \delta_{x_i})}{2 \cdot \delta_{x_i}} \quad \text{............(4.13)}$$

For case (v), it takes the following form:

$$\frac{\partial F_0}{\partial x_i} \approx \frac{\Delta F_{0,i}}{\Delta x_i} = \frac{F_0(x_i + \delta_{x_i}) - F_0(x_i)}{\delta_{x_i}} \qquad (4.14)$$

The variance of the uncorrected factor of safety is then calculated using equation 1.10.

4.4 Development of the Spreadsheets

Following the same pattern as for the models based on Bishop's simplified method (chapter 3), three different spreadsheets were developed with respect to the probabilistic model developed based on Janbu's simplified method. First spreadsheet is based on the direct differentiation assuming $n_i(\theta)$ is a deterministic quantity (case (i) in 4.3). Second spreadsheet is based on the direct differentiation assuming $n_i(\theta)$ is probabilistic. The third spreadsheet covers Duncan (2000) approach and other small increment methods. A sample set of spreadsheets is given in annex 5.

Case (i): Spreadsheet for the model based on Bishop's simplified method – direct differentiation assuming $n_i(\theta)$ is deterministic (File Name: *Janbu-Prob-Direct)*

The spreadsheet consists of three worksheets viz, Deterministic Worksheet, Calculations Worksheet and Probabilistic Worksheet.

Same pattern is followed here as in the models based on Bishop's method.

The Deterministic worksheet reads input data, performs some initial calculations, and displays the final output of the factor of safety. The purpose of initial calculations was explained in section 3.4.

When displaying the final factor of safety, it shows the value of the last two trials also, so that the user can see whether the final answer has converged or not. These values are directly copied from the "Calculations worksheet".

The Calculations worksheet copies all the input data from the deterministic worksheet, and performs the calculations to find out the uncorrected factor of safety (i.e.: F_0). The final value for uncorrected factor of safety is arrived only after five trials, to avoid situations with non-converged factors of safety. Once F_0 is computed, it is corrected with f_0 to give the corrected factor of safety, F. Apart from that, the "Calculations worksheet" also calculates the partial derivatives of uncorrected factor of safety with respect to the probabilistic parameters.

"Probabilistic worksheet" allows the input of all the data that quantifies the uncertainties of the probabilistic parameters, and finally computes two values for probability of failure one assuming normal distribution and the other assuming lognormal distribution for the probability distribution of factor of safety. Yet again, depending on the way the variability of pore pressures is considered (section 2.2), spreadsheet program is divided in to two subsets.

Figures 4.2 to 4.5 illustrate the formulation the spreadsheet using flow diagrams.

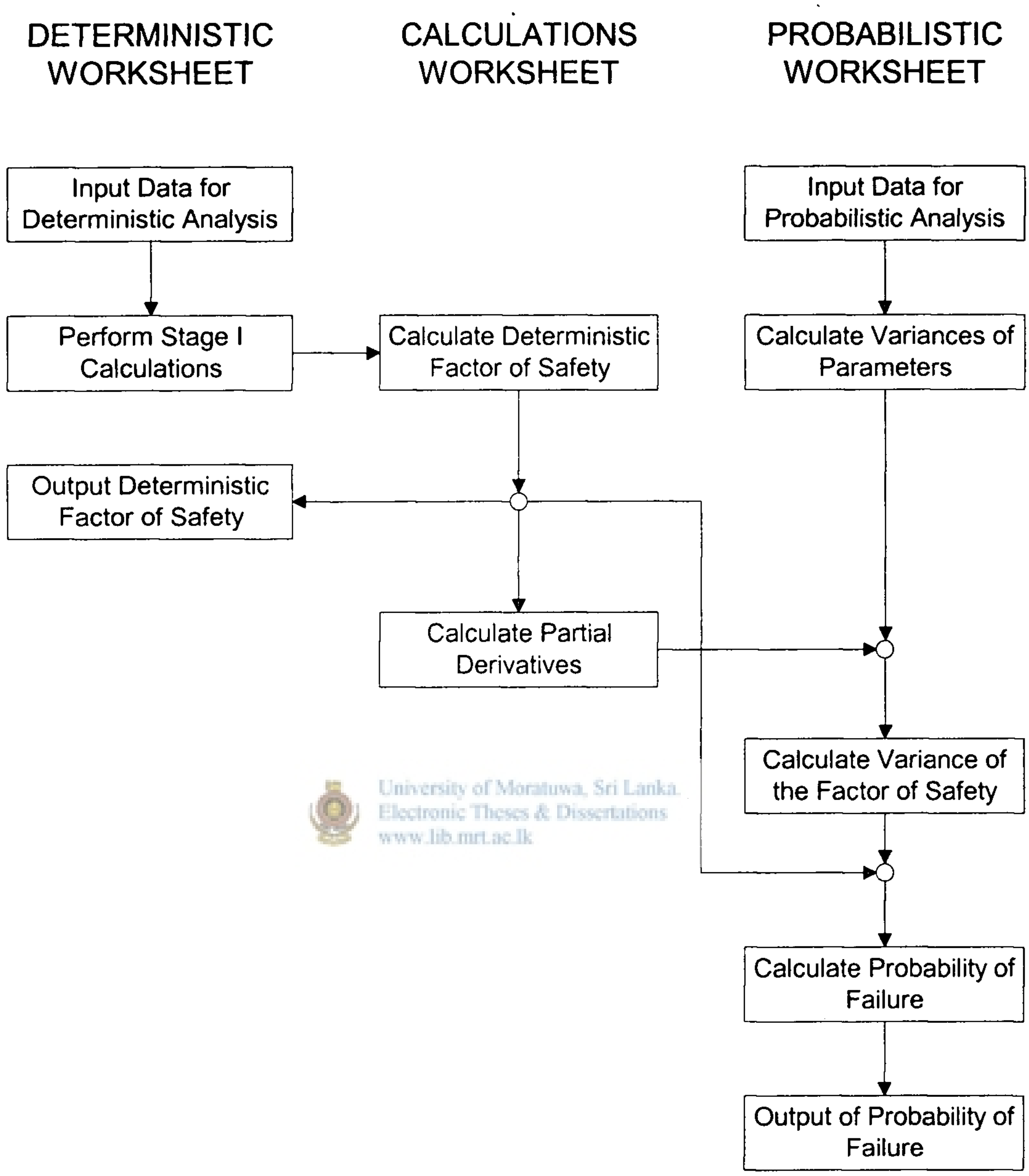


Figure 4.2: Flow chart showing the overview of the Spreadsheet (Janbu-Prob-Direct)

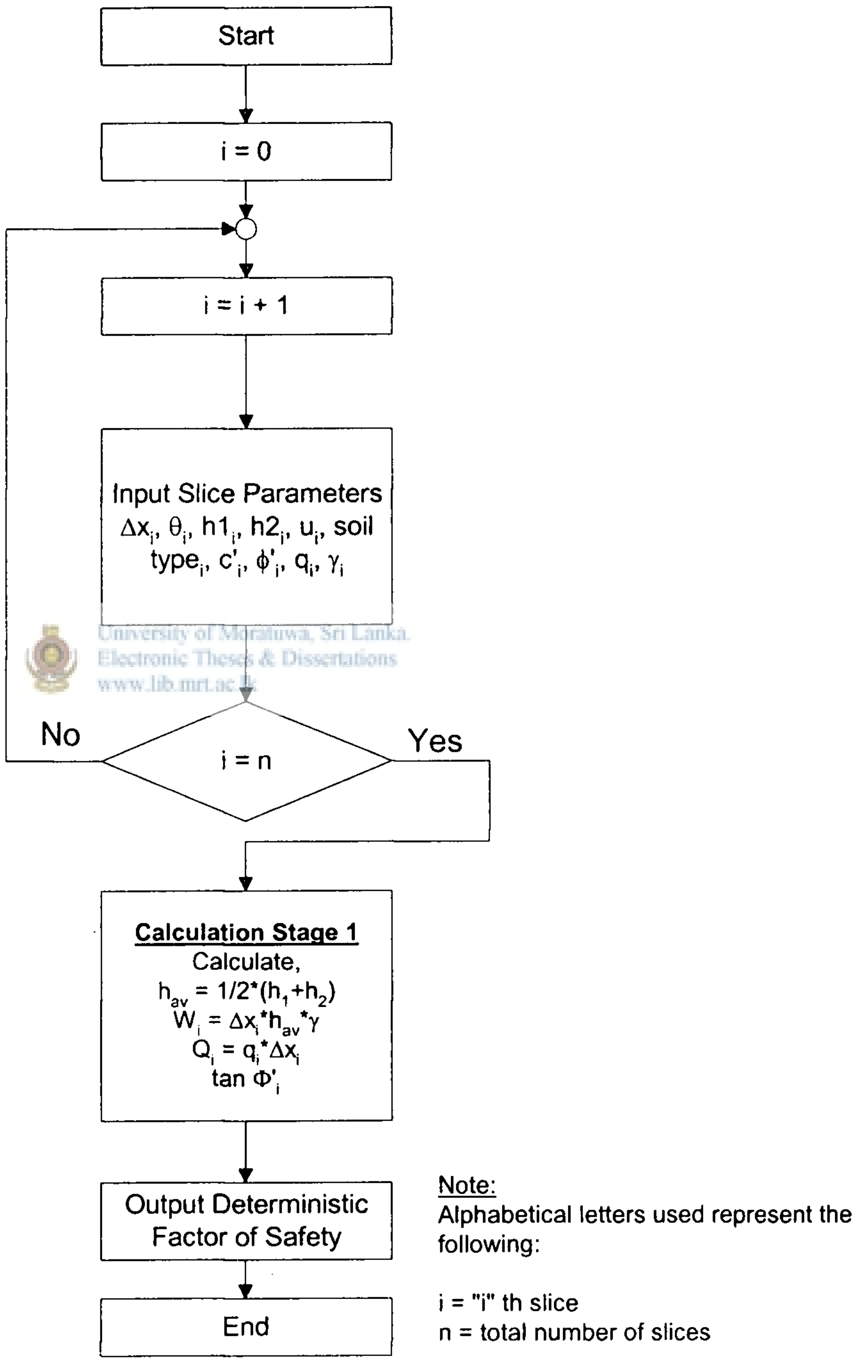


Figure 4.3: Flow chart for Deterministic Worksheet (Janbu-Prob-Direct)

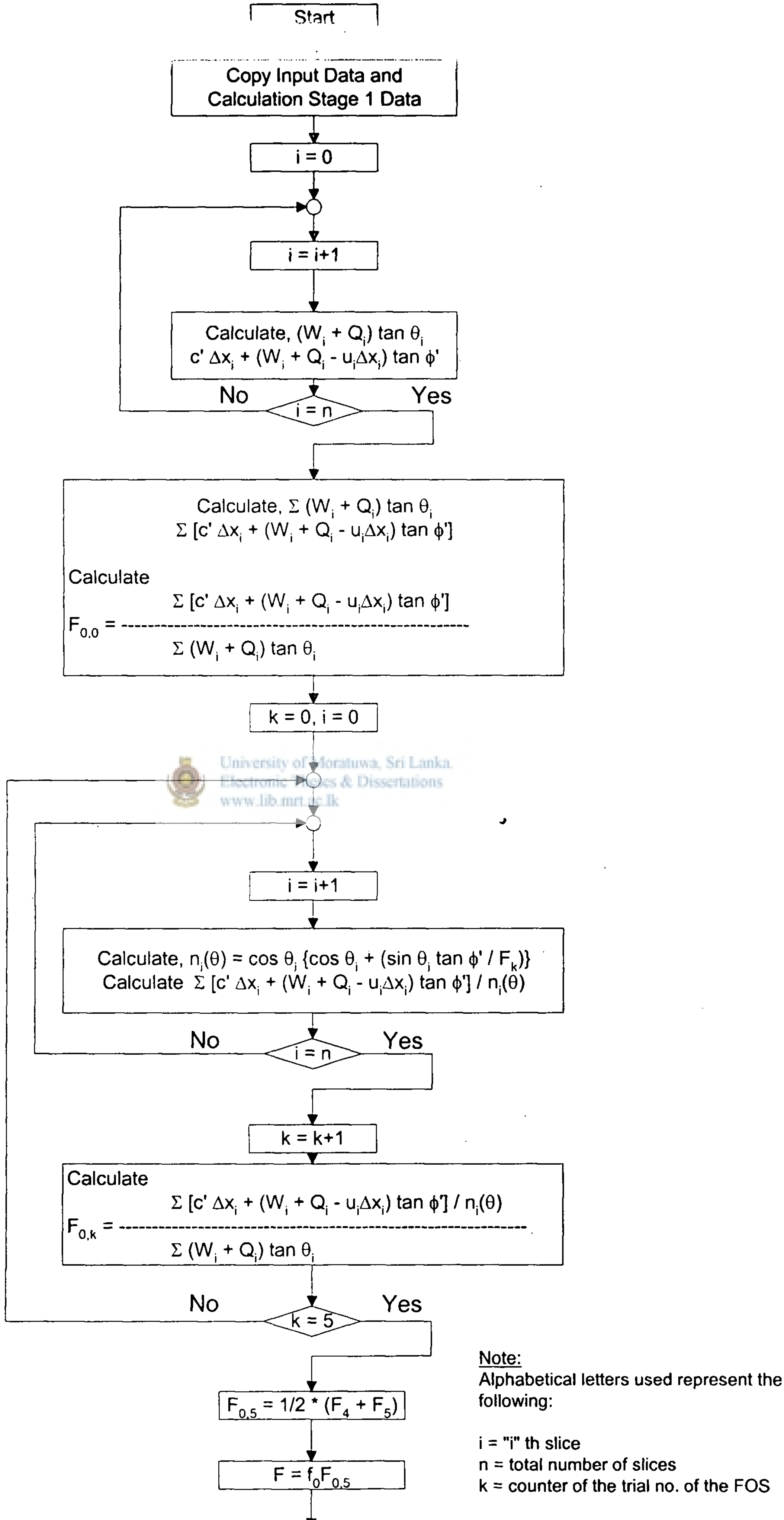


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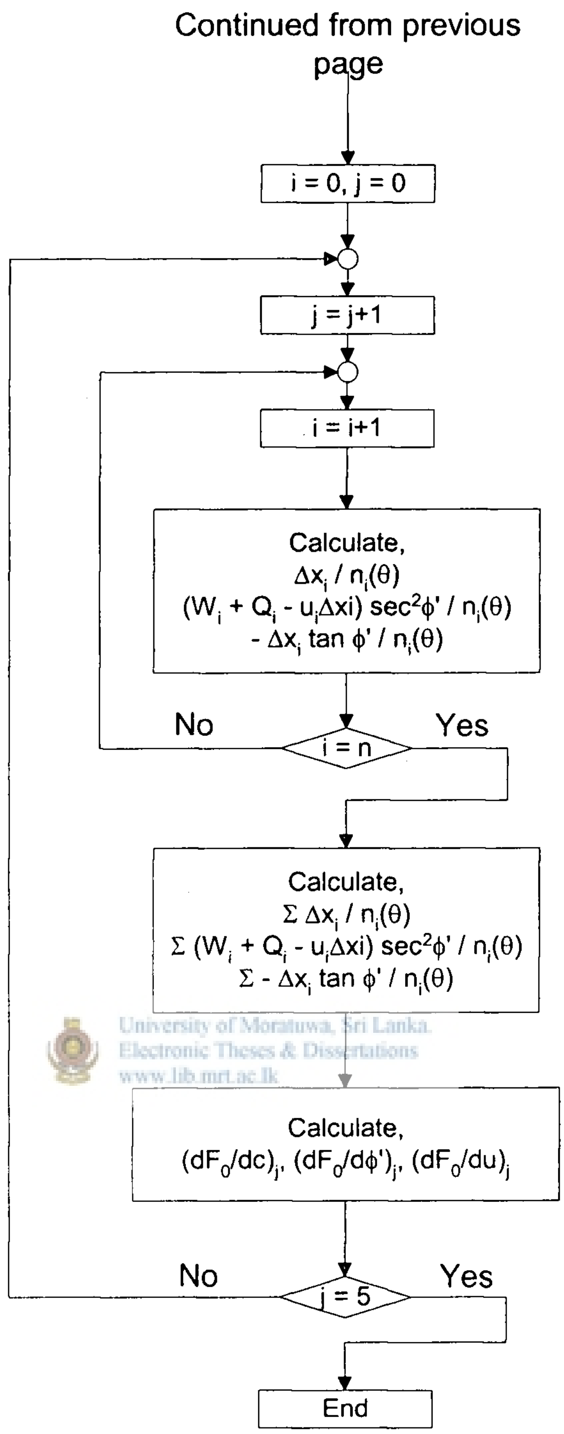
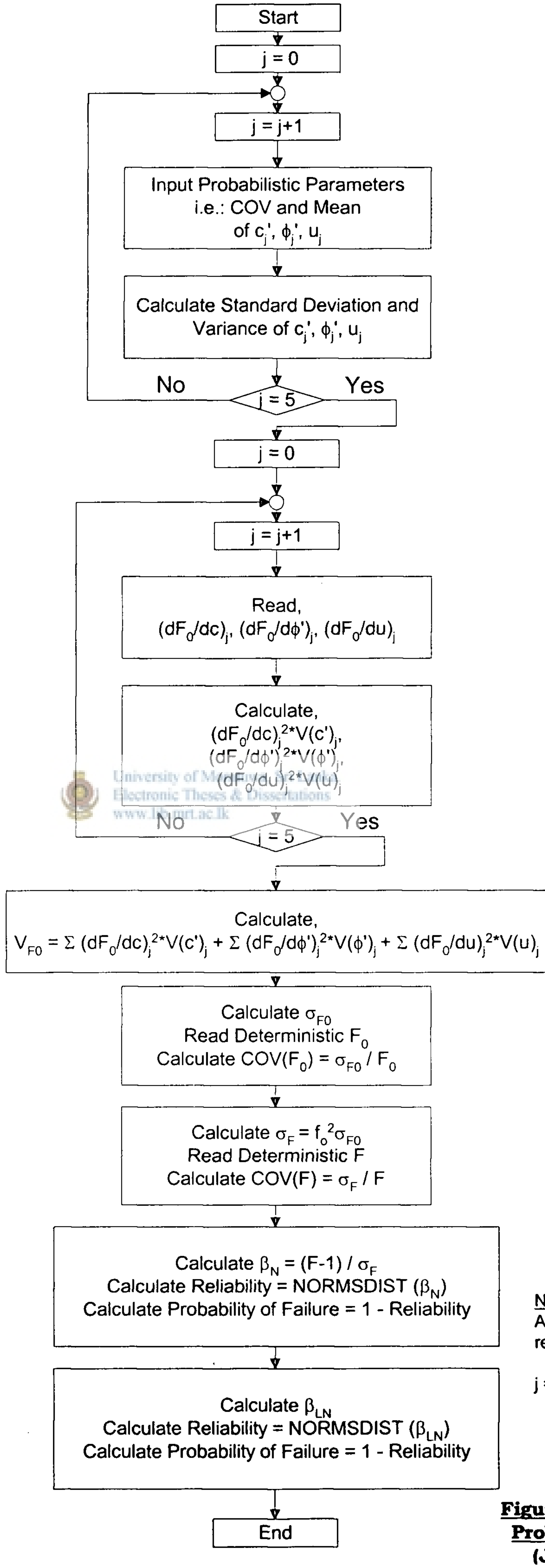
Figure 4.4: Folw diagram showing the Calculations worksheet (Janbu-Prob-Direct)



Note:
Alphabetical letters used represent the following:

i = "i" th slice
n = total number of slices
k = counter of the trial no. of the FOS

Figure 4.4: Folw diagram showing the Calculations worksheet (Janbu-Prob-Direct)



Note:
Alphabetical letters used represent the following:

j = number representing soil ty

Figure 4.5: Flow Chart for Probabilistic Worksheet (Janbu-Prob-Direct)

Case (ii): Spreadsheet for the model based on Bishop's simplified method - direct differentiation assuming $n_i(\theta)$ is probabilistic (File Name: *Janbu-Prob-Direct-Exact)*

Only change in this model is the equation that calculates the partial derivative of factor of safety with respect to the angle of internal friction (i.e.: $\partial F_0/\partial\phi'$). Hence, the flowchart is the same except the equation that computes $\partial F_0/\partial\phi'$.

Case (iii): Spreadsheet for the model based on Bishop's simplified method – Duncan (2000) and Small Increment methods (File Name: *Janbu-Prob-Small Increment)*

This spreadsheet consists of two main worksheets to perform deterministic and probabilistic calculations, and then a set of additional worksheets to perform deterministic calculations with varied parameters.

The deterministic worksheet calculates the mean factor of safety using the mean values of the parameters.

Probabilistic worksheet allows user to enter uncertainty of probabilistic parameters in terms of their coefficient of variation. It then calculates the standard deviation and the variance, but prompt the user to enter values for increments of c', ϕ' and u.

The other set of spreadsheets are then updated appropriately to change their properties (i.e.: c' ϕ', u) and deterministic factors of safety (i.e.: $F_{0,c1}^+$, $F_{0,c1}^-$, ...etc) are calculated according to new parameters (see section 3.4 for more details).

Probability of failure is calculated using finite difference calculus, and, the calculations result two values for probability of failure one using central difference formula, and the other using forward difference formula.

If the user is interested in obtaining the probability of failure according to Duncan (2000) method, the increments should be equal to the standard deviation of each parameter, and the central difference probability of failure should be referred to. Instead, any small increment can be entered if a user requires to increase the accuracy of the approximation.

Pore water pressure variations are treated in both ways as explained in section 2.2. If the pore pressures are dependant of the soil type, user can introduce separate values of coefficient of variation for each layer. If it is not dependent on the soil type, the user can enter a single value for coefficient of variation, which is constant for the whole slope. These spreadsheets require mean pore pressure values to be entered either to each soil layer, or to the whole slope, and the weighted average is recommended. A check similar to that explained in section 3.4 is made to assign zero values for the cells that contain negative pore pressure values (the reasons were explained in section 3.4).

The formulations of the spreadsheets are presented using flow diagrams in figures 4.6 and 4.7.

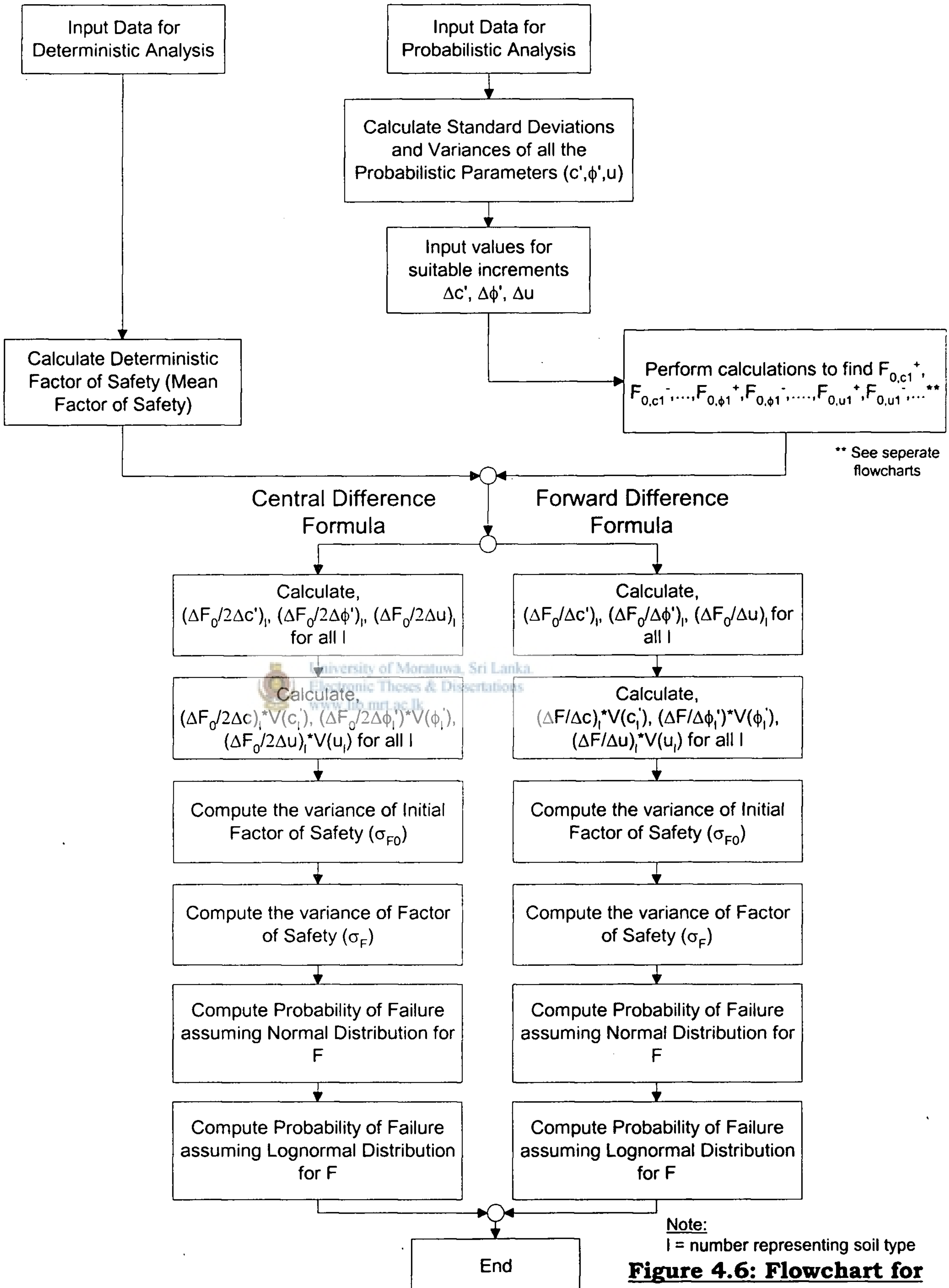
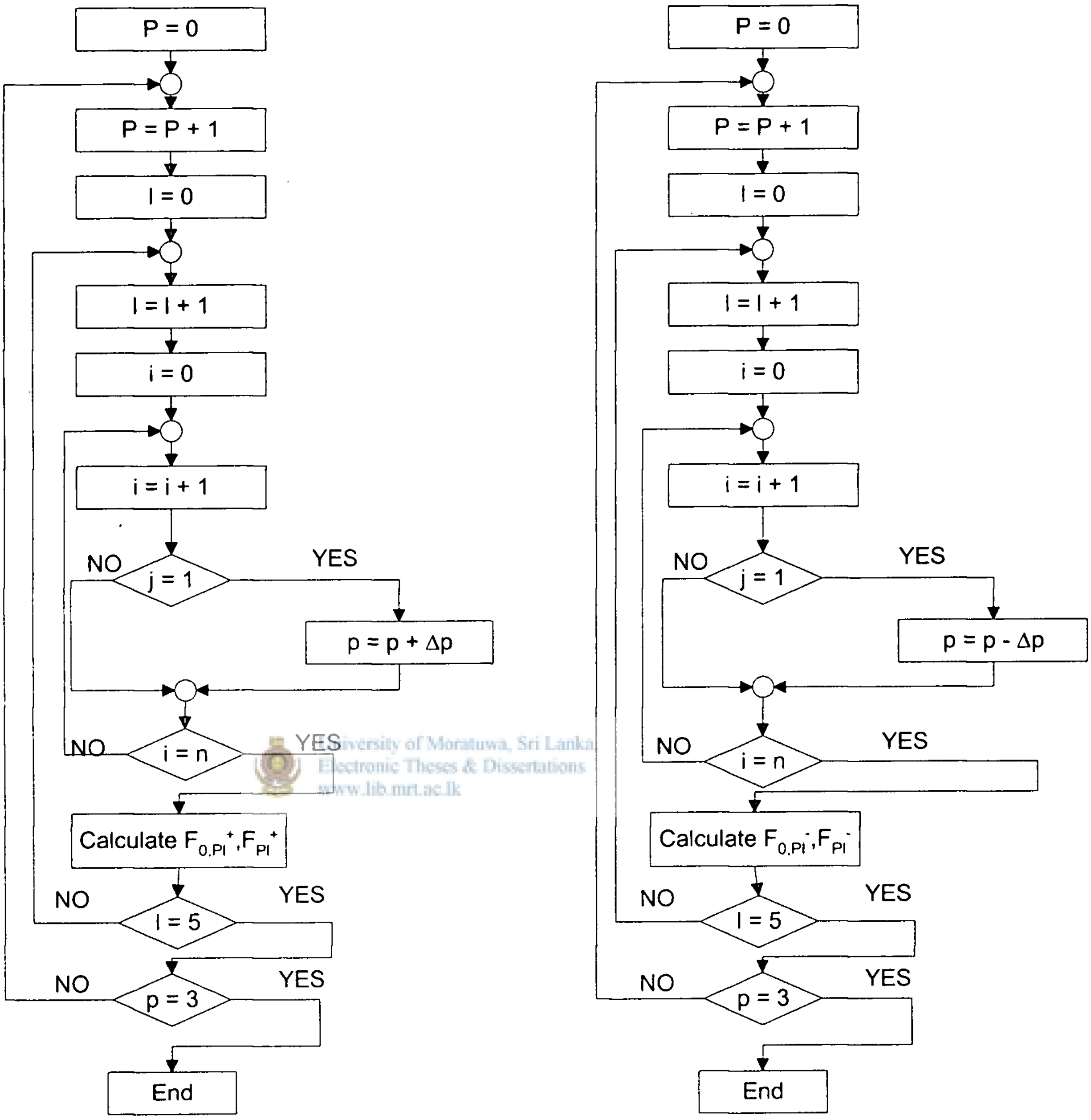


Figure 4.6: Flowchart for Small Increment Program (Janbu-Prob-SmallIncrement)



Flow diagram for the calculation of F_x^+

Flow diagram for the calculation of F_x^-

Note:
Alphabetical letters used represent the following:

i = "i" th slice
n = total number of slices
j = number representing soil type
I = number representing soil type
p = probabilistic parameter such as c', Φ', u
$F_{0,pl}$ represent cases of $F_{0,c1}$, $F_{0,c2}$, $F_{0,\Phi1}$, $F_{0,\Phi2}$ etc.

Figure 4.7: Flow diagram for calculation of Fx+ and Fx- (Janbu-Prob-SmallIncrement)

4.5 Application of the Models

4.5.1 General

These problems are also selected from Giam (1989), hence referee results for minimum factor of safety and critical failure surface are available from a group of specialists to validate the performance of our programs in deterministic computations. Results of Monte Carlo analysis based on the appropriate model (i.e.: Bishop or Janbu's simplified) along with that based on Spencer's method are used to validate the probabilistic computations. Out of them, Spencer's method was said to be one of the best methods available in slope stability analysis.

4.5.2 Example 2 (Ref: ACAD3)

This (figure 4.8) is an example for which, the analysis through a circular failure surface is quite unsuitable. The geological feature of the weak layer controls the position of the critical failure surface, hence some form of a non-circular analysis has to be used. Therefore, this is an ideal example to test the capabilities of programs that can handle highly irregular failure surfaces.

The water table is assumed to coincide with the base of the weak layer. The effect of negative pore pressure above the water table is to be ignored (i.e.: u = 0, above water table). The effect of tension crack is also to be ignored in this problem. Hence, although the analysis is an effective stress one, pore pressures do not enter into the calculations unless an inappropriate failure surface is chosen.

When the problem was analyzed by referee programs, which used Spencer method, Morgenstern and Price method and Generalized Wedge method that can handle non-circular failure surfaces, the given critical failure surface was obtained. Number of trial failure surfaces was tried in the process. Giam (1989) confirmed this critical failure surface through studies done with Upper Bound Plastic Theory (program EMU) and Finite Element techniques (using program CRISP). Since the critical failure surface was well established in that manner, it was used in the probabilistic studies discussed here.

According to Giam (1989), many of the respondents of their survey had not had a program in their possession to handle non-circular failure surfaces. Hence, they had used Bishop's analysis with a judicious choice of failure surface to attempt an approximate solution. The Bishop solutions for factor of safety were reported to be very high because the circular failure surface can have only a limited length in the weak soil layer. Hence, this example is thought to be suitable to show the importance of selecting a suitable failure mechanism in probabilistic analysis as well, if realistic results are required.

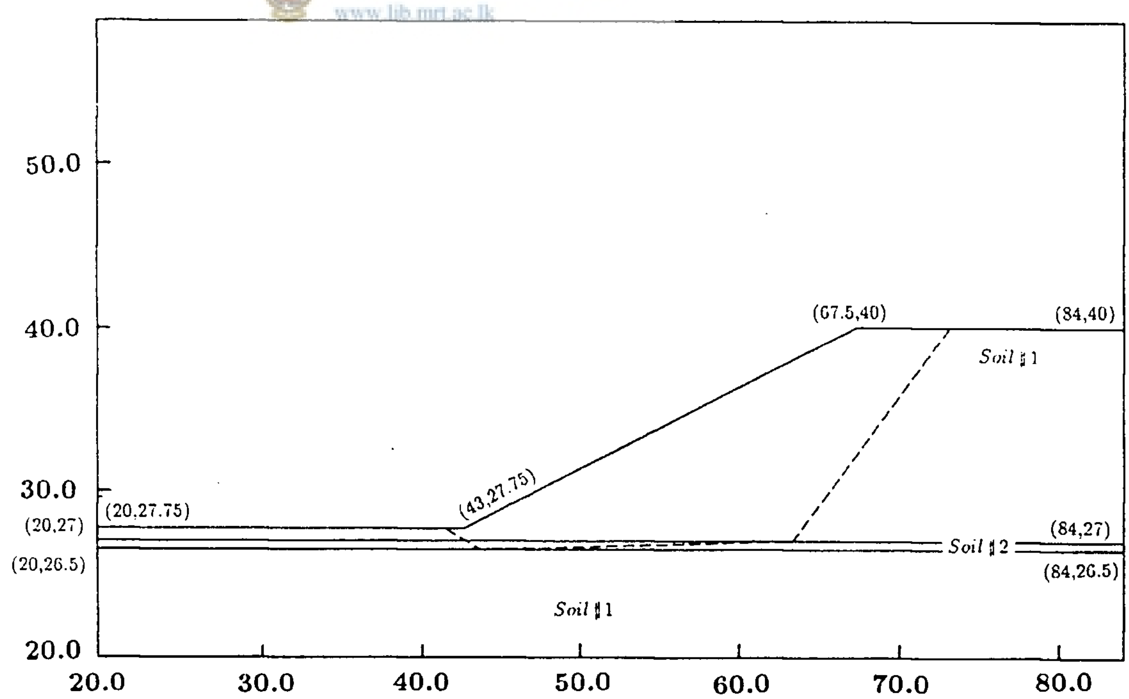


Figure 4.8: Example 2 Geometry

The effective strength parameters used for the deterministic analysis are given in table 4.1.

Soil Type	c' (kN/m²)	ϕ' (°)	γ (kN/m³)
1	28.5	20	18.84
2	0	10	18.84

Table 4.1: Deterministic Soil Parameters for Example 2

Deterministic Analysis

Deterministic analysis performed was twofold. First, non-circular analysis was performed for the selected failure surface shown in figure 4.8. Then, circular analysis was performed for a judicious circular failure surface obtained from SLIDE computer program. Division of the soil mass into slices, and extraction of slice information were done using AutoCAD. They were then fed manually into the spreadsheets.

The modification factor f_0 considered in the Janbu's analysis is 1.05.

Probabilistic Analysis

Reasonable values of coefficient of variation were selected based on some published values (Lee et.al, 1983, Duncan, 2000) and they are given in table 4.2.

Soil Type	COV (c')	COV(ϕ')
1	0.3	0.1
2	0	0.2

Table 4.2: Coefficients of Variation values for c' and ϕ'

Non-circular analyses were performed from all five methods discussed under section 4.1. For the small increment methods, an increment equal to 10% of the standard deviation was used. Monte Carlo analyses were performed using both Janbu's simplified method and Spencer's method, using the SLOPE/W computer program (Geo Slope Office, 1998). Standard deviation values used in Monte Carlo analyses were those computed from coefficient of variation values given in table 4.2.

Circular analyses were performed from all five methods discussed under section 3.1. Small increment was again the 10% of the standard deviation. Monte Carlo analyses were performed based on Bishop's and Spencer's methods using SLOPE/W computer program. The basic outline of the Monte-Carlo analysis performed using SLOPE/W computer program is presented in Annex 1. All other supporting documents for this example are given in Annex 2.

Results

Results of the analyses are given in tables 4.3 and 4.4. The graphical representation is given in figures 4.9 and 4.10.

	Analysis Program	Deterministic Model	Factor of Safety	Probability of Failure	
				Normal	Lognormal
1	Referee Solution		1.27	This perform only the deterministic analysis	
2	Direct Differentiation (n(θ) = deterministic)	Janbu' s simplified	1.2479[c]	4.92%	3.68%
3	Direct Differentiation (n(θ) = probabilistic)	Janbu' s simplified	-do-[c]	3.93%	2.80%
4	Duncan (2000) method	Janbu' s simplified	-do-[c]	8.34%	6.98%
5	Small Increment (Central Difference)	Janbu' s simplified	-do-[c]	8.35%	6.99%
6	Small Increment (Forward Difference)	Janbu' s simplified	-do-[c]	8.37%	7.00%
7	Monte-Carlo[a] Det. = 1.196[b]	Janbu' s simplified[a]	1.197–1.203[d]	10.669% - 12.35%[d]	SLOPE/W assumes normal distribution only
8	Monte-Carlo a Det. = 1.25[b]	Spencer	1.278 - 1.287[d]	3.84% - 4.827%[d]	

Note:

a. SLOPE/W computer program only uses uncorrected factor of safety for Janbu's simplified method

b. In SLOPE/W, deterministic value is slightly different from mean values

c. The uses same deterministic model

d. Monte-Carlo analysis gives different values for different trials. Hence a range of values are specified here for mean factor of safety and probability of failure

Table 4.3: Results of Non-Circular Analysis for Example 2

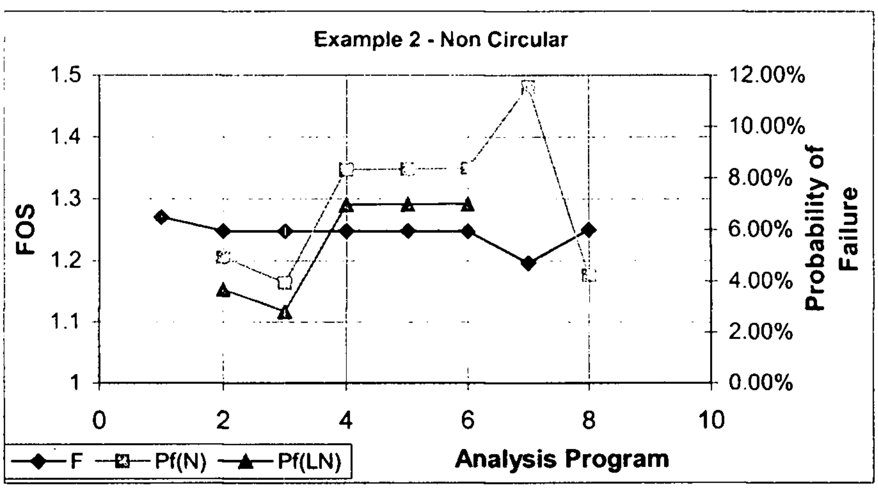


Figure 4.9: Results of Non-Circular Analysis for Example 2

	Analysis Program	Deterministic Model	Factor of Safety	Probability of Failure	
				Normal	Lognormal
1	SLIDE		1.561	This perform only the deterministic analysis	
2	Direct Differentiation (M(θ) = deterministic)	Bishop' s simplified	1.57[b]	0.29%	0.04%
3	Direct Differentiation (M(θ) = probabilistic)	Bishop' s simplified	-do-[b]	0.22%	0.02%
4	Duncan (2000) method	Bishop' s simplified	-do-[b]	0.55%	0.09%
5	Small Increment method (Central Difference)	Bishop' s simplified	-do-[b]	0.55%	0.09%
6	Small Increment (Forward Difference)	Bishop' s simplified	-do-[b]	0.55%	0.09%
7	Monte-Carlo Det. = 1.643[a]	Bishop' s simplified	1.642–1.644[c]	0.099% - 0.114%[c]	SLOPE/W assumes normal distribution only
8	Monte-Carlo Det. = 1.639[a]	Spencer	1.639 to 1.641[c]	0.101% - 0.124%[c]	

Note:

a. In SLOPE/W, deterministic value is slightly different from mean values

b. The uses same deterministic model

c. Monte-Carlo analysis gives different values for different trials. Hence a range of values are specified here for mean factor of safety and probability of failure

Table 4.4: Results of Circular Analysis for Example 2

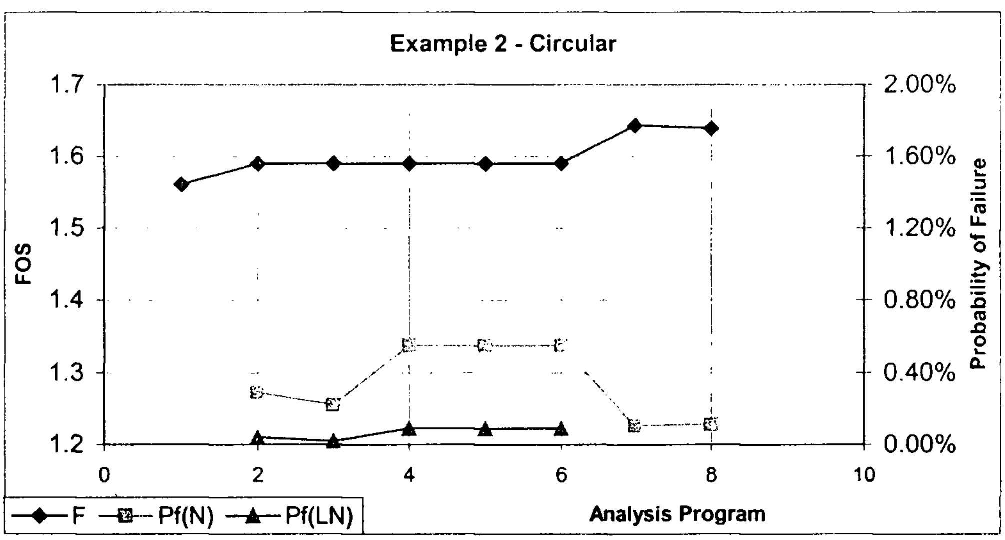


Figure 4.10: Results of Circular Analysis for Example 2

Discussion of Results

The deterministic factor of safety value for non-circular analysis obtained from author's model agrees very well with the Spencer result obtained from SLOPE/W computer program. They differ from quoted referee value only by 0.02. Hence, the results are well acceptable. Janbu value from SLOPE/W differs from the above since it only gives the uncorrected factor of safety, F_0. When it is corrected using the correction factor of 1.05 (the value used in author's models), it gives values very close to the author's ones.

Probabilistic results from author's models can be broadly divided into two ranges. The direct differentiation results normal probability of failure values between 3.93% and 4.92%. But the values obtained from approximate methods show a considerable difference from these values having a range of values between 8.34% and 8.37%. Author's results from direct differentiation agree well with the probability of failure obtained from Spencer based Monte Carlo analysis. Janbu based Monte Carlo analysis cannot be used in the comparison since it gives results based on the uncorrected factor of safety.

For the Monte-Carlo analyses, the mean factor of safety slightly changes from the deterministic factor of safety (see annex 1), and it also gave slightly different values for different trials. Therefore, in table 4.3, deterministic factor of safety is separated from mean factor of safety. Also, mean factor of safety and probability of failure values obtained from number of trials, which include different Monte Carlo analyses with 1000, 5000 and 50000 trials, are given as a range of values. However, in the graphical representation given in figure 4.9 and 4.10, average values out of these ranges are used.

As expected, factor of safety values from circular analyses are high, and the corresponding probability of failure values are less than the actual values. Especially, probability of failure values are very low, giving values below 0.5%. Hence, it shows the inappropriateness of the circular analysis to this type of slopes. Therefore, it is essential in probabilistic analysis as well, to select the appropriate failure mechanism (or deterministic model), if realistic results are required.

Without considering the inappropriateness of the circular failure surface, if the results from various models are compared, all the values are quite close (In between 0.1% and 0.55%). Again the values computed by approximate differentials were slightly greater than those computed by the direct differentiation. Assumption that the factor of safety has a lognormal distribution resulted in lower values of probability of failure.

4.5.3 Example 3: (Ref: ACAD4)

This example (figure 4.11) introduces number of complications simultaneously – varying pore water pressures in the region of interest, toe and crest surcharges, both uniform and non-uniform and a weak layer to control the position of the critical surface. The pore pressures are to be computed using a flow net appropriate for the given piezometric surface.

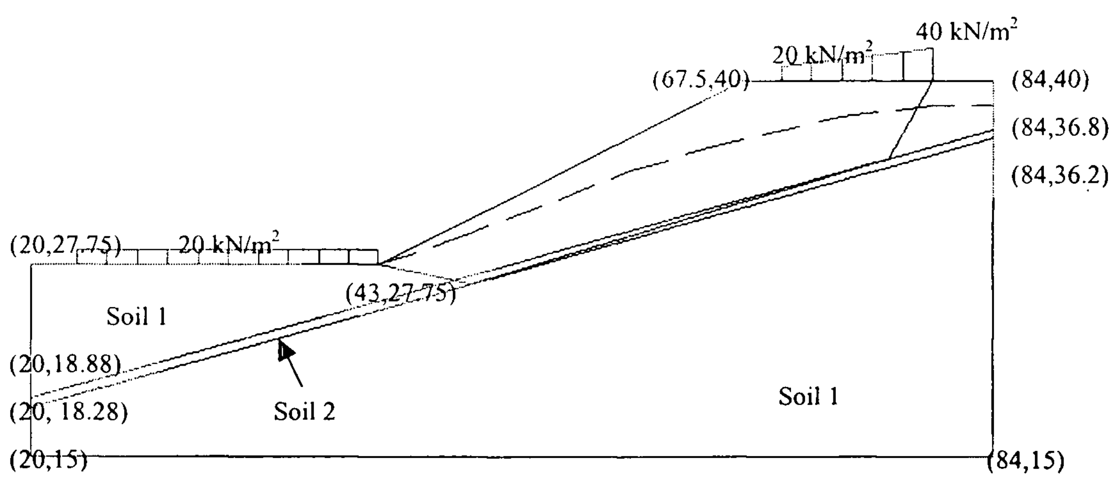


Figure 4.11: Example 3 Geometry

The analysis is based on effective stresses, and the strength parameters considered are given in table 4.5.

Soil Type	c′ (kN/m^2)	ϕ' (^{0})	γ (kN/m^3)
1	28.5	20	18.84
2	0	10	18.84

Table 4.5: Deterministic Soil Parameters for Example 3

Deterministic Analysis

Analysis was performed in two ways. First, non-circular analysis was performed for the failure surface given in figure 4.11. As with the previous problem, the critical failure surface was established through analyses done with referee programs that used methods such as Spencer method, Janbu's rigorous method, generalized wedge method, upper bound plastic theory and finite element techniques. Then, circular failure surface analysis was performed with a judicious failure surface obtained from SLIDE computer program.

Pore water pressures were estimated by constructing a flow net as shown in Annex 2.

Failure mass for non-circular analysis was divided into 14 slices, limiting the maximum slice width to 3.2m. However, the average slice width was 2.9m. Janbu's modification factor used was 1.045.

For the circular analysis, the failure surface obtained from SLIDE was used. Same vertical lines were used to divide the failure mass into slices. Finally, total of 12 slices came within the failure mass, having an average slice width of 2.9m.

Probabilistic Analysis

Reasonable values of coefficient of variation were selected based on some published values (Lee et.al, 1983, Duncan, 2000) and they are given in table 4.6.

Soil Type	COV (c′)	COV(ϕ′)
1	0.3	0.1
2	0	0.2

Table 4.6: Coefficient of Variation values for c′ and ϕ′ (Example 3)

As in example 3, Non-circular analyses were performed from all five methods discussed under section 4.1. For the small increment methods, an increment equal to 10% of the standard deviation was used. Monte Carlo analyses were performed using both Janbu's method and Spencer's method, using the SLOPE/W computer program (Geo Slope Office, 1998). Standard deviation values used in Monte Carlo analyses were the computed from coefficient of variation values given in table 4.6.

Circular analyses were performed from all five methods discussed under section 3.1. Small increment was again the 10% of the standard deviation. Monte Carlo analyses were performed based on Bishop's and Spencer's methods.

Pore pressures were treated in both ways that were discussed in section 2.2. Coefficient of variation values and the mean values of pore water pressures for the case where they are treated on the basis of soil layers are given in table 4.7. The mean pore pressures for each soil layer were selected to be the weighted average.

Soil Type	Mean u (kN/m²)	COV (u)
1	13.29	0.3
2	36.05	0.2

Table 4.7: Mean and Coefficients of Variation of u for Example 3

For the case where the pore pressure variability is defined for the whole slope, the mean value was again the weighted average. The coefficient of variation for this case was obtained from the method explained in section 3.5.2.2. Hence, the mean pore water pressure was 31.13 kN/m^2 and the coefficient of variation was 0.21.

In Monte-Carlo analysis, an equivalent standard deviation for the piezometric head was selected in such a way that it gives rise to the same standard deviation of average pore water pressure. Therefore the value of the standard deviation of head was 0.66m. All the supporting documents for this example are given in Annex 2.

Results:

Results of the analysis are given in table 4.8 and 4.9. As discussed in Example 2, deterministic and mean values were different for SLOPE/W analysis. Also, probabilistic analysis gave slightly different values for different trials. Hence deterministic values have been separated from probabilistic values and also probabilistic values are given as a range.

	Analysis Program	Pore Pressure COV	Deterministic Model	Factor of Safety	Probability of Failure	
					Normal	Lognormal
1	Referee Solution	Not Applicable		0.78	Performs only the deterministic analysis	
2	Direct Differentiation	Based on soil layers	Janbu's simplified	0.733[c]	99.56%	98.96%
3	(n(θ) = deterministic)	Constant for the slope	Janbu's simplified	-do-[c]	99.34%	98.61%
4	Direct Differentiation	Based on soil layers	Janbu's simplified	-do-[c]	99.86%	99.56%
5	(n(θ) = probabilistic)	Constant for the slope	Janbu's simplified	-do-[c]	99.74%	99.30%
6	Duncan (2000)	Based on soil layers	Janbu's simplified	-do-[c]	99.46%	98.79%
7	method	Constant for the slope	Janbu's simplified	-do-[c]	99.12%	98.27%
8	Small Increment	Based on soil layers	Janbu's simplified	-do-[c]	99.46%	98.79%
9	(Central Difference)	Constant for the slope	Janbu's simplified	-do-[c]	99.12%	98.27%
10	Small Increment	Based on soil layers	Janbu's simplified	-do-[c]	99.46%	98.79%
11	(Forward Difference)	Constant for the slope	Janbu's simplified	-do-[c]	99.12%	98.27%
12	Monte-Carlo[a] Det F= 0.67[b]	Based on Piezometric Head	Janbu's simplified[a]	0.666 – 0.678[d]	99.46% - 99.76%[d]	SLOPE/W assumes normal distribution only
13	Monte-Carlo Det F=0.741[b]		Spencer	0.731 – 0.742[d]	99.78% - 99.92%[d]	

Note:

a. In SLOPE/W Janbu analysis, results are based on uncorrected factor of safety

b. Deterministic value is slightly different from mean value

c. These use the same deterministic model

d. Different Monte-Carlo trials result in different values. Hence a range is specified here for mean values

Table 4.8: Results of Non-Circular Analysis for Example 3

	Analysis Program	Pore Pressure COV	Deterministic Model	Factor of Safety	Probability of Failure	
					Normal	Lognormal
1	Direct Differentiation (M(θ) = deterministic)	Based on soil layers	Bishop's simplified	1.1189[b]	25.33%	26.53%
2		Constant for the slope	Bishop's simplified	-do-[b]	25.42%	26.64%
3	Direct Differentiation (M(θ) = probabilistic)	Based on soil layers	Bishop's simplified	-do-[b]	21.74%	22.31%
4		Constant for the slope	Bishop's simplified	-do-[b]	22.41%	23.09%
5	Duncan (2000) method	Based on soil layers	Bishop's simplified	-do-[b]	24.09%	25.05%
6		Constant for the slope	Bishop's simplified	-do-[b]	24.66%	25.79%
7	Small Increment (Central Difference)	Based on soil layers	Bishop's simplified	-do-[b]	24.04%	24.99%
8		Constant for the slope	Bishop's simplified	-do-[b]	24.62%	25.68%
9	Small Increment (Forward Difference)	Based on soil layers	Bishop's simplified	-do-[b]	24.14%	25.11%
10		Constant for the slope	Bishop's simplified	-do-[b]	24.88%	25.99%
11	Monte-Carlo Det F= 1.110[a]	Based on Piezometric Head	Bishop's simplified	1.122	25.95%	SLOPE/W assumes normal distribution only
12	Monte-Carlo Det F=1.122[a]		Spencer	1.133	23.90%	
	Note: a. Deterministic value is slightly different from mean value b. These use the same deterministic model					

Table 4.9: Results of Circular Analysis for Example 3

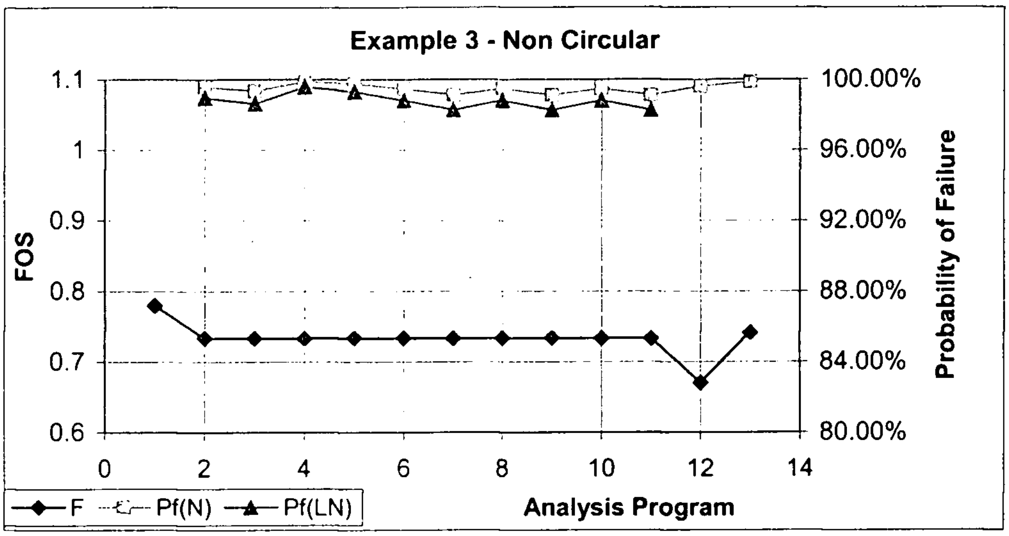


Figure 4.12: Results of Non-Circular Analysis (Example 3)

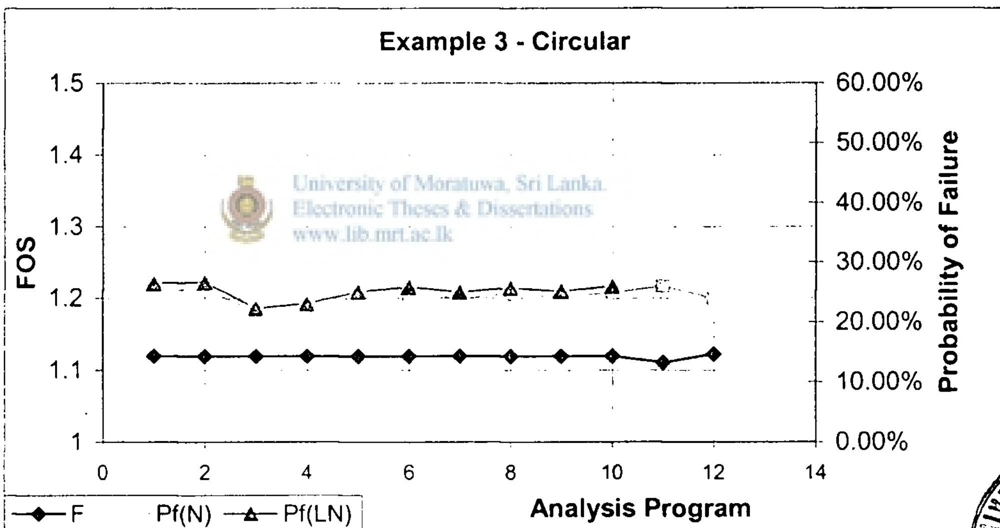


Figure 4.13: Results of Circular Analysis (Example 3)

Discussion of Results

The factor of safety for non circular analysis from author's models slightly differ from the quoted referee values by 0.05, but agree very well with the Spencer deterministic factor of safety obtained from the SLOPE/W computer program. Hence, the models were assumed to be working properly in the deterministic computations. As expected, Janbu's uncorrected factor of safety from the computer program was different, but once corrected it became much closer to the author's factor of safety.

Results from all the methods show a probability of failure around 99% indicating that the slope is highly unstable. Even results based on uncorrected Janbu analysis showed this situation. An information that can be obtained is that for this slope, the small difference in the factor of safety within the given region of interest is not a crucial factor to affect the probability of failure.

Circular analysis, as expected, gave different results with comparatively lower probability of failure values for this slope. It again shows the inappropriateness of the circular analysis to a problem of this nature.

However, when the results of the circular analysis are compared within themselves, they show all the author's models, except the method that assumes $M(\theta)$ is probabilistic, perform well to give close results with those obtained from computer programs.

4.6 Concluding Remarks

Probabilistic models that can handle highly irregular non-circular failure surfaces were presented. Performance of the models was illustrated with two different examples covering two different realistic situations. Comparison with accepted computer programs indicated that author's models that assume $n(\theta)$ as a deterministic quantity performs highly satisfactorily. Performance of approximate methods based on Janbu's models agree very well within themselves, but produced slightly higher probabilities of failure in example 2. Performance of the model that assumes $n(\theta)$ as a probabilistic quantity also gave somewhat satisfactory results, but may also need further checking.

It was also shown that for problems with weak layers that can govern the shape and position of the actual failure surface, the use of a circular failure surface is highly inappropriate. This fact is proved to be true for probabilistic analysis as well. Hence, it is essential to understand the possible failure mechanisms, before any kind of analysis, whether deterministic or probabilistic, are applied.

Although inappropriate for the examples considered in this chapter, circular analysis performed gave further data to validate the probabilistic models based on Bishop's simplified method. From the two slope problems studied performance of models were found to be satisfactory, except for the slightly lower values given under the assumption M(θ) is deterministic.

Chapter 5

PROBABILISTIC BASED ASSESSMENT OF DIFFERENT STABILIZATION METHODS

5.1 Introduction

Landslides are frequently responsible for considerable losses of both money and lives. Severity of landslide problem has been worsened with the increased development and change in land use. Blockage of natural streams, deforestation, building on unstable slopes, modification of slopes for buildings and highway expansions are some of the reasons that have increased the risk of landsliding throughout the world. On the other hand, side slopes in earth works must be designed to have an acceptable margin of safety. Hence, the stabilization of slopes has become increasingly important in geotechnical engineering.

Whether it is a natural slope, or an artificial slope, the causes of instability are quite similar. They can be summarized as follows:

1) the slope is too high or too steep for the material of which it is composed

2) the materials are too weak to sustain the slope at its present profile
3) the pore water pressures are too high, and thus adversely affect the soil strength
4) the material contain weak inclusions or discontinuities
5) the slope is affected adversely by some external influence, for example seismic loading, or applied loads from a structure.

Hence, the principles behind the rational approach in designing a new slope and stabilization of an existing slope are similar.

Commonly adopted slope stabilization measures can be broadly classified as:

1) cut and fill solutions
2) drainage, and
3) use of structural systems

According to Bromhead (1992), the first response to any slope instability problem must always be to consider the use of re-grading or cuts and fills as the main element of the scheme. The methods include changing slope geometry to produce a flatter slope, head unloading by removal of soil and replacing with lightweight material, and having a toe load. Flattening of slope may improve the stability, but it would make large area of land unusable. Head unloading is a satisfactory measure in short-term, but may require additional measures in long-term. Toe loading, the most effective stabilization measure that falls under cut and fill solutions provide immediate results, and also once placed, it is unlikely to be removed. In addition, it may serve in dual purpose reducing toe erosion as well.

Drainage alone can be considered as the sole stabilization method if the development of excess pore water pressure is found to be the triggering factor in the slope instability. It becomes immediately effective where large flows in permeable strata can be intercepted. Slope stabilization by drainage involves both surface drainage improvement and subsurface drainage improvement. Surface drainage and landscaping of the site reduces the ingress of water into the unstable soil mass, while subsurface drains inserted into relatively impermeable soil layers facilitate the rapid dissipation of pore water pressures. Subsurface drains can be in the form of sub-horizontal drains at a small inclination to the horizontal or directional drains following a critical failure surface.

Structures constructed in unstable slopes are the third means of primary stabilization, and mainly divided into two classes viz., active and passive methods. Active methods include methods such as ground anchors and rock bolts, while the passive methods include methods such as soil nailing, unstressed anchor dowels and piling across slip surfaces. Both active and passive methods can be used successfully, but to become successful, passive schemes require further movement of the slide to mobilize the full resistance of the structural system.

Once the probabilistic analytical models have been developed, the next attempt was to investigate the possible use of the concept of probability of failure in practice. Hence, it was decided to evaluate the effectiveness of various stabilization measures in probabilistic terms.

Almost all the slope failures in central Sri Lanka are triggered by excessive rainfall. Hence, the use of surface and subsurface drainage would be the primary method of stabilization. As such, the effectiveness of drainage was studied in the research within a probabilistic framework.

In slopes where considerable movements have already taken place, strength would have reduced to residual values and some form of additional external support such as soil nailing would be helpful in improving the safety margin. As such, additional probabilistic models were developed to study the slopes stabilized by soil nailing.

Soil nailing is a practical and cost-effective method used very effectively in many countries including France, USA, Australia, Germany etc. The method includes insertion of number of passive elements into the ground such that they cross potential failure surfaces. As the ground deforms, the nails become stressed in tension, thus resisting movements. The method has gained its popularity because of number of advantages it carry including the low cost, requirement of only light construction equipment, fast rate of construction and the flexibility associated with the method to change the design according to what is encountered during construction. In addition it allows the use of a grassy facing to go in hand with the increasing environmental considerations. Therefore, author believes that it is a method worth discussing further, although it is yet to become popular in Sri Lanka.

Soil nailing had successfully been used in stabilization of cut slopes, excavation support and repair of other structures such as retaining walls. Comprehensive coverage of the method is available in American Society of Civil Engineers (1997), Bruce and Jewel (1986, 1987), Johnson et.al. (1995), Mitchell and Villet (1987), Ortigao et.al. (1995) and Xanthakos et. al. (1994).

The effectiveness of drainage can be evaluated in probabilistic terms without any modification of the basic models developed under chapters 3 and 4. However, discussion of the effectiveness of soil nailing systems needed the basic models for both deterministic models and probabilistic models to be modified to include their effects.

The deterministic analytical models developed under the undergraduate research project of the author were available for the soil nailing technique (Mettananda et.al., 2001), hence, these models were selected for further improvement.

5.2 Development of Probabilistic Models based on Bishop's Simplified Method to analyze Soil Nailed structures

5.2.1 Basis of the Method

Deterministic equation derived to account for the soil nails (Mettananda et.al., 2001) was selected as the basis of the probabilistic models. The equation is given as:

$$\therefore \quad F = \frac{\sum\left\{\left[c'\Delta x_i + \left(w_i + Q_i - u_i\Delta x_i + T_{N,i}\sin\alpha\right)\tan\phi'\right]\left[\frac{1}{M_i(\theta)}\right]\right\}}{\sum\left[\left(w_i + Q_i\right)\sin\theta_i - T_{N,i}\cos\left(\theta_i + \alpha_i\right)\right]} \quad \ldots\ldots\ldots\ldots(5.1)$$

where $M_i(\theta)$ is given by equation 3.2. In this equation;

$$T_N = \text{lesser of } [\text{Nail strength, Pullout Resistance}]$$

$$= \text{lesser of}\left[n\frac{\pi d^2}{4}f_y \;\; , f_b \times n \times \pi d l\left(c'+\sigma'\tan\phi'\right)\right] \ldots\ldots\ldots(5.2)$$

The terms used in the above equations are illustrated in figure 5.1.

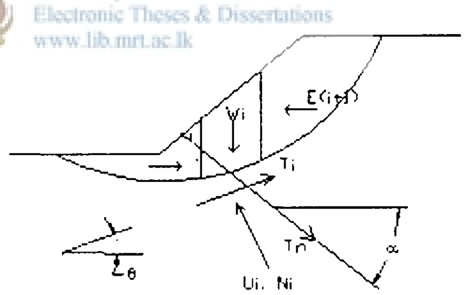


Figure 5.1: Forces acting on a Slice (Bishop's Model – Nailed Slope)

First order second moment method was used to develop the probabilistic models. Mean factor of safety is calculated using mean values of parameters, while the variance is calculated using equation 1.10. As illustrated in chapter 3, direct differentiation method (assuming M(θ) is deterministic) was found to be most successful in evaluation the partial derivative. Hence, it was used to evaluate the effectiveness of soil nailing.

5.2.2 Assignment of Uncertainties

Soil strength parameters and pore water pressures are treated as probabilistic parameters. Force mobilized in nails was treated as a deterministic quantity to avoid unnecessary complications of the resulting equations. Pore water pressures were assumed to have a constant coefficient of variation throughout the slope.

5.2.3 Derivation of Partial Derivatives

The partial derivatives obtained assuming $M_i(\theta)$ is deterministic are as follows:

$$\frac{\partial F}{\partial c'} = \frac{\sum\left(\frac{\Delta x_i}{M_i(\theta)}\right)}{\sum\left((W_i + Q_i)\sin\theta_i - T_{N,i}\cos(\theta + \alpha)\right)} \quad \ldots\ldots\ldots\ldots(5.3)$$

$$\frac{\partial F}{\partial \phi'} = \frac{\sum\left\{(W_i + Q_i - u_i\Delta x_i + T_{N,i}\sin\alpha)\frac{\sec^2\phi'}{M_i(\theta)}\right\}}{\sum\left\{(W_i + Q_i)\sin\theta_i - T_{N,i}\cos(\theta + \alpha)\right\}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(5.4)$$

$$\frac{\partial F}{\partial u} = \frac{\sum\left(-\frac{\Delta x_i\tan\phi'}{M_i(\theta)}\right)}{\sum\left\{(W_i + Q_i)\sin\theta_i - T_{N,i}\cos(\theta + \alpha)\right\}} \ldots\ldots\ldots\ldots\ldots\ldots(5.5)$$

5.2.4 Development of Spreadsheet

The spreadsheet consisted of four worksheets, viz., Deterministic Worksheet, Probabilistic Worksheet, Calculations Worksheet and Nail Resistance worksheet.

The deterministic worksheet, as usual, allows user to enter parameters regarding the slope. In addition, it allows entering of data regarding the nails passing through each slice. These data include;

- number of nails passing through the slice over a unit width
- diameter of nails
- effective length of nails beyond the failure surface
- the bond coefficient (this is analogous to the bond coefficient used in other reinforcing techniques)
- strength of nail material
- average depth from the top, and
- the inclination of the nails to the horizontal.

Nail resistance worksheet reads all these input data and computes the mobilized nail force to be the lesser of the pullout resistance and the tensile strength. The pullout strength is dependent on the overburden stress, and it is automatically calculated using the depth to the nail. However, if there is any surcharge involved, the user has to input the value manually in this worksheet, since it is not concentrated only to that particular slice. User has to assume 2:1 stress distribution, and enter values into any of the slices, if it is necessary to account for the surcharge effect on the pullout resistance. Otherwise, it will underestimate the mobilized force in nails. Also, when there is a thin weaker layer is present, and if a nail passes through both stronger and weaker layers, some reasonable values for strength parameters have to be manually inserted in the nail resistance worksheet for the particular nail. Without considering this effect, if the strength parameters relevant to the particular slice are used, the force mobilized in nails may not be correct.

Calculation worksheet reads all the input data from the deterministic worksheet and the nail force from the nail resistance worksheet, and then calculates the final factor of safety of the slope, after iterating over four trials. It is observed here that the convergence is slower than that for the slopes without nails. However, it converged at the end of the third trial for a number of examples considered. In addition, calculations worksheet, as usual, computes the partial derivatives applicable.

The probabilistic worksheet as in the earlier cases, gets input data, and the partial derivatives, and computes factor of safety assuming both normal distribution and the lognormal distribution. Formulations of each worksheet are illustrated in figures 5.2 to 5.6.

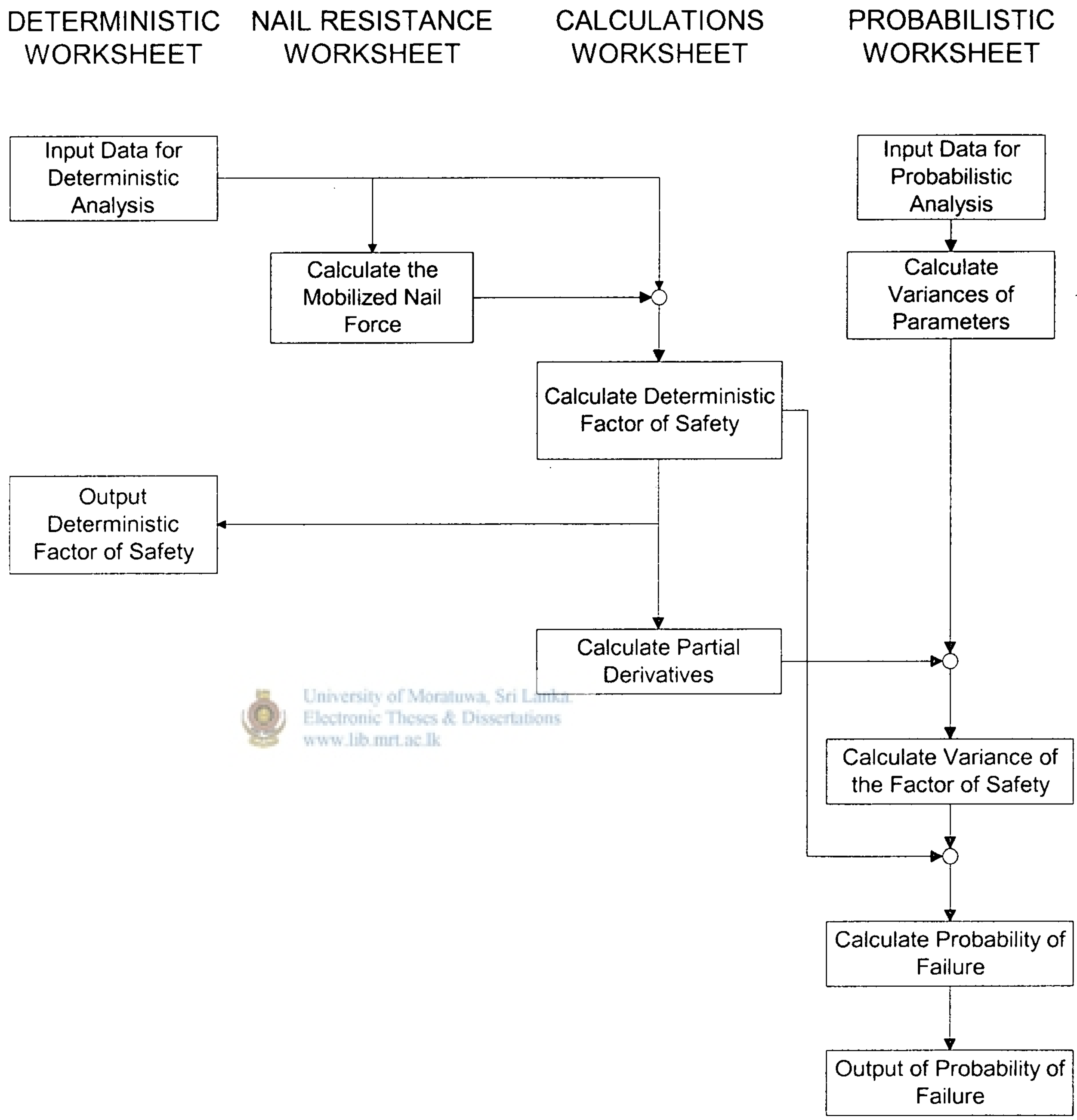
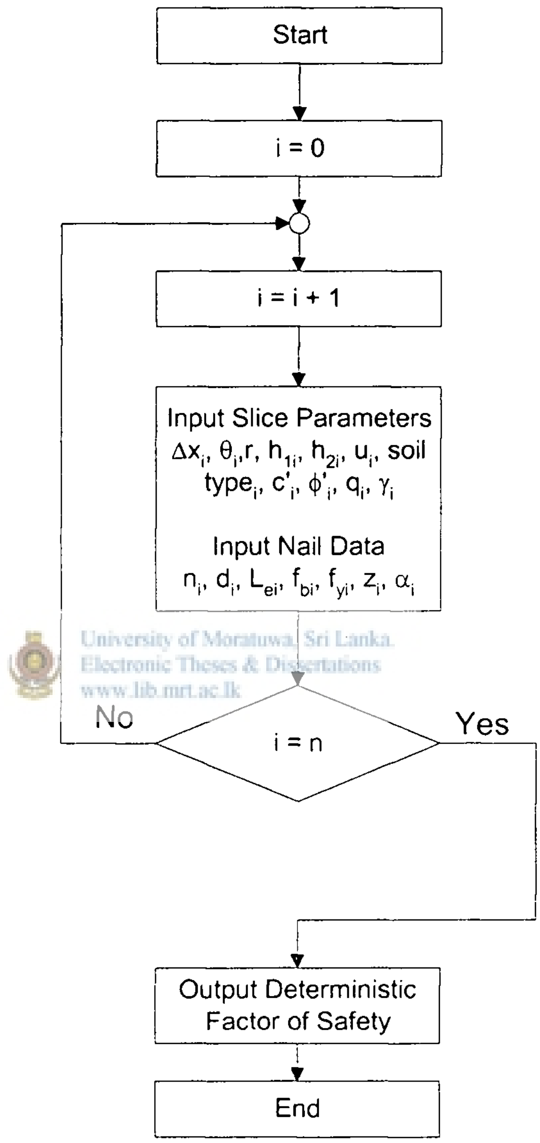


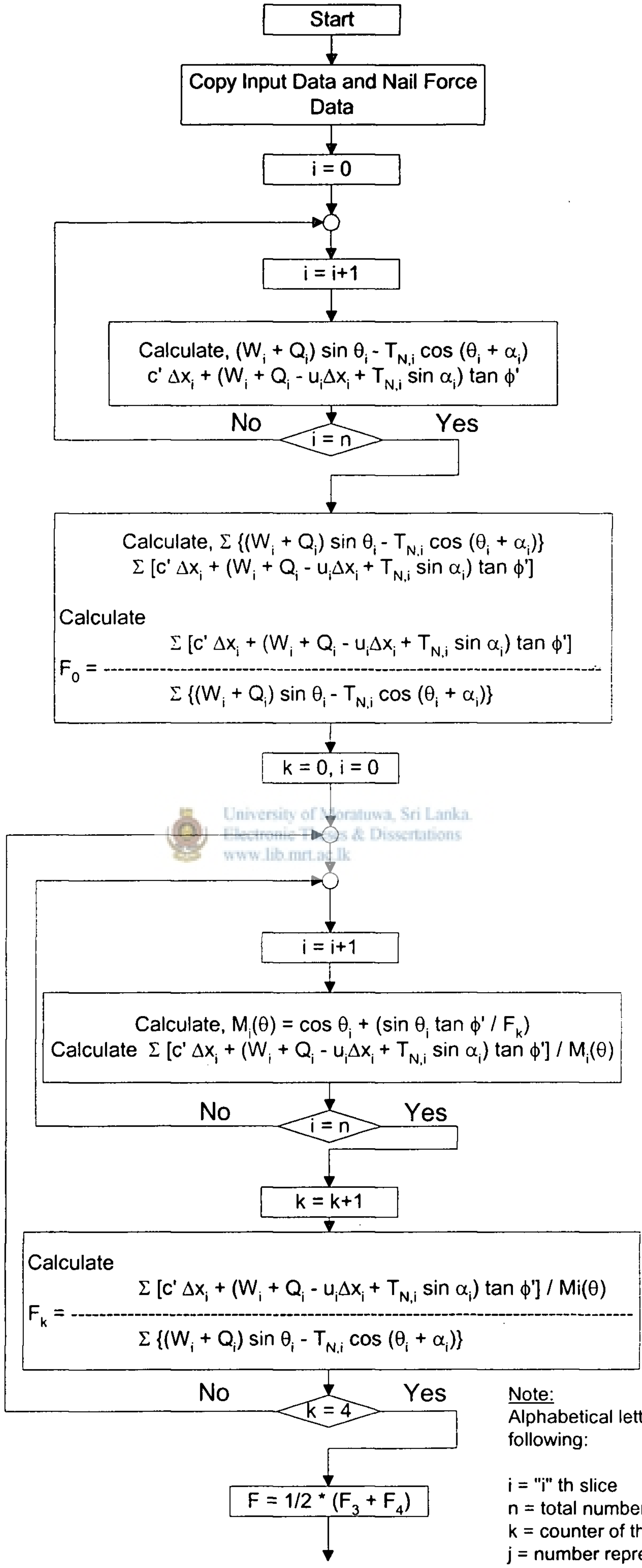
Figure 5.2: Flow chart showing the overview of the Spreadsheet (Soil Nailed Slope -Based on Bishop's Method)



Note:

i = "i" th slice
n = total number of slices

Figure 5.3: Flow chart for Deterministic Worksheet (Soil Nailed Slope - Bishop's Method)



Note:
Alphabetical letters used represent the following:

i = "i" th slice
n = total number of slices
k = counter of the trial no. of the FOS
j = number representing soil type

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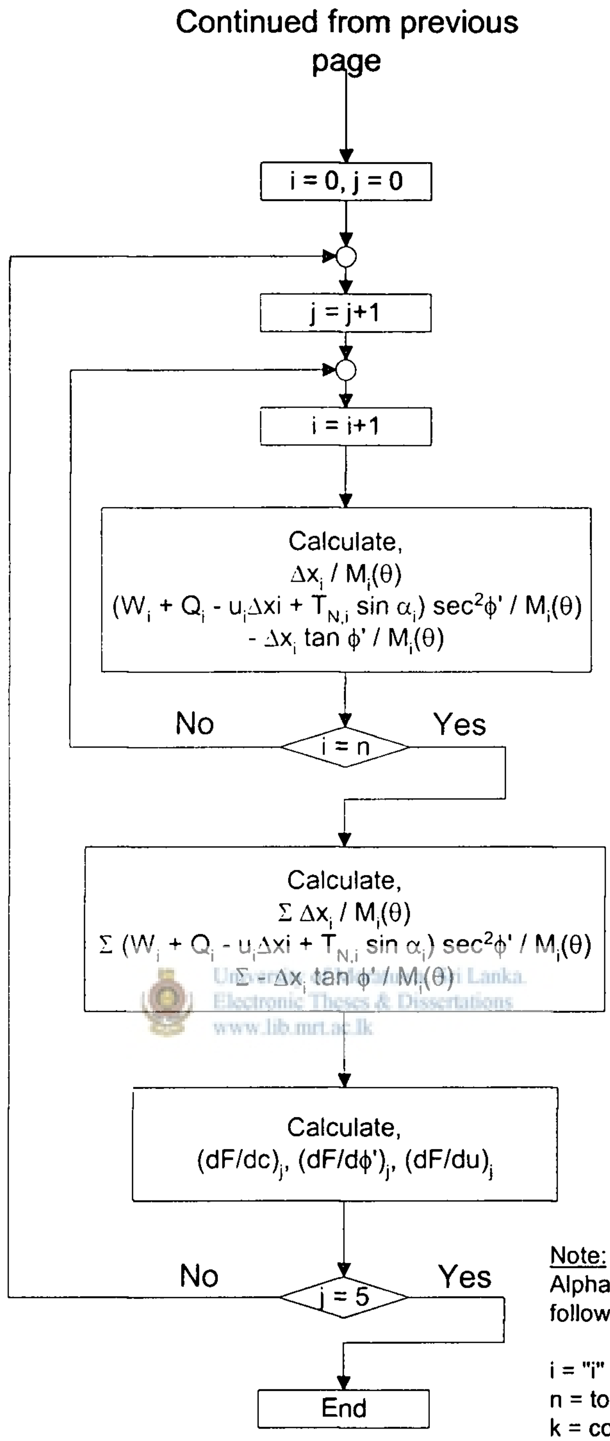
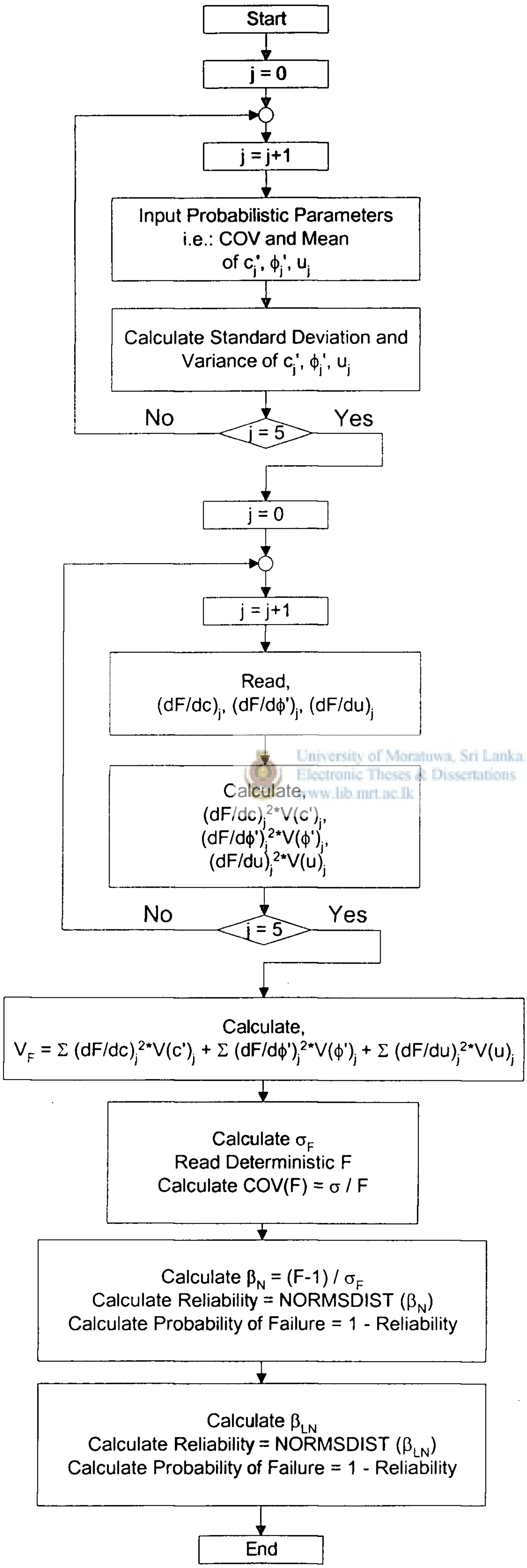
Figure 5.4: Folw diagram showing the Calculations worksheet (Soil Nailed Slope - Based on Bishop's Method)



Note:
Alphabetical letters used represent the following:

i = "i" th slice
n = total number of slices
k = counter of the trial no. of the FOS
j = number representing soil type

Figure 5.4: Folw diagram showing the Calculations worksheet (Soil Nailed Slope - Based on Bishop's Method)



Note:

j = number representing soil type

Figure 5.5: Flow Chart for Probabilistic Worksheet (Soil Nailed Slope - Bishop's Method)

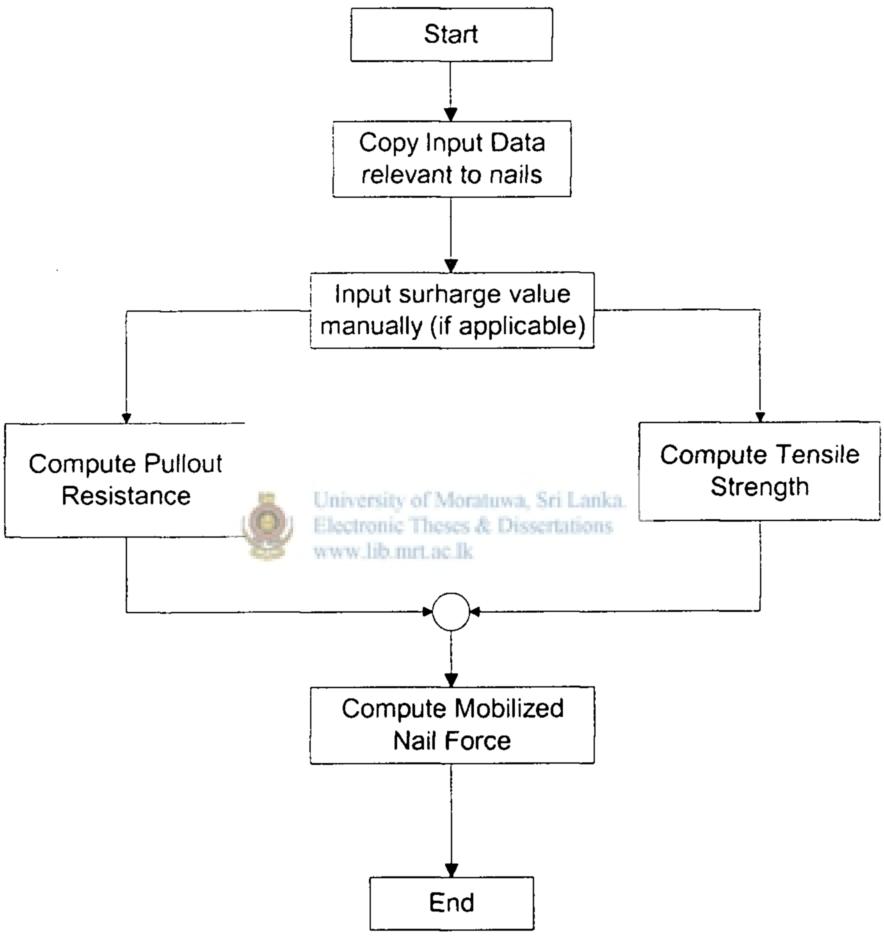


Figure 5.6: Flow diagram for Nail Resistance Worksheet (Soil Nailed Slope - Based on Bishop's Method

5.3 Development of Probabilistic Models based on Janbu's Simplified Method to analyze Soil Nailed structures

5.3.1 Basis of the Model

Deterministic equation derived to account for the soil nails (Mettananda et.al., 2001) was selected as the basis of the probabilistic models. The equation for uncorrected factor of safety is given as:

$$F_0 = \frac{\sum \{(c' \Delta x_i + (W_i + Q_i - u_i \Delta x_i)\tan\phi')/n_i(\theta)\}}{\sum W_i \tan\theta_i} \quad \ldots\ldots(5.6)$$

where $n_i(\theta)$ is given by equation 4.2. In this equation T_N has the same meaning as in the section 5.2.1. The corrected factor of safety is then given by:

$F = f_0 {*} F_0$ ....(5.7)

The terms used in the above equations are illustrated in figure 5.1.

First order second moment method was used to develop the probabilistic models. Mean factor of safety is calculated using mean values of parameters, while the variance is calculated using equation 1.10. Similar to the methods discussed in section 5.2, direct differentiation method (assuming $n_i(\theta)$ is deterministic) is used in this model to evaluate the partial derivatives.

5.3.2 Assignment of Uncertainties

Soil strength parameters and pore water pressures are treated as probabilistic parameters. Force mobilized in nails is treated as a deterministic quantity to avoid unnecessary complications of the resulting equations. Pore water pressures were assumed to have a constant coefficient of variation throughout the slope.

5.3.3 Derivation of Partial Derivatives

The partial derivatives obtained assuming $n_i(\theta)$ is deterministic are as follows:

$$\frac{\partial F_0}{\partial c'} = \frac{\sum \left(\frac{\Delta x_i}{n_i(\theta)} \right)}{\sum W_i \tan\theta_i} \quad ....(5.8)$$

$$\frac{\partial F_0}{\partial \varphi'} = \frac{\sum \left\{ (W_i + Q_i - u_i \Delta x_i) \frac{\sec^2 \phi'}{n_i(\theta)} \right\}}{\sum W_i \tan\theta_i} \quad ....(5.9)$$

$$\frac{\partial F_0}{\partial u} = \frac{\sum \left(- \frac{\Delta x_i \tan\phi'}{n_i(\theta)} \right)}{\sum W_i \tan\theta_i} \quad ....(5.10)$$

5.3.4 Development of the Spreadsheet

As for that discussed in section 5.2.4, spreadsheet consists of four worksheets. Except some changes in Calculations worksheet and the Probabilistic worksheet other worksheets are almost similar. In the Calculations worksheet uncorrected factor of safety is first calculated and then corrected to give the final factor of safety. In addition, partial derivatives are also computed on the basis of uncorrected factor of safety. In Probabilistic worksheet also, variance of the uncorrected factor of safety is computed first, and then corrected to give the variance of corrected factor of safety using equation 4.4. Formulations of each worksheet are illustrated in figure 5.7 to 5.11.

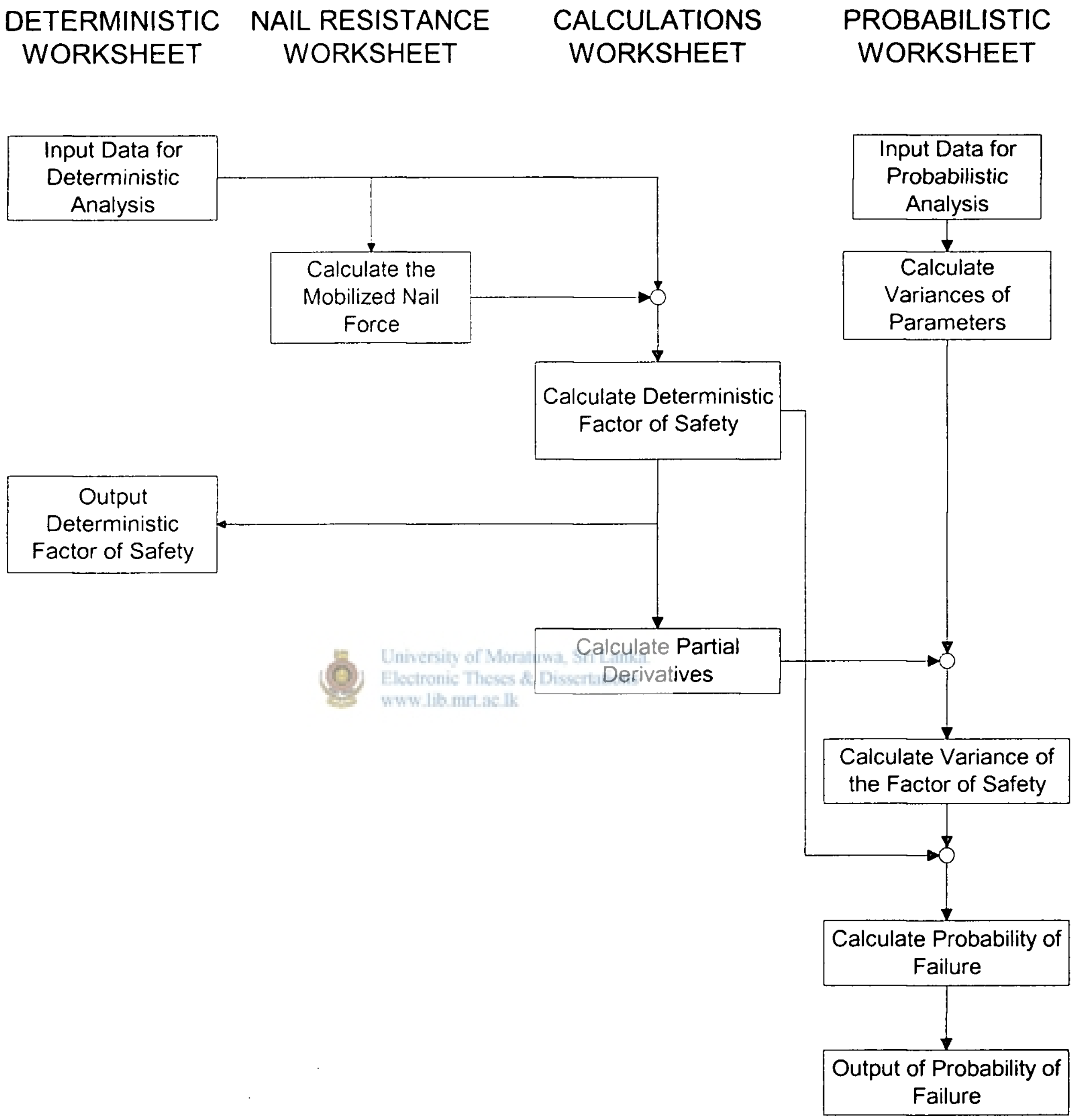
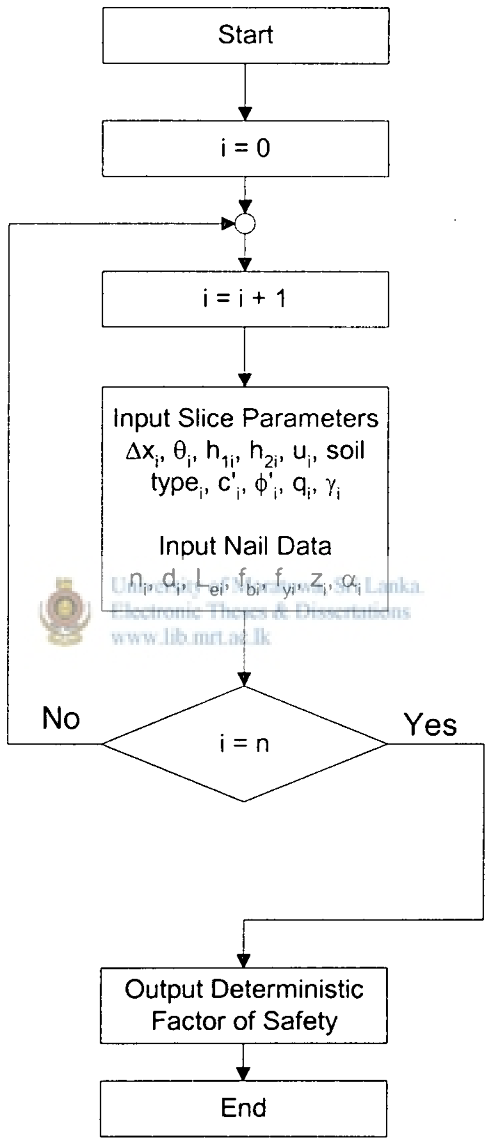


Figure 5.7: Flow chart showing the overview of the Spreadsheet (Soil Nailed Slope -Based on Janbu's Method)



Note:
Alphabetical letters used represent the following:

i = "i" th slice
n = total number of slices

Figure 5.8: Flow chart for Deterministic Worksheet (Soil Nailed Slope - Based on Janbu's Method)

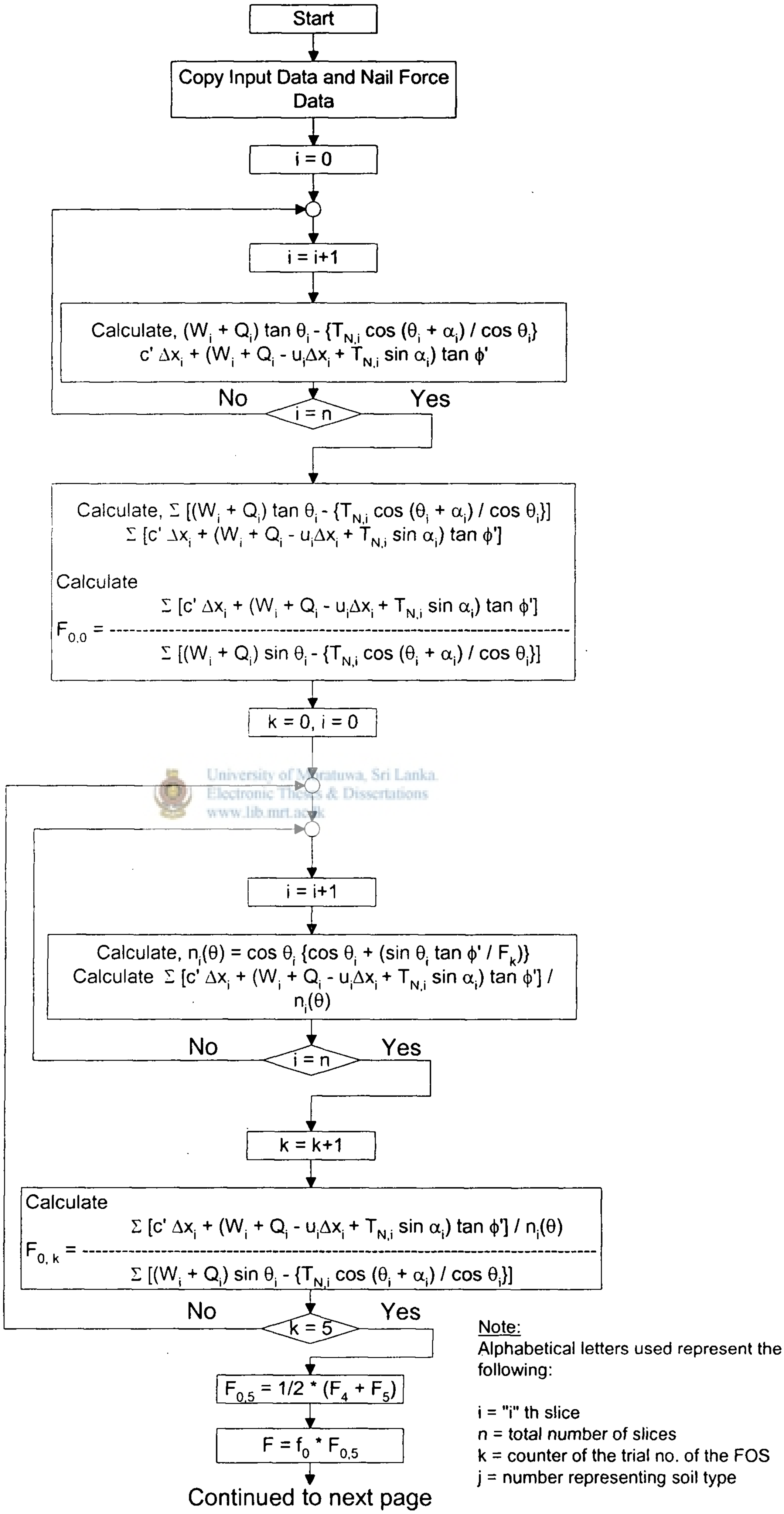
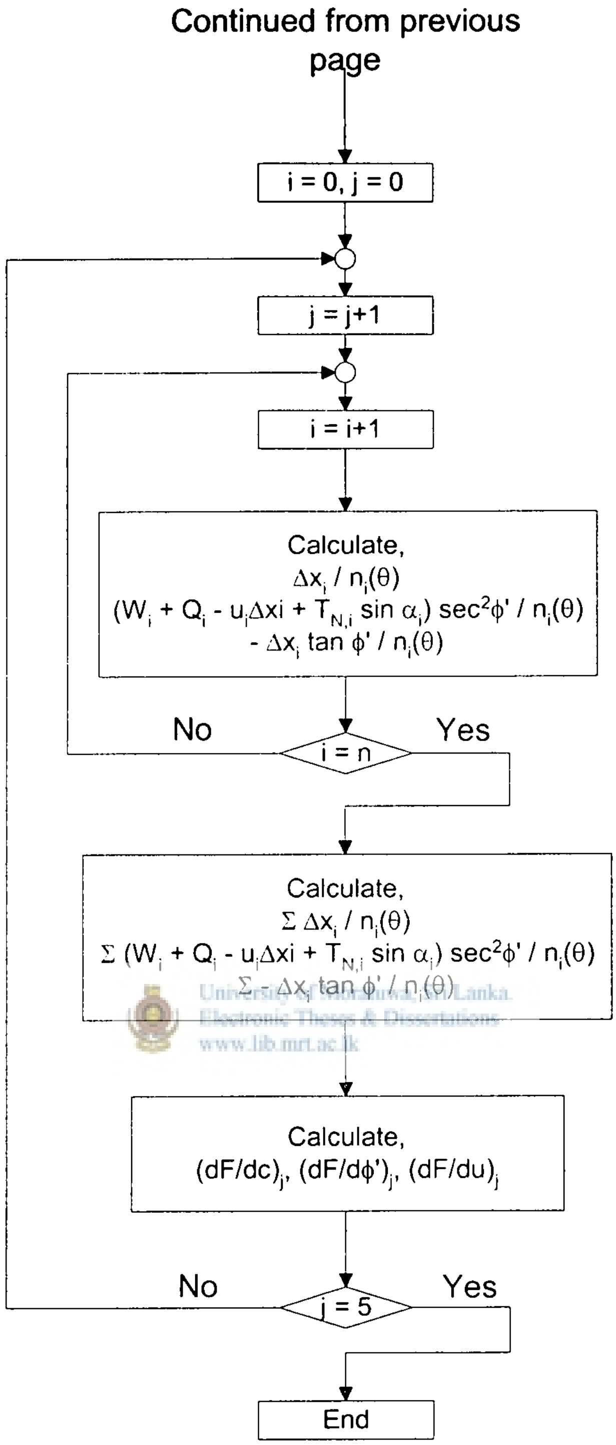


Figure 5.9: Folw diagram showing the Calculations worksheet (Soil Nailed Slope - Based on Janbu's Method)



Note:
Alphabetical letters used represent the following:

i = "i" th slice
n = total number of slices
k = counter of the trial no. of the FOS
j = number representing soil type

Figure 5.9: Folw diagram showing the Calculations worksheet (Soil Nailed Slope - Based on Janbu's Method)

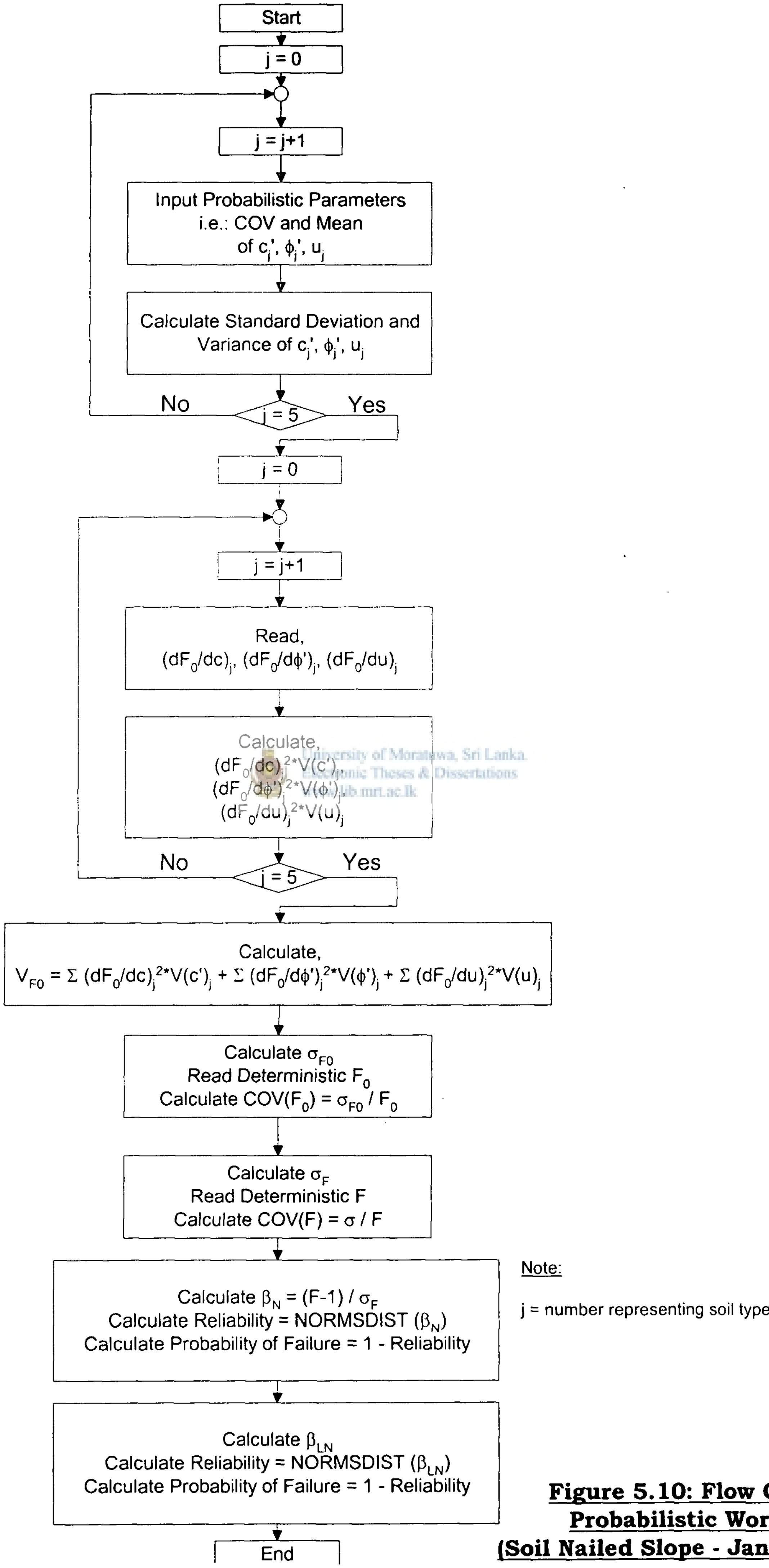


Figure 5.10: Flow Chart for Probabilistic Worksheet (Soil Nailed Slope - Janbu's Method)

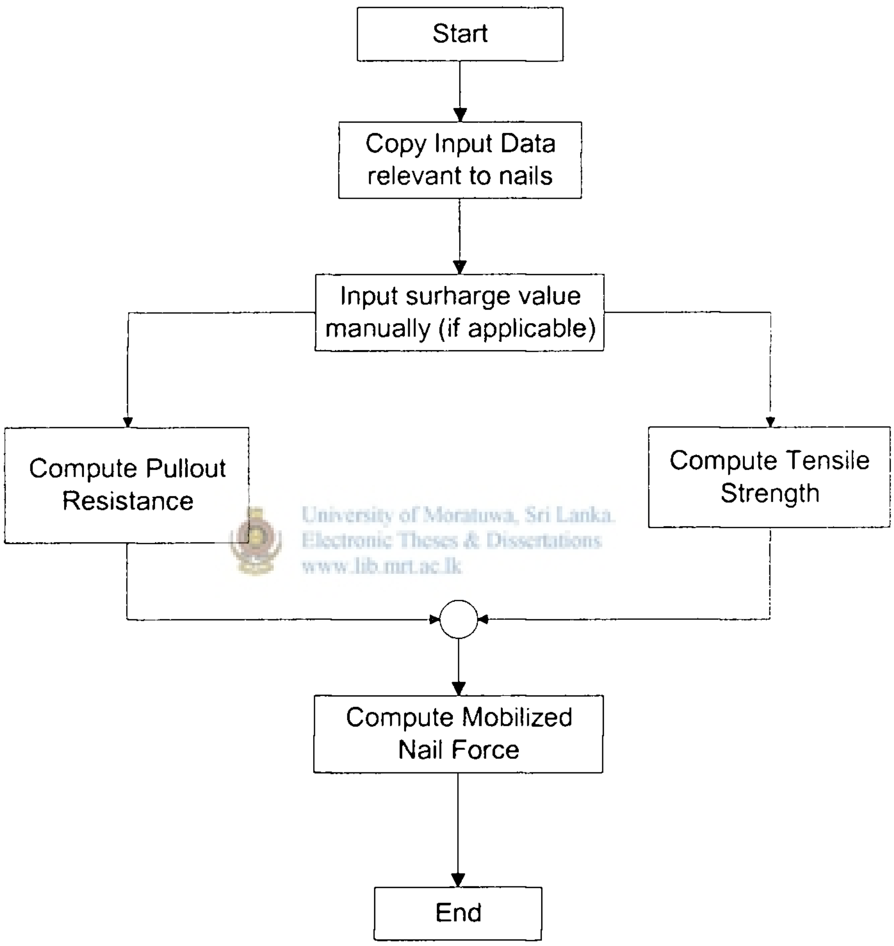


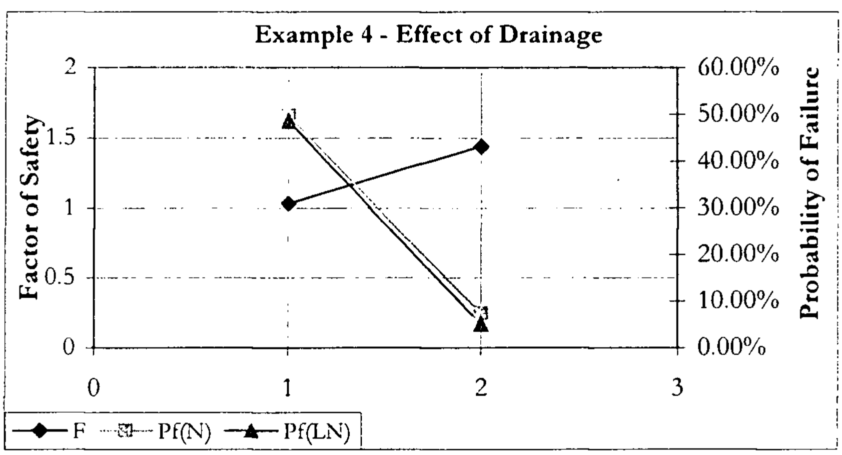
Figure 5.11: Flow diagram for Nail Resistance Worksheet (Soil Nailed Slope - Based on Janbu's Method)

5.4 Illustrative Example for the Stabilization using Drainage (Example 4)

Two examples discussed under the section 3.5 can be used to illustrate the effectiveness of drainage as a stabilization measure. Example 1(b) represents the slope with a perched water table, while example 1(a) represent the situation where the water table has been lowered by the introduction of subsurface drains. The factors of safety and the corresponding values of probability of failure are presented in table 5.1. The graphical representation is given in figure 5.12. The probability of failure corresponds to the model that uses direct differentiation assuming $M_i(\theta)$ is deterministic. Pore pressures have a constant coefficient of variation for the whole slope.

	Perched Water Table	Lowered Water Table
Factor of Safety	1.03	1.44
Probability of Failure (Normal Distribution)	45.19 %	7.43 %
Probability of Failure (Lognormal Distribution)	49.47 %	5.06 %

Table 5.1: Results showing the Improvement of Stability by Drainage (Example 4)



Case 1: Perched Water Table
Case2: Lowered Water Table

Figure 5.12: Graphical representation of Results (Example 4)

5.5 Illustrative Example for the Stabilization using Soil Nailing (Example 5)

This is a modified version of example 1, having eliminated the complication of different soil layers. This version had also been used in the survey described in Giam (1989). The slope consists of a homogeneous soil profile with $c = 3\ kN/m^2$ and $\phi = 19.6^0$. The bulk density is $20\ kN/m^3$. The coefficients of variation were $cov(c) = 0.2$ and $cov(\phi) = 0.3$. Depending on the geometry a near circular failure surface can be expected.

When the slope was initially analyzed, it gave a factor of safety of 0.99. The probabilities of failure were 51.07% for the normal distribution assumption and 56.44% for the lognormal distribution assumption, indicating a highly unstable situation.

Hence, as a stabilization measure, a soil nail arrangement was designed assuming driven type of soil nails. The arrangement uses 25mm diameter, 12m long nails. The horizontal and vertical spacing were 0.75m. The assumed bond coefficient was 1.0. The proposed nail arrangement is shown in figure 5.13.

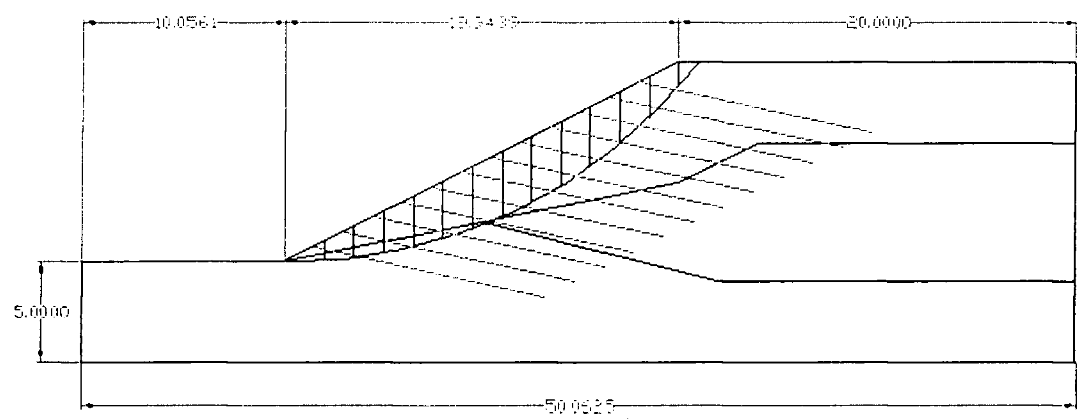


Figure 5.13: Proposed Nail Arrangement for Example 5

In the presence of this nail arrangement, the factor of safety has improved to 1.68. The probability of failure has lowered to 7.14% for normal distribution assumption and to 3.77% for lognormal distribution assumption. The graphical and tabulated representations of the results are given in figure 5.14 and table 5.2 respectively.

	Without Soil Nails	**With Soil Nails**
Factor of Safety	0.99	1.68
Probability of Failure (Normal Distribution)	51.07 %	7.14 %
Probability of Failure (Lognormal Distribution)	56.44 %	3.77 %

Table 5.2: Results showing the Improvement of Stability by Soil Nailing (Example 5)

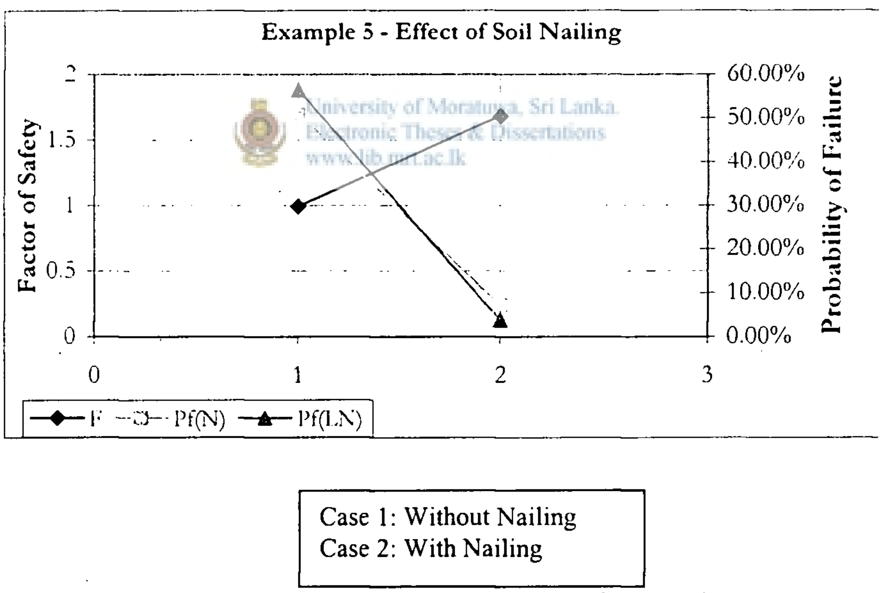


Figure 5.14: Graphical representation of Results (Example 5)

5.6 Illustrative Example for the Stabilization using both Drainage and Soil Nailing (Example 6)

This is the same example used in section 4.5.3. The slope under present conditions is in an unstable state with a factor of safety of 0.73, and a probability of failure around 99%. As a stabilization measure, it was decided to evaluate the effectiveness of lowering the water table. Hence, the lowering of the water table below the failure surface was considered. This procedure was found to be unsatisfactory as it resulted in a factor of safety of 0.94 and a probability of failure of 66.35% for normal distribution assumption and 68.59% for lognormal assumption. Therefore, some other stabilization measures have to be proposed, and the possible use of soil nailing was studied.

However, depending on the depth of the failure surface in the head region nails cannot be used in that area. This region requires nails at least about 30m long, to be effective. But, the nails more than 23m long have not been reported in literature and the most preferred lengths are in the range of 7m to 16m. Hence nails could be used only in the lower part of the failure surface. The proposed nail arrangement required only 13m long nails. All of them are 25mm diameter driven type, high strength steel bars. Nail spacing was 0.5m in both horizontal and vertical directions. The assumed bond coefficient was 1.0. The results showed that a greater improvement in stability could be achieved with nailing. Proposed nail arrangement is shown in figure 5.15. The results are tabulated in table 5.3 and the graphical representation is given in figure 5.16.

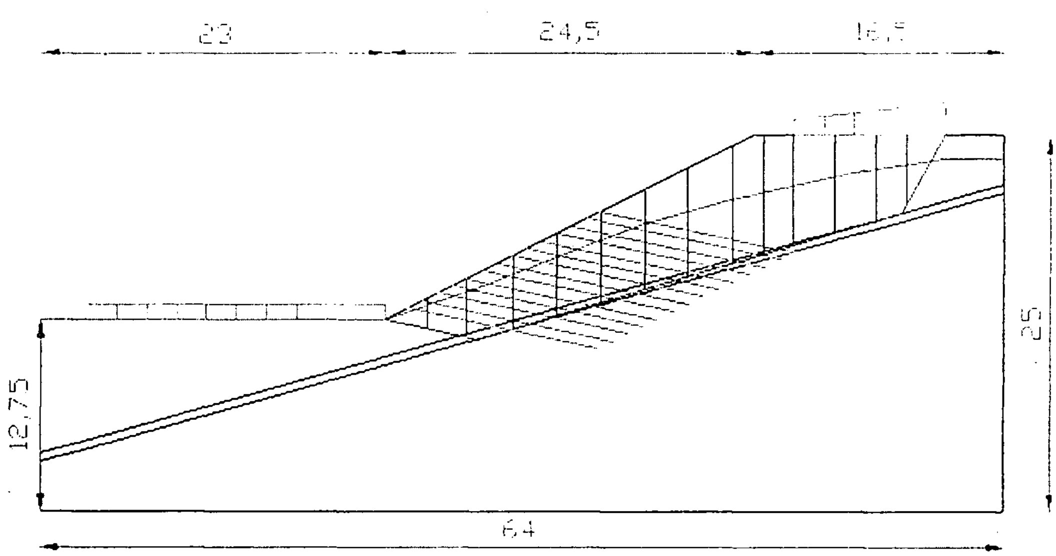


Figure 5.15: Proposed nail arrangement for Example 6

	Normal Slope	Drainage only	Nailing only	Both Nailing and Drainage
F	0.73	0.94	1.14	1.44
Pf (N)	99.34%	66.35%	20.71%	1.83%
Pf (LN)	98.61%	68.59%	21.15%	0.75%

Table 5.3: Results of Example 6

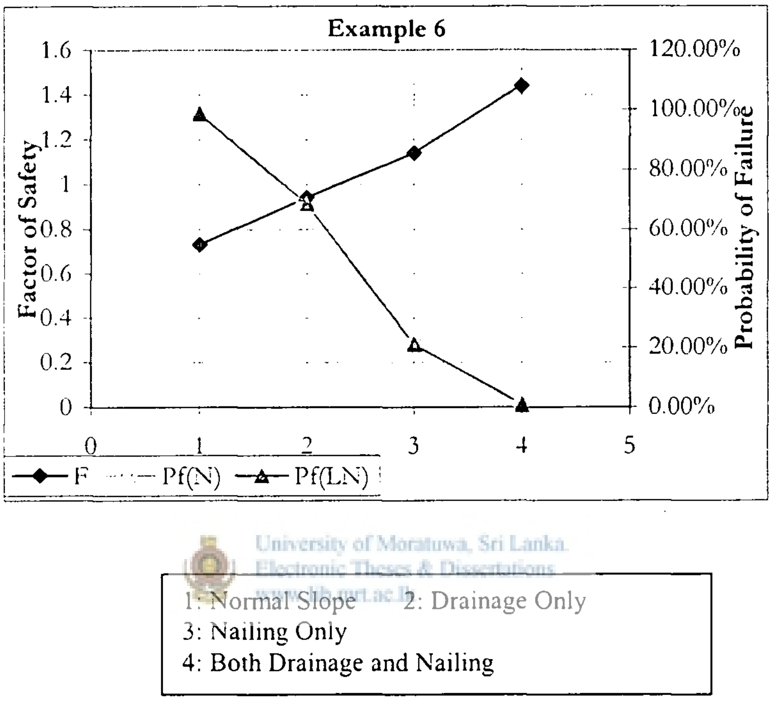


Figure 5.16: Graphical representation of results (Example 6)

5.7 Concluding Remarks

Methods were developed in the earlier chapters to evaluate the probability of failure, giving due consideration to the uncertainties associated. The cases of both the circular and non-circular failure surfaces were handled. In this chapter, the methods developed were used to assess the effectiveness of various slope stabilization techniques. In particular, attention was paid to the processes of drainage and soil nailing techniques as stabilization measures. The assessment of stabilization techniques was done through several examples covering both circular and non-circular failure surfaces.

When the results are presented, it was decided to present deterministic factor of safety along with the probability of failure. This is because, that the factor of safety is still the most familiar parameter for all geotechnical engineers. Probability of failure values were presented for both normal distribution assumption and lognormal distribution assumption. Since there is still no firm decision regarding what the most suitable method, these comparisons might give some idea to a potential future researcher.

In the examples, author has not discussed about an acceptable value of probability of failure to distinguish between stable and non-stable states, but just showed the improvement of the probability that can be obtained from proposed stabilization measures. Once a large database is set up to contain records of both failed slopes and safe slopes, it will be possible to discuss about acceptable values of probability of failure.

Once this need is accomplished, it would be possible to use the concept of probability of failure as a supplement to the factor of safety in the design of safe slopes. The probability of failure is a more complete parameter for the assessment of the stabilization techniques as all uncertainties can be formally recognized.

Chapter 6

APPLICATION TO SRI LANKAN CASE HISTORIES OF NATURAL SLOPES

6.1 Stabilized Watawala Landslide

6.1.1 Introduction

Watawala is located in the western slope of the central hill country of Sri Lanka. It is the area, which experiences the highest annual rainfall in the country. Watawala landslide is known to be an old, repetitive and retrogressive landslide (Rajaratnam and Bhandari, 1994). According to the records available the first signs of ground subsidence had been recorded about 50 years ago. Since then, it had been reactivated several times during periods of heavy rain, generally from May to October.

In 1992/93, a major slide occurred resulting the destruction of the railway line, which was then the main supply route to the upcountry. Several ad hoc measures had been taken to repair the railway line, but they had aggravated the landslide in the long term. Rajaratnam and

Bhandari (1994) reported that the landslide in June 1993 covered an area of 22 920 m^2 (approx.) and about 322 700 m^3 slide volume.

Due to the huge destruction caused to the country's economy, stabilization of the slide was of paramount importance. Hence it was well investigated and long-term remedial measures were implemented in 1995.

Watawala landslide is the best-studied landslide in Sri Lanka. The mechanism of landslide, boundary shears and the piezometric profile were reliably known, thus providing a fit case for the back analysis. In our research the slope was modeled with the best available information and the analysis was performed in probabilistic terms. Figures 6.1 and 6.2 show the geomorphological map and the plan view of the Watawala slide area.

6.1.2 Investigation of the Landslide

In the early 1990's, National Building Research Organization (NBRO) Sri Lanka had launched a comprehensive investigation program to unearth the causes of instability and to design remedial measures.

The slide boundary had been established by a systematic program of field mapping, site investigation, slope instrumentation and monitoring. Side boundaries had been identified with the visual observations while the basal boundary had been located by the use of slope indicator observations, shearing of deflection tube, sudden drop in N-values, bending of bore hole casings, water loss at bore holes and the direct evidences of upthrust of the toe and the ground subsidence at the crest. The details of sub surface profile, location of instrumentations and the details of identified failure surfaces are presented in Annex 8.

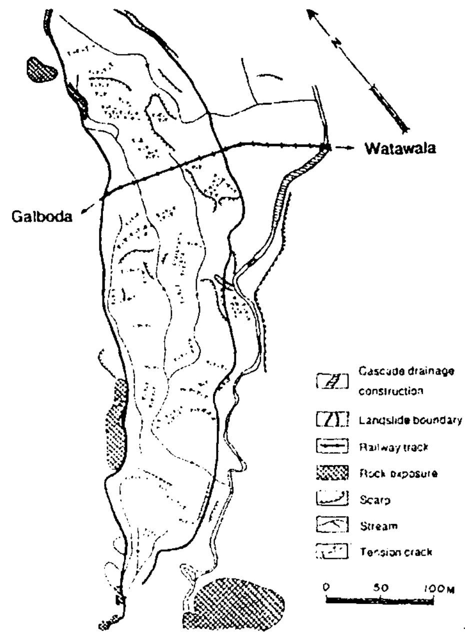


Figure 6.1: A Geomorphological Map of the Watawala Earthslide (Rajaratnam and Bhandari, 1994)

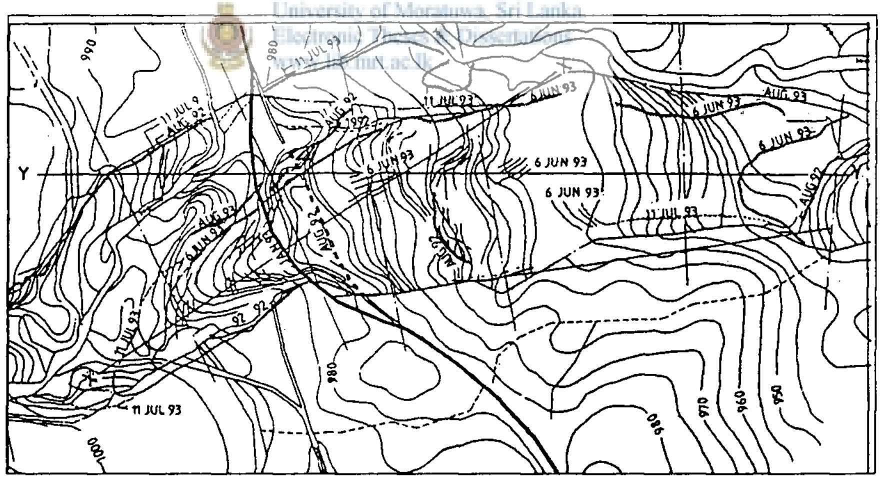


Figure 6.2: Plan View of Watawala Earthslide (Rajaratnam and Bhandari, 1994)

(slide boundary, cracks in the ground with dates and longitudinal setions x-x and y-y are shown)

Maximum and minimum piezometric levels prevailing within the site had been mapped by the data obtained from 9 cassagrande open standpipe piezometers and 4 vibrating wire piezometers. According to Rajaratnam and Bhandari (1994), pore water pressures had been artesian particularly in the head region of the landslide. Major failure surface along with maximum and minimum piezometric lines are shown in figure 6.3.

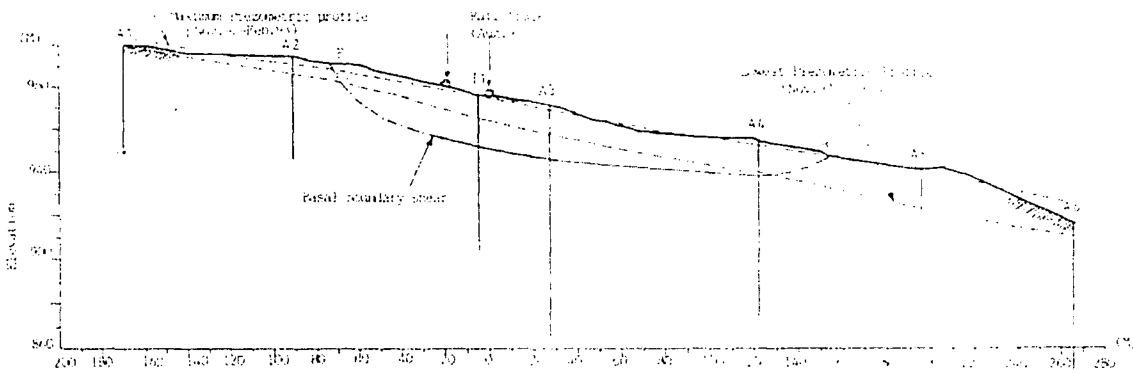


Figure 6.3: Longitudinal Section Y-Y of the Watawala Landslide [Rajaratnam and Bhandari (1994)]

(Basal boundary shear, the location of drill holes and the maximum and minimum water levels are also shown)

Shear resistance of soil had been determined by testing of undisturbed samples and also field shear box tests on actual slip surface. The reported strength parameters for undisturbed samples had been distributed over a wide range with c' = 28 - 46 kN/m^2 and ϕ' = 21^0 - 28.5^0. The parameters derived from the field shear tests were c' = 0 and ϕ_r' = 16^0 (approx.). Since laboratory tests correspond only to low order of strains and since the actual slip surface had undergone large orders of strains, it had been proposed to use field shear strength parameters assuming them to be the residual parameters (Rajaratnam and Bhandari, 1994).

6.1.3 Stabilization of the Watawala Landslide

Stabilization work of Watawala slope was carried out by John Holland International (Pty) Ltd, Australia. Stabilization involved improvement of both surface and subsurface drainage to lower the ground water levels. Surface drainage was improved by recontouring and construction of surface drains, so that they can intercept and divert the surface runoff reducing infiltration. Subsurface drainage was improved by installing directional drains and eductors. Conceptual model of the rehabilitation work is given in figure 6.4. Plan view of the underground directional drains and eductor drains are given in annex 8.

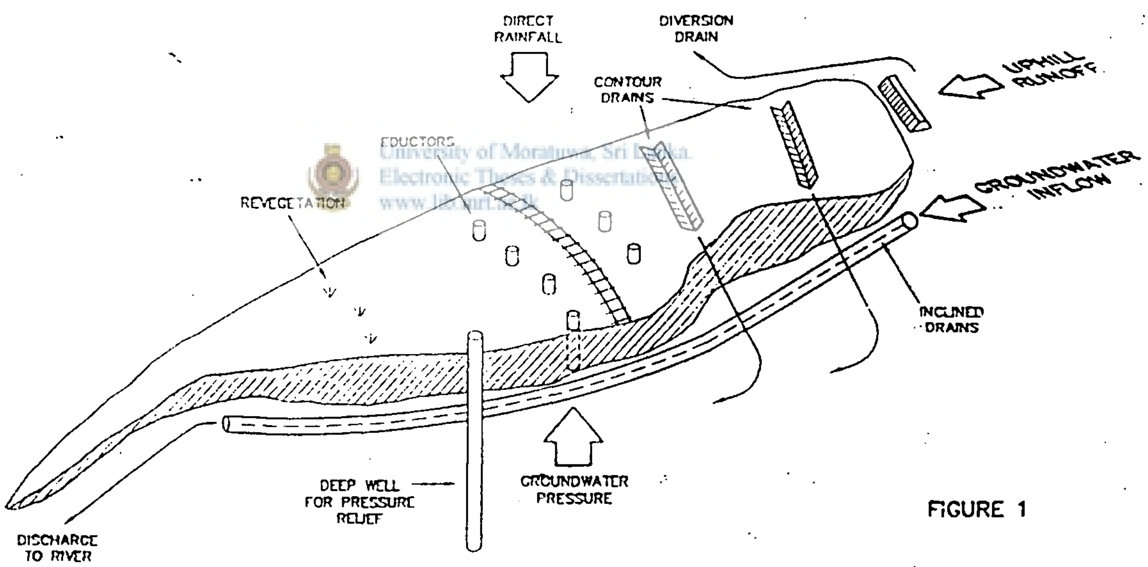


Figure 6.4: Conceptual Model of the Rehabilitation Work (Watawala Landslide)

The stabilization work took place in 1995, and the drains are still reported to function properly. To date slope is safe and the stabilization had been effective. Hence, this is a good case to check whether this actual improvement of stability is reflected in the probabilistic analysis.

6.1.4 Extraction of Information

Slope geometry and the failure surface were drawn to scale and the co-ordinates at key points were obtained. Then everything was redrawn on the AutoCAD screen, failure mass was divided into slices, and the relevant details were extracted. Pore water pressures were computed using the infinite slope assumption, where the flow lines are assumed to be parallel to each other. Since the cross section and the plan view (figures 6.2 and 6.3) indicated a uniform slope, this assumption seems reasonable.

6.1.5 Analysis

Deterministic analysis was performed through the Janbu's method using the residual strength parameters $c' = 0$ and $\phi'_r = 16^0$. Failure mass was divided into 14 slices. Although slice width is assumed to be small in the derivation of analytical models, the average value had to be taken as 25m to work within the limitations of the developed spreadsheets. Janbu correction factor taken was 1.028.

Probabilistic analysis was performed using coefficients of variation of 0.2 for angle of internal friction, and 0.14 for pore water pressures. Although the main objective was to evaluate the effectiveness of the stabilization work, it was decided to analyze the problem using all the models developed based on Janbu's simplified method to provide another example to evaluate the performance of the models. Hence Monte Carlo analyses were also performed.

For the Monte Carlo analyses, standard deviation of piezometric head was taken to be 2.15m for the high water table situation and 1.05m for low water table situation, so that they correspond to the same coefficient of variation of the average pore water pressure used in the other analyses.

The results of the analyses are given in tables 6.1 and 6.2. Graphical representation is given in figures 6.5 and 6.6.

	Analysis Program	Deterministic Model	Factor of Safety	Probability of Failure	
				Normal	Lognormal
1	Direct Differentiation (n(θ) deterministic)	Janbu's simplified	0.8733	71.70%	74.82%
2	Direct Differentiation (n(θ) probabilistic)	Janbu's simplified	-do-	72.32%	75.24%
3	Duncan (2000) method	Janbu's simplified	-do-	71.45%	74.65%
4	Small Increment - Central Difference	Janbu's simplified	-do-	71.42%	74.63%
5	Small Increment - Forward Difference	Janbu's simplified	-do-	71.40%	74.62%
6	Monte-Carlo[a] Det: 0.84[b]	Janbu's simplified[a]	0.844-0.845[c]	90.228% - 90.288%[c]	SLOPE/W assumes only normal distribution
7	Monte-Carlo Det: 0.876[b]	Spencer	0.879-0.881[c]	95.765% - 95.794%[c]	

Note:

a. SLOPE/W computer program only uses uncorrected factor of safety for Janbu's simplified method
b. In SLOPE/W, deterministic value is slightly different from mean values
c. Monte-Carlo analysis gives different values for different trials. Hence a range of values are specified here for mean factor of safety and probability of failure

Table 6.1: Results for High Water Table Situation (Watawala Slope)

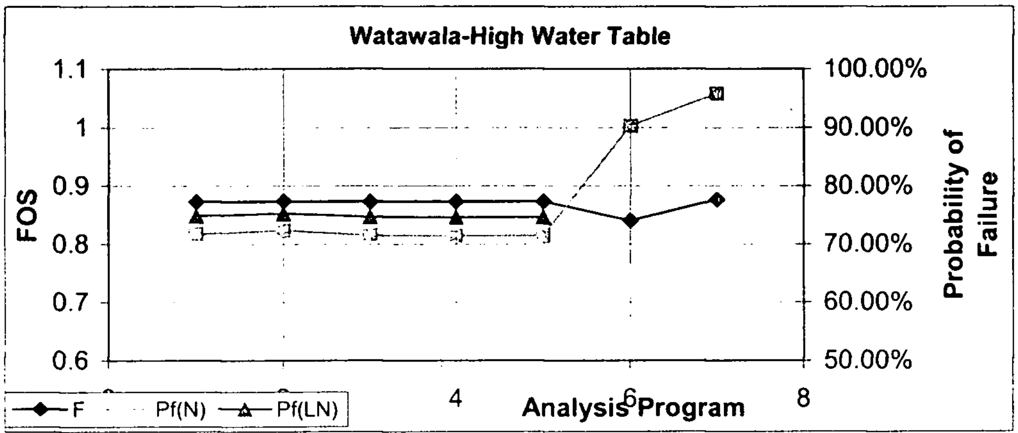


Figure 6.5: Graphical representation of Results (Watawala slope – High Water Table Situation)

	Analysis Program	Deterministic Model	Factor of Safety	Probability of Failure	
				Normal	Lognormal
1	Direct Differentiation (n(θ) deterministic)	Janbu's simplified	1.4917	6.23%	3.77%
2	Direct Differentiation (n(θ) probabilistic)	Janbu's simplified	-do-	5.67%	3.30%
3	Duncan (2000) method	Janbu's simplified	-do-	6.12%	3.68%
4	Small Increment - Central Difference	Janbu's simplified	-do-	6.10%	3.66%
5	Small Increment - Forward Difference	Janbu's simplified	-do-	6.28%	3.81%
6	Monte-Carlo[a]	Janbu's simplified[a]	1.294	0.00%	SLOPE/W assumes only normal distribution
7	Monte-Carlo	Spencer	1.348	0.00%	

Note:

a. SLOPE/W computer program only uses uncorrected factor of safety for Janbu's simplified method

Table 6.2: Results for Low Water Table Situation (Watawala Slope)

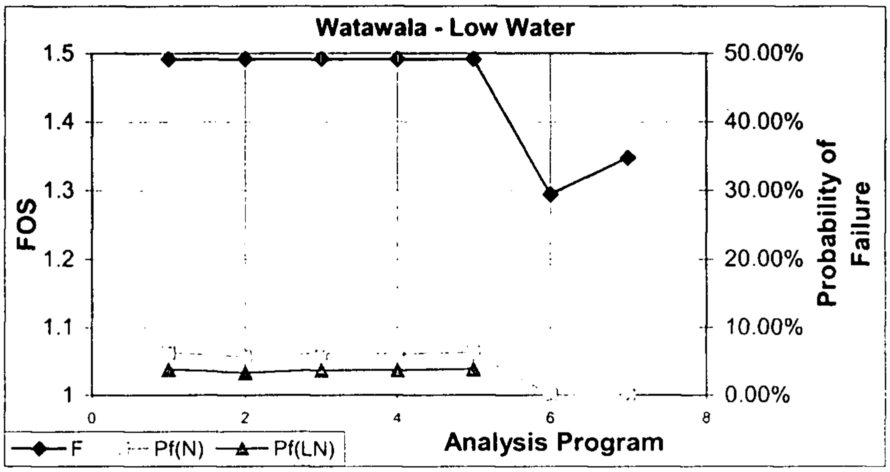


Figure 6.6: Graphical representation of Results (Watawala slope – Low Water Table Situation)

6.1.6 Discussion of Results

From the results it can be seen that the results from different methods from author's programs agree with each other except in the method that assumes n(θ) is probabilistic. However, this problem shows some significant differences between Monte Carlo results and author's results. Since there was a difference in the way these programs consider the uncertainty of pore pressures, it is not possible to arrive at a conclusion whether one method is superior to the other one.

Results of the analysis for two piezometric conditions show that a great improvement in stability can be expected from drainage. This is represented both in deterministic and probabilistic analyses, and confirmed somewhat by fact the stabilized slope is behaving satisfactorily to date.

6.2 Slope at Marangahawela (Badulla District)

6.2.1 Introduction

This represents another landslide that had been initiated very recently in the Badulla district of Sri Lanka. The area is located in the southwestern slope of the central hill country. Colombo-Ratnapura-Wellawaya-Baticaloa (CRWB) main road lies across this slope, hence an identification of instability is very crucial. Plan view of the Marangahawela site is given in figure 6.7.

Sign of a slope failure was first indicated by the subsidence of the CRWB main road lying across the landslide area. As soon as this was noticed, an investigation had been carried out to cover the suspected area. The investigation had consisted of 4 boreholes and subsequent laboratory testing of soil samples. From these investigations, a probable failure surface had been identified, and it had been analyzed using Bishop's simplified method. According to the results of the analysis, lowering of the water table had been identified as a possible remedial measure by the relevant authorities, and it had been implemented.

6.2.2 Stabilization of the Marangahawela Slope

As the stabilization measure, a system containing a drainage well had been proposed. Three subsurface subhorizontal drains were installed in the form of perforated pipes as shown in figure 6.8 and the water flowing through them are collected to the drainage well. The water collected in this drainage well is then taken away from the slide area by means of another subsurface drain.

To observe the groundwater levels piezometers had been installed in all four boreholes. Measurements are taken continuously on these

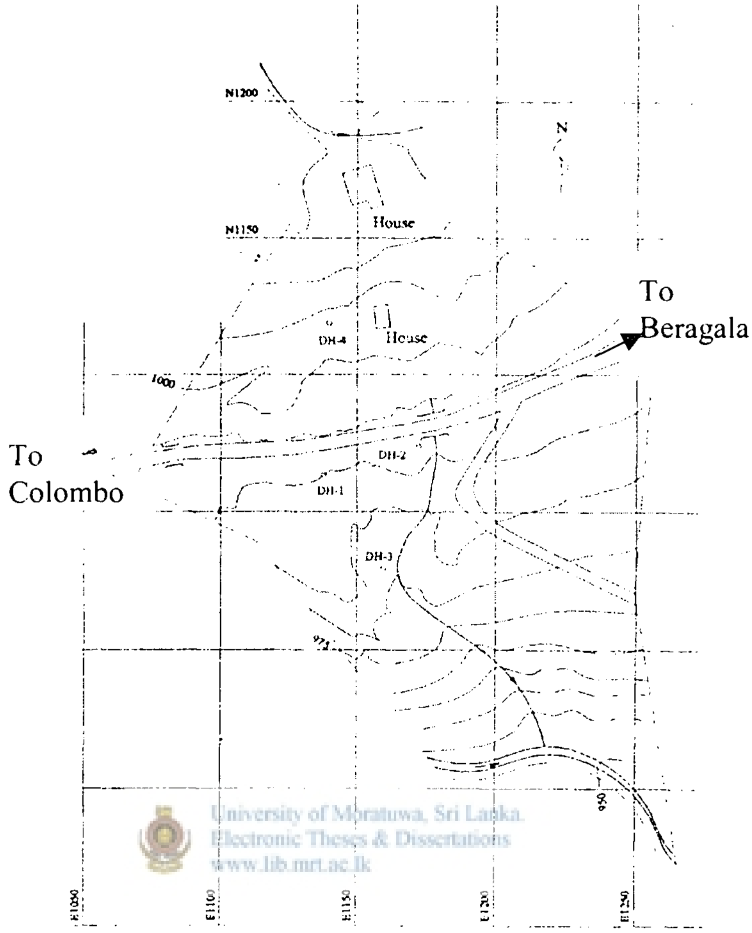


Figure 6.7: Plan view of Marangahawela Site

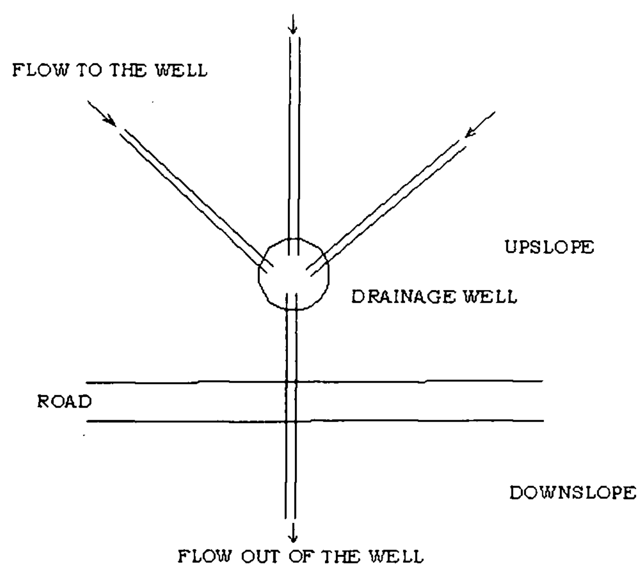


Figure 6.8: Plan view of the sub surface drains and drainage well

piezometers, and a huge drop in the water levels had been noticed once the subsurface drains were installed. In addition, the flow through the sub surface drains are also being monitored continuously, and a remarkable increase of flow had been recorded during periods of heavy rain prevailed in April/ May 2002. From these observations, the officials involved in the remedial work are satisfied that the expected lowering of the water table has been achieved.

6.2.3 Analysis

It was decided to evaluate the effectiveness of the stabilization measure through the developed programs. The identified failure surface was drawn in AutoCAD and the slice details were obtained. Although the initial computations (done by Road Development Authority) had been based on Bishop's simplified analysis, a non-circular nature was observed in the failure surface and Janbu's method was used in this study. The shear strength parameters and the maximum and minimum piezometric levels were the same as for the original analysis. Hence $c' = 5\ kN/m^2$ and $\phi' = 16^0$ were used. The failure surface and the maximum and minimum piezometric levels used are shown in figure 6.9.

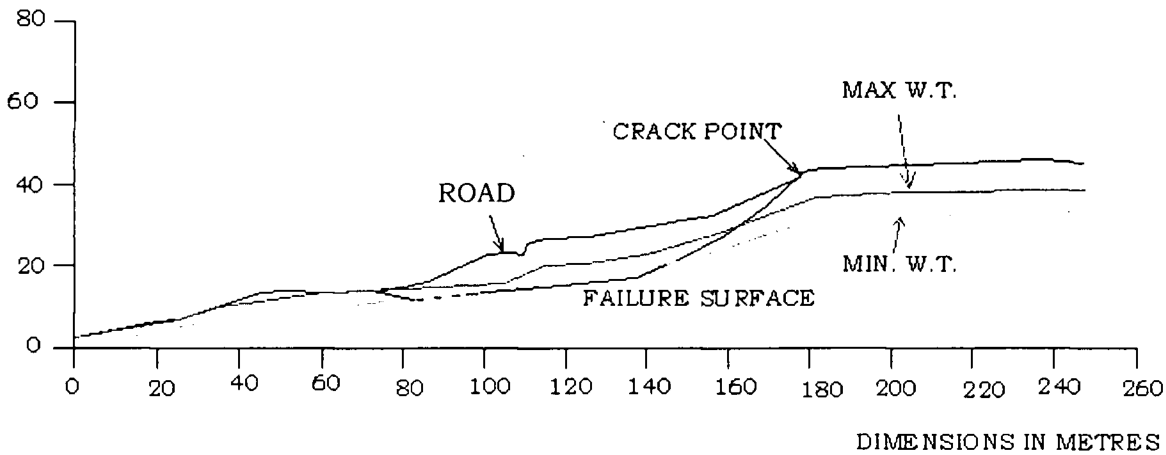


Figure 6.9: Cross-section of Marangahawela Slope

The deterministic analysis gave factors of safety values that are almost close to the original analysis with F = 1.15 for high water table situation, and F = 1.36 for low water table situation. In the absence if actual data relevant to the uncertainties, probabilistic analysis was performed using some assumed coefficient of variation values. Hence 0.2 was used for strength parameters (i.e.: c' and ϕ') and 0.25 was used for pore pressures. This resulted in the following values for the probability of failure.

	Pf(N)	Pf(LN)
High Water Table	31.77%	35.19%
Low Water Table	17.47%	16.63%

Table 6.3: Probability of failure for Marangahawela Slope (with probabilistic parameter set 1)

The probability of failure around 16-17% seems unreasonable, if the stabilization had been effective. It should be noted that for the case of stabilized Watawala slope, the probability of failure was only around 6%. Also, Duncan (2000) has cited a case of a failed slope where the factor of safety was 1.17 and the probability of failure was 18%.

Hence, another set of lower coefficients of variation was assumed and the case was reanalyzed. For the coefficients of variation of 0.1 for cohesion, 0.2 for friction angle and 0.15 for pore pressures the results presented in table 6.4 were obtained.

	Pf(N)	Pf(LN)
High Water Table	23.71%	24.76%
Low Water Table	7.99%	6.02%

Table 6.4: Probability of Failure for Marangahawela Slope (with probabilistic parameter set 2)

With this set, probability of failure of about 6-7% can be taken as reasonable (this is just based on the information available at this moment), if the stabilization works performs well. However, it is too early to say whether the stabilization work has satisfactorily prevented the slide. Hence these results can be kept open for future use. If there is any failure taken place again it implies that the remedial measure, which improved the factor of safety up to 1.36 has not been sufficient. In other words it gives a clear indication that the factor of safety alone is not sufficient to assess the stability of slopes, since the parameters involved had been carrying uncertainty.

Another important observation is that despite the fact that factor of safety is 1.15 under high water table condition the slope has shown some signs of movements. However, according to the basic mechanics, if the factor of safety is greater than 1, the slope should be stable. This is an indication that the computed factor of safety has not provided a satisfactory assessment of the stability of the slope, as in the case cited by Duncan (2000). This is due to the uncertainties involved in the parameters used for the analysis. This is why the probabilistic analysis is so important. Even using small coefficients of variation values, the slope had a probability of failure around 23-24%, when the water table is high.

6.3 Concluding Remarks

Two cases regarding actual slope failures were presented. Analysis of Watawala slope gave another set of results to discuss the validity of the models based on the Janbu's simplified method. In addition, the results showed that probability of failure can be taken as an appropriate concept to discuss the effectiveness of the remedial measures.

Marangahawela slope was a good case study to discuss the unsuitability of factor of safety as the sole parameter to assess the stability of a slope.

Chapter 7

PROBABILISTIC EVALUATION OF SAFETY OF CUT SLOPES

7.1 Introduction

Non-engineered constructions in slopes and surroundings are one of the major causes that can increase the risk of landslides. Although proper investigations are carried out in major construction works, non-engineered constructions cannot be easily avoided in small-scale constructions such as small houses. Instead of rigorous computations, if somebody can arrive at some basic guidelines that can be understood by general public, there can be an opportunity of reducing the hazards since people are aware of the consequences. Therefore establishment of design guidelines for disaster mitigation activities of natural slope stability has become an important aspect in the establishment of environmentally friendly, hazard free excavations in natural slopes.

With the objective of developing such guidelines, National Building Research Organization (NBRO) of Sri Lanka had carried out a thorough investigation under the Sri Lanka Urban Multi-hazard

Disaster Mitigation Project (SLUMDMP) (National Building Research Organization, 1998). The special attention had been paid to the assessment of unsupported earth cuttings in residual soils and colluvium in the Rathnapura Municipal Council area.

Under the said project, stability of a large number of unsupported earth cuttings had been assessed to cover both cuts by the sides of roads and near buildings. Whole analysis had been based on the deterministic concepts. The purpose of this chapter is to discuss the possible use of probabilistic analysis in this kind of a project to evaluate the stability and the effectiveness of the remedial measures.

Hence, two cases, where soil nailing can be used as a remedial measure have been selected. The details of these cases were obtained under the kind approval of the National Building Research Organization of Sri Lanka.

7.2 Soil strength parameters

Resource area consists mainly of residual soil, colluvium and weathered rock. Properties had been evaluated through a series of laboratory testing on undisturbed samples. Tests include multi-stage consolidated undrained triaxial tests with pore pressure monitoring, and multi-stage unconsolidated undrained triaxial tests. The results are given as a range of parameters, and the values corresponding to residual soils are shown in table 7.1.

Effective strength parameters		$c' = 2 - 12\ kN/m^2$ $\phi' = 26^0 - 32^0$
Undrained strength parameters	Saturated	$c_u = 10 - 22\ kN/m^2$ $\phi_u = 2^0 - 3^0$
	Unsaturated	$c_u = 98 - 115$ kPa

Table 7.1: Strength parameters of residual soils – Rathnapura MC area

7.3 Groundwater conditions

Groundwater conditions had been established by the observations made at the site. Observations include inspection of test pits, auger holes and dug wells.

7.4 Need for probabilistic approach

Average values of strength parameters had been used for different kind of soils after testing on number of samples. In addition, methods of obtaining the groundwater conditions are not that accurate. Hence the values used in the analysis are subjected to some sort of uncertainty. This uncertainty can be accounted with the use of a probabilistic analysis.

7.5 Example Cut Slope 1 (Ref: RMC/012)

This slope (figure 7.1) is found adjacent to a house and consists of a residual soil formation overlying weathered rock. Identified water table location is shown in figure 7.1. Slope had been analyzed in the original research using both the peak strength parameters and residual strength parameters, and the location of failure surfaces had been limited by limiting tangents. But in this study, location of failure surface was not limited by limiting tangents. Hence, identified critical failure surfaces are different, thus giving different values for factor of safety.

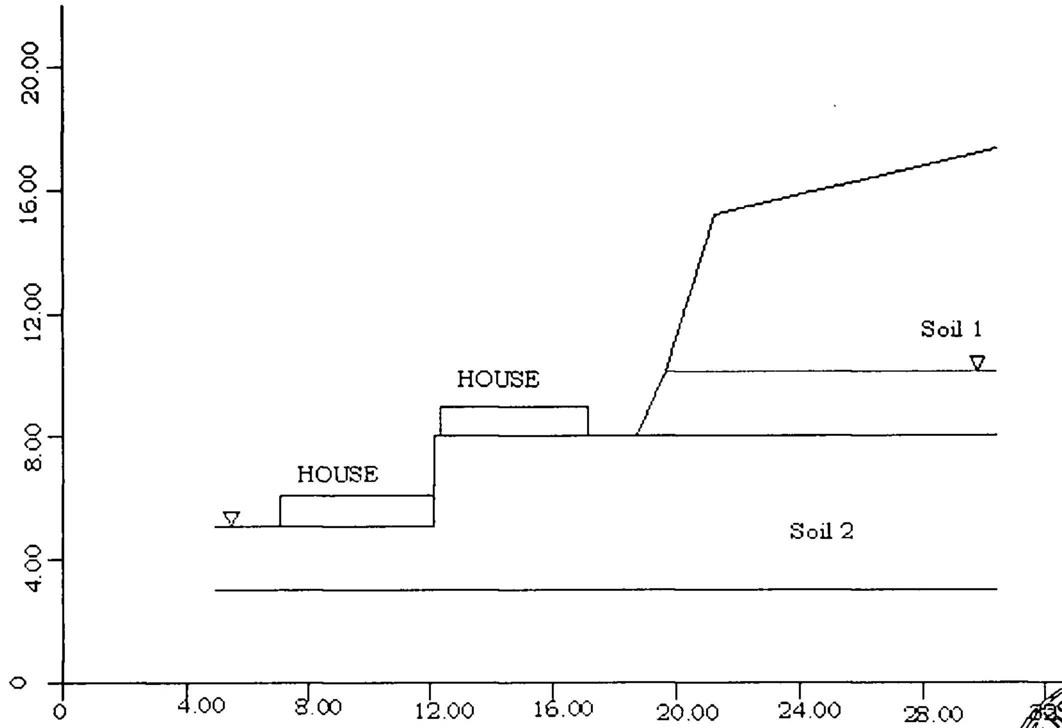


Figure 7.1: Geometry of cut slope 1

Analysis was done using the peak strength parameters obtained by undisturbed testing on saturated samples. As that can be seen, an effective cohesion of 10 – 12 kN/m^2 is available in these dense soil formations in the fully saturated condition also. The parameters used for the analysis are given in table 7.2. Coefficient of variation of pore water pressure was 0.25.

Soil Type	c' (kN/m^2)	$\phi'(^o)$	cov (c')	cov (ϕ')	γ (moist) kN/m^3	γ (saturated) kN/m^3
1	12	29	0.3	0.2	18	19.5
2	15	32	0.2	0.3	19	21.0

Table 7.2: Peak strength parameters for cut slope 1

The slope was initially analyzed using SLIDE computer program to identify the most critical circular failure surface. Then the same failure surface was analyzed using author's programs after taking the slice dimensions from the AutoCAD screen. The analysis shows that the slope is in the verge of failure with a factor of safety of 1.008 and a probability of failure of 48.37% if the factor of safety is assumed to be normally distributed and 52.11% if the factor of safety is assumed to follow lognormal distribution. However, this represents the fully saturated situation, and the slope is much stable under partially saturated conditions, due to high apparent cohesion resulting from the matric suction.

However, if the matric suction is lost due to the infiltrated rainwater the probability of failure and the factor of safety would be lowered to the values quoted above and the slope is on the verge of failure. The lowering of water table to be lower than the base of the potential failure surface was considered as one stabilizing measure. The improvement of factor of safety and the probability of failure achieved by this technique is found to be only marginal (Tables 7.4 and 7.5). Hence, another stabilization technique had to be considered and the possibility of using soil nailing was studied.

When a nail arrangement is designed considering only the critical failure surface, another failure surface may become critical then. Hence, a number of potential failure surfaces were considered before finalizing on the final nail arrangement. Designed final nail arrangement is summarized in table 7.3. A shotcrete facing can be used to provide a local stability of soil near the face.

Length of nails	7m
Orientation	15^{0} below horizontal
Vertical spacing	1 m
Horizontal spacing	1 m, on a regular grid
Diameter of steel bars	25 mm high yield steel
Nail type	Driven
Durability requirement	Hot dip galvanizing

Table 7.3: Soil nail arrangement for cut slope 1

Four possible failure surfaces were considered and they are given in figure 7.2 along with the proposed nailing arrangement. Results of the analyses of four failure surfaces under the natural condition and the proposed stabilization method are given in tables 7.4 to 7.6.

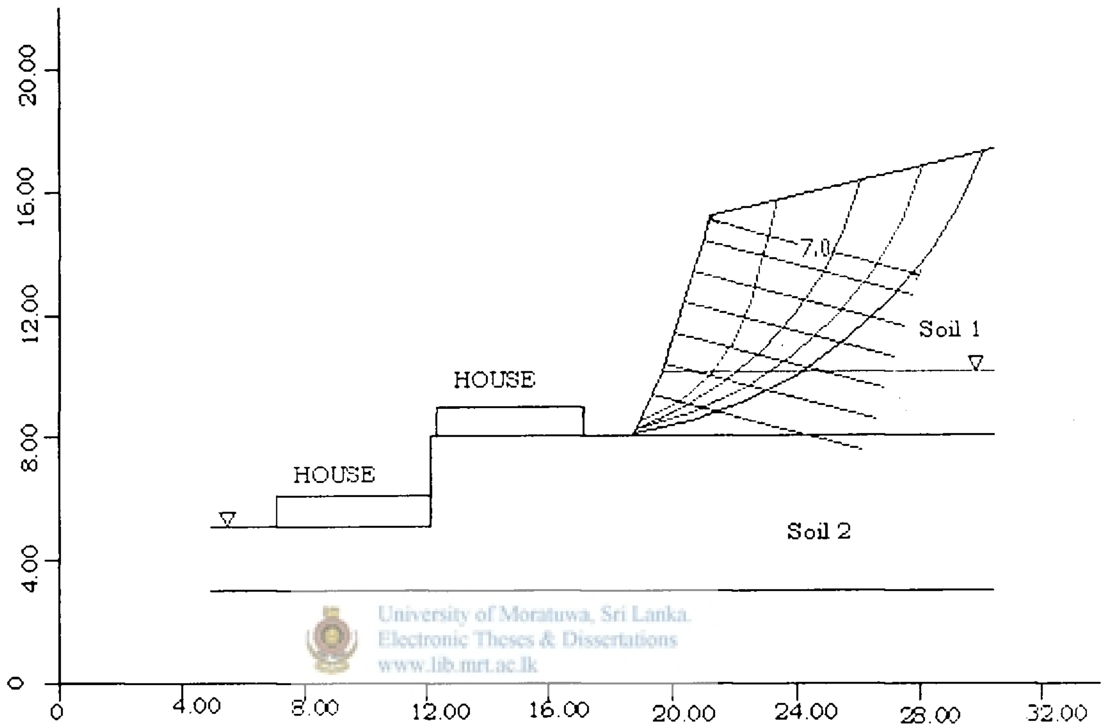


Figure 7.2: Proposed nail arrangement and the failure surfaces considered for cut slope 1

Failure Surface	Factor of safety	Probability of failure	
		Normal	Lognormal
1	1.0079	48.37%	52.11%
2	1.0217	45.63%	49.36%
3	1.1520	25.23%	26.61%
4	1.2478	15.82%	15.16%

Table 7.4: Results for Cut Slope 1 – with the given water table

Failure Surface	Factor of safety	Probability of failure	
		Normal	Lognormal
1	1.0873	33.64%	36.32%
2	1.0831	34.56%	37.39%
3	1.2208	17.79%	17.59%
4	1.3253	10.70%	8.98%

Table 7.5: Results for Cut Slope 1 – with the water table reduced below failure surfaces

Failure Surface	Factor of safety	Probability of failure	
		Normal	Lognormal
1	1.5635	3.08%	1.24%
2	1.45	5.56%	3.38%
3	1.5249	4.18%	2.05%
4	1.5249	4.12%	2.01%

Table 7.6: Results of cut slope 1 – with the proposed nail arrangement

7.6 Example Cut Slope 2 (Ref: RMC/002)

The section (figure 7.3) is found adjacent to the road and consists of a residual soil formation of two different densities. Slope had been analyzed in the original research using both the peak strength parameters and residual strength parameters, and for this slope also the factors of safety values computed in this research are different to that obtained in the original analysis performed by NBRO (National Building Research Organization, 1998). The reasons might be the limitations that were there in the selection of the trial failure surfaces in the NBRO analysis.

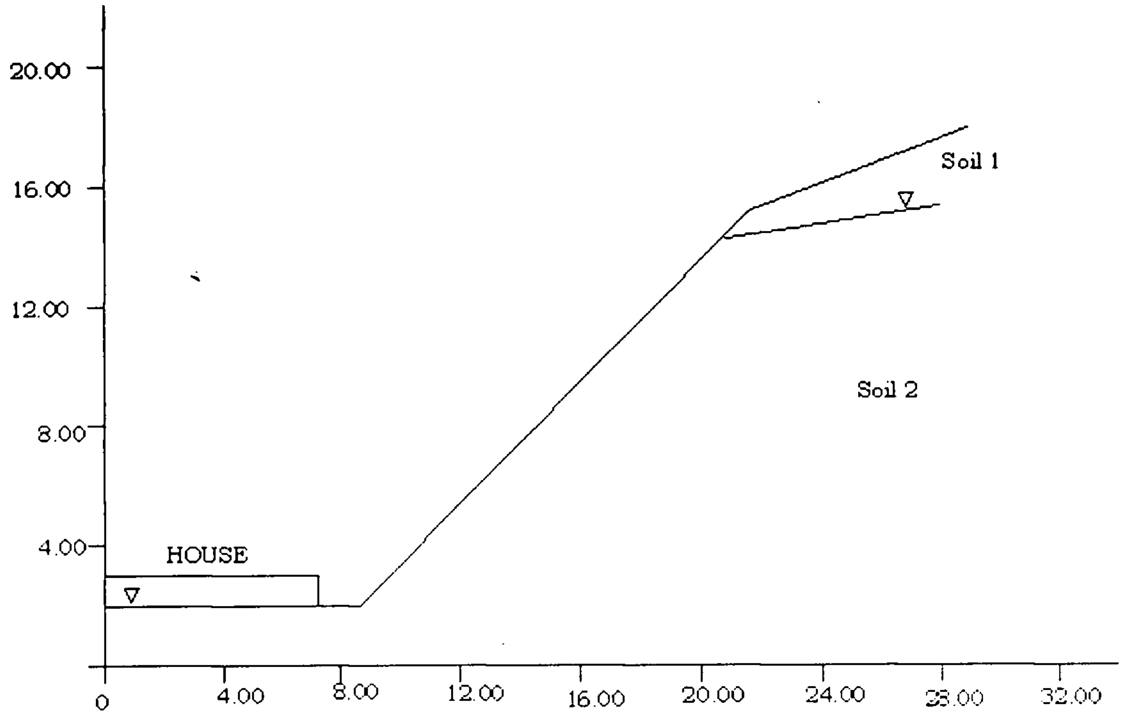


Figure 7.3: Geometry of cut slope 2

Analysis was done using the peak strength parameters obtained by undisturbed testing on saturated samples. It can be seen that, an effective cohesion of about 12 kN/m^2 is available even under fully saturated condition. The parameters used for the analysis are given in table 7.7. Coefficient of variation for pore water pressure was 0.25.

Soil Type	c' (kN/m^2)	ϕ' (^{0})	cov (c')	cov (ϕ')	γ (moist) kN/m^3	γ (saturated) kN/m^3
1	12	29	0.3	0.2	18	19.5
2	21	32	0.2	0.3	19	21.0

Table 7.7: Peak strength parameters for cut slope 2

The slope was also analyzed using SLIDE computer program to identify the most critical circular failure surface. Then the same failure surface was analyzed using author's programs after taking the slice dimensions from the AutoCAD screen. The analysis indicates that the slope to be unstable with a factor of safety of 0.85, a probability of failure of 74.23% for normal distribution assumption and 77.10% for lognormal distribution assumption. The reason behind the slope being stable at present can be explained using unsaturated soil mechanics; however, risk of instability cannot be neglected with the loss of matric suction due to heavy rains.

Hence, nail arrangements were designed to stabilize this slope as well. If the water table can be lowered to lie below the failure surfaces, it is possible to improve the stability, but with the prevailing conditions, such a lowering is highly unlikely.

Nail arrangement designed considering a number of failure surfaces is given in table 7.8. A hydroseeded facing can be used to provide a local stability of soil near the face and to give a pleasant greenish view that blends nicely with the environment.

Length of nails	12m
Orientation	15^0 below horizontal
Vertical spacing	0.75 m
Horizontal spacing	1 m, on a diamond grid
Diameter of steel bars	25 mm high yield steel
Nail type	Driven
Durability requirement	Hot dip galvanizing

Table 7.8: Soil nail arrangement for cut slope 2

Two possible failure surfaces were considered and they are given in figure 7.4 along with the proposed nail arrangement. Results of the analyses of four failure surfaces are given in tables 7.9 and 7.10.

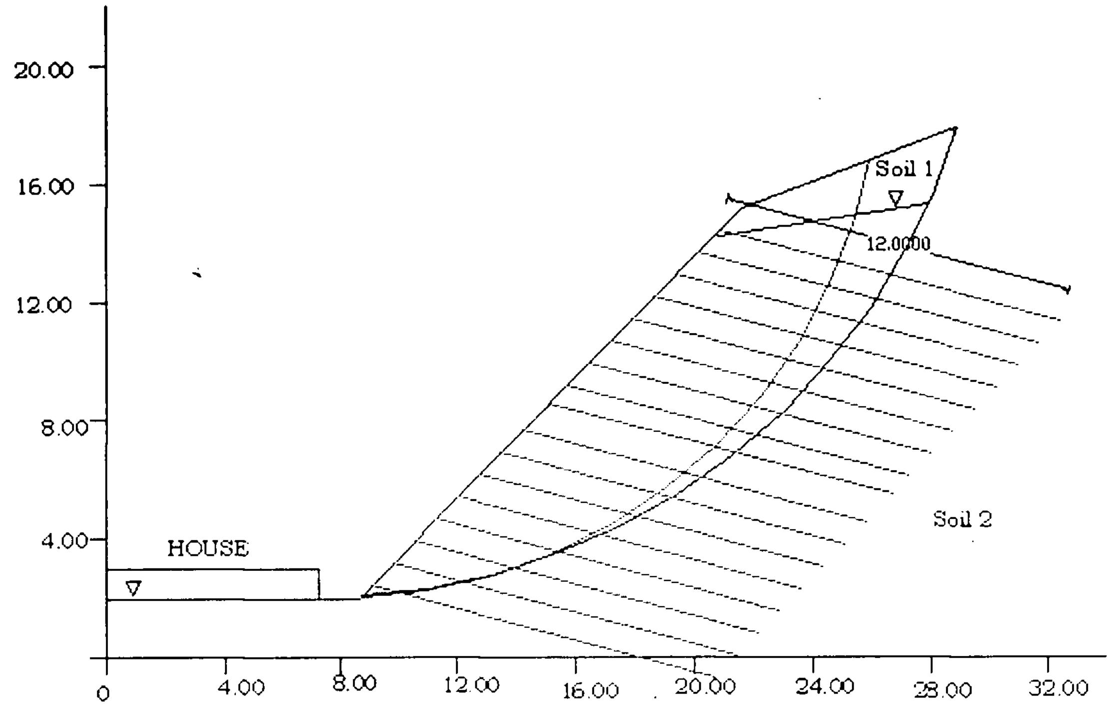


Figure 7.4: Proposed nail arrangement and the failure surfaces considered for cut slope 2

Failure Surface	Factor of safety	Probability of failure	
		Normal	Lognormal
1	0.8510	74.23%	77.10%
2	0.8761	69.41%	73.26%

Table 7.9: Results for cut slope 2 – with the given water table

Failure Surface	Factor of safety	Probability of failure	
		Normal	Lognormal
1	1.92	4.46%	1.32%
2	1.5756	9.77%	6.62%

Table 7.10: Results of cut slope 2 – with the proposed nail arrangement

7.7 Concluding remarks

Soil nailing can satisfactorily be used in stabilizing man-made cut slopes, since the slope angle is high. For the simplicity only the driven type of nails are used in the given nail arrangements. However, if drilled and grouted nails are used, it is possible to have effective diameters around 100mm to 150mm, thus increasing the pullout resistance of nails. Hence, nail spacing may be increased.

Developed probabilistic models were used to evaluate the improvement in stability in probabilistic terms. Always probability of failure is presented along with the appropriate factor of safety since factor of safety is still the most familiar parameter to indicate stability to most geotechnical engineers. However, with the given comparison, it can be seen that the concept of probability of failure is a good supplement to discuss the effectiveness of various stabilization methods. The main justification associated with the concept of probability of failure is that it formally recognizes the uncertainties associated in geotechnical parameters.

Chapter 8

CONCLUSIONS

Under the research described in this thesis, probabilistic analytical models were developed to cover the following:

- For Normal Slopes
    - Circular Failure Surfaces
    - Non-circular Failure Surfaces
- For Slopes stabilized by Soil Nailing
    - Circular Failure Surfaces
    - Non-circular Failure Surfaces

Models developed for normal slopes were facilitated to perform computations using five different approaches ranging from theoretically sound methods to some approximate methods. Also, two methods were used to incorporate the variable nature of the pore water pressures. It was aimed at finding out behavior of each method and selecting the best suitable method. Monte Carlo analysis was also performed using a commercial computer program to provide a basis for the comparisons.

Four cases each were discussed under models based on Bishop's method and Janbu's simplified method respectively. The examples discussed under the model based on Bishop's method were examples 1(a), 1(b), 2 and 3 (discussed in chapters 3 and 4). The examples discussed under the models based on Janbu's simplified method were examples 2, 3 and Watawala slope for high and low water table situations (discussed in chapters 4 and 6). The overall behavior of each method within each model was studied.

For the model based on Bishop's method, all the methods except that assumes M(θ) to be probabilistic gave values very close to each other. For the model based on Janbu's simplified method, all five methods gave very close results. In addition, a significant difference of results could not be observed between two methods that introduced variability of pore pressures in two different ways, when the weighted average is used for the average pore pressure and coefficient of variation values. However, when the results of models developed by the author are compared with the Monte Carlo results, they agree well for dry slopes, but there were some differences in the values for slopes having a phreatic surface. The graphical representations of the summarized results are given in figures 8.1 and 8.2.

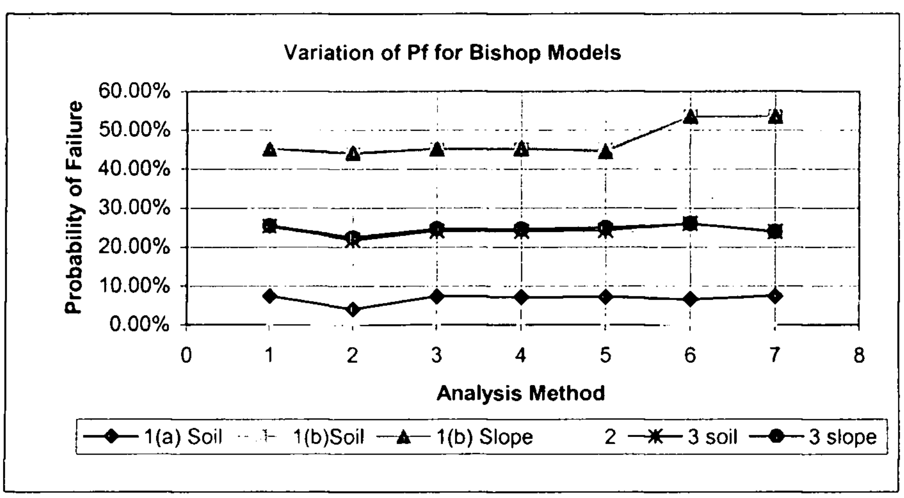


Figure 8.1: Variation of Probability of Failure with Analysis Methods (Summary of Examples – Bishop's method)

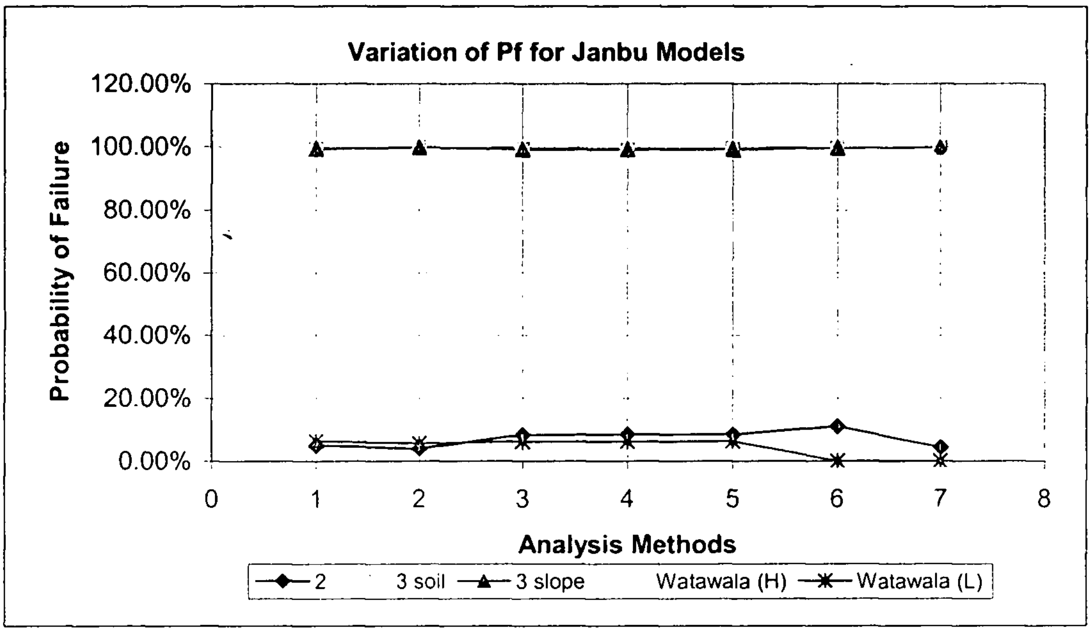


Figure 8.2: Variation of Probability of Failure with Analysis Methods (Summary of Examples – Janbu's method)

The reasons for the difference of values associated between author's models and Monte Carlo results can be assigned to the difference in the methods of introducing the uncertainty of pore pressure. However, a justification could not be arrived for the different values resulted when M(θ) is taken to be probabilistic.

In addition, discussion in chapter 4 showed how the selection of an inappropriate failure mechanism or a deterministic model can produce erroneous results. Hence when there is a special geological feature that can control the position and the shape of the failure surface, it is very important to select the appropriate deterministic model before proceeding with the probabilistic analysis.

According to the observations made in this research, author suggest the use of any of his methods except that assumes M(θ) as probabilistic in probabilistic slope analyses. But, out of the five different ways assumed, the following two methods were identified as simpler and easier than the other methods:

1. Method that assume M(θ) or n(θ) is deterministic
2. Duncan (2000) approach

If any person is not willing to evaluate the partial derivatives in a theoretical manner, Duncan (2000) provides an easy way of performing probabilistic analysis. But, if the partial derivatives can be evaluated, method that assume either M(θ) or n(θ) as deterministic seem to be more efficient utilizing lesser computer disk and memory space.

Author prefers to use the method that assume either M(θ) or n(θ) as deterministic. Hence, models developed for slopes that are stabilized by soil nailing used only this approach.

Analysis of hypothetical problems indicated the possible use of the developed probabilistic methods in the assessment of the effectiveness of various stabilization techniques. Analysis of Watawala slope with some reasonable coefficient of variation parameters also indicated in probabilistic terms how the stability of the slope is improved by drainage. From the coefficient of variation values assumed, it showed that a probability of failure of about 6% seem to be acceptable. If the coefficients of variation could have been directly obtained from the field test data, this analysis would have been more realistic.

The analysis of Marangahawela slope provided a very good case to show the inadequacy of the factor of safety alone in evaluating the stability of a slope. It gave a factor of safety around 1.15 for a slope that has shown signs of instability, similar to the case quoted by Duncan (2000). In addition, it showed how the probability of failure is affected with the magnitudes of uncertainties. Hence this case study highlighted the importance of probabilistic analysis, as a supplement to the conventional factor of safety.

Analysis of cut slopes in Ratnapura MC area showed the possible use of the probabilistic analysis in these types of projects.

With the above observations, author wishes to conclude this discussion reiterating the importance of the probabilistic analysis. The main advantage in probabilistic analysis is that it formally incorporates the uncertainties. As such, it is recommended that in addition to conventional factor of safety that all are familiar with, the probability of failure should also be evaluated using appropriate coefficients of variation to account for the uncertainties in the geotechnical parameters. It will be a very good supplement and will be immensely useful to the Geotechnical Engineer in his assessment of the safety of an existing slope or the effectiveness of the proposed stabilization measures. Models developed under this research could perform satisfactorily in this respect.

Proposals for Future Research

Following areas have been identified as potential areas for future research.

1. A large data base can be collected to contain probability of failure values for both failed and stable slopes so that guidelines for acceptable values of probability of failure can be established in future in Sri Lankan context.
2. Further research can be performed to find out the uncertainties associated with the current practices of parameter estimation prevailing in Sri Lanka. It will not only be helpful to provide reasonable values for the probabilistic analysis but also be useful to find out ways and means of reducing such

uncertainties, so that more reliable data can be estimated in future.

3. The probabilistic models developed in this research can be used to assess the risk of landslides in the landslide prone areas in Sri Lanka. This will enable to identify the areas with high risk using a formal hazard-consequence approach.

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Annex 1

MONTE CARLO ANALYSIS PERFORMED BY SLOPE/W SOFTWARE

The following have extracted from the On-line help of the SLOPE/W software (Geo Slope Office, 1998) to show the way it performs Monte Carlo simulation:

- The use of a probabilistic analysis will not affect the deterministic solution. SLOPE/W computes the factor of safety of all slip surface first and determines the critical slip surface as if no probabilistic analysis is chosen.

- A probabilistic analysis is performed on the critical slip surface only.

- The factor of safety presented on the SOLVE main window during the probabilistic analysis is the deterministic minimum factor of safety of all computed slip surfaces; however when the analysis is completed, the factor of safety presented on the SOLVE main window is the mean factor of safety of all Monte Carlo trials.

- In a probabilistic analysis, the input value of a parameter represents the mean value, and the variability of the parameter is assumed to be normally distributed with a known standard deviation.

- During the Monte Carlo trial, it is not unusual that some of the trials may not have a converged solution (i.e., factor of safety = 999.0). When this happen, the 999.0 factor of safety is not considered in the statistical analysis.

- The number of Monte Carlo trials is dependent on the level of confidence and the amount of variability in the input parameters. Theoretically, the greater the number of Monte Carlo trials, the more accurate the solution.

A diagram showing the typical probability distribution is given in figure A1.1

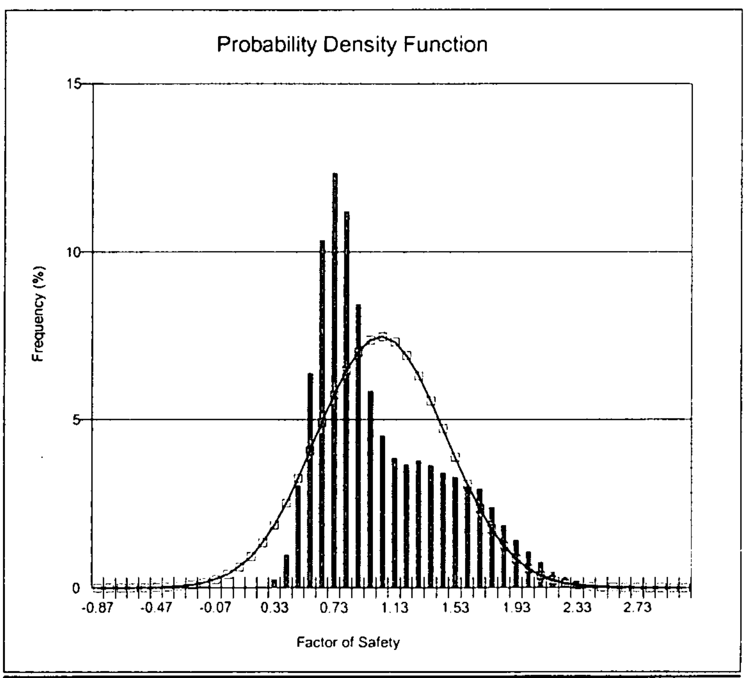

Figure A1.1: Typical Probability Distribution of F (Geo Slope Office, 1998)

Variability in Pore-Water Pressure

In a SLOPE/W probabilistic analysis, the variability in pore-water pressure is represented by a standard deviation of the pore-water pressure head. In the beginning of a Monte Carlo trial, a net change in the pore-water pressure head is computed based on a random number and the normal distribution of the pore-water pressure variability. Depending on the random number, the net change can be positive and negative. The net change is then added to the pore-water pressure conditions of the entire slope.

In the case where the resulting pore-water pressure generates an equivalent water table higher than the ground surface of the slope, SLOPE/W restricts the resulting pore-water pressure head to be not higher than the ground surface. Figure A1.2 illustrates the Monte Carlo trial positions of the piezometric lines used in the analysis when the standard deviation is 1 unit for standard deviates between +3 to -3. It should be noted that the piezometric lines for +2 and +3 standard deviates are restricted in the downstream slope so that no ponding is allowed.

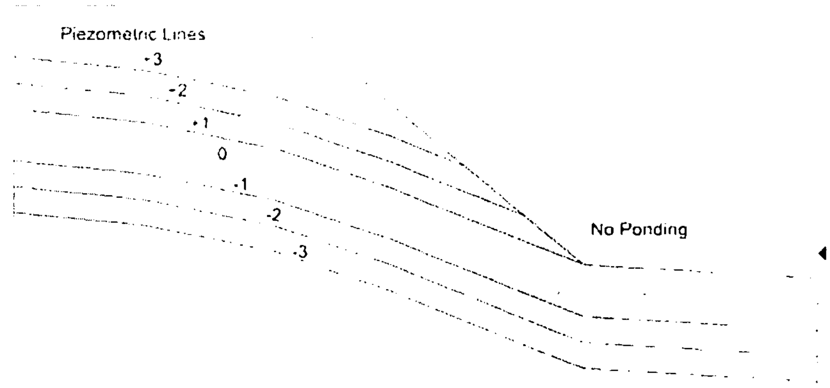

Figure A1.2: Estimation of Piezometric Line Positions in a Monte Carlo Trial (Geo Slope Office, 1998)

When the pore-water pressure at the base of a slice is higher than the weight of the slice, the slice has a negative effective normal, which may cause convergence difficulties in solving the factor of safety equations. Restricting the piezometric line to the slope surface will limit convergence difficulties by preventing extremely high pore-water pressures at the base of the slices.

It is physically more correct to restrict the maximum rise of the pore-water pressure head to the ground surface; however, this restriction introduces some bias to the variability of the pore-water pressure conditions in the slope during the Monte Carlo trials. That is, the variability of the pore-water pressure along the downstream slope is no longer normally distributed. This bias has some effect on the probability density distribution function of the trial factors of safety.

Annex 2

ADDITIONAL DETAILS OF THE EXAMPLES

Example 1 (a)

Details of the critical failure surface

Center = (34.23, 42.62)

Radius = 18.26 m

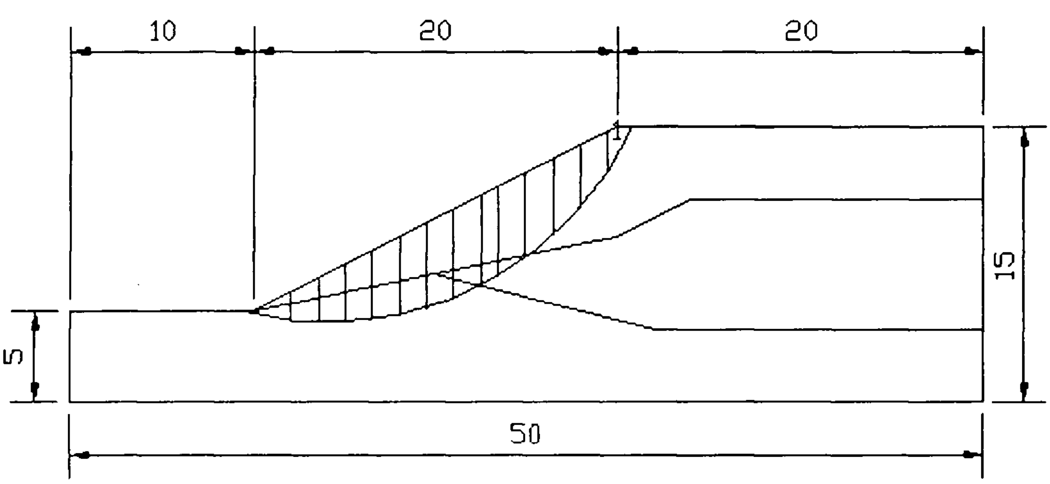

Figure A2.1: Critical failure surface considered in Example 1(a)

Slice	Slice Width Δxi (m)	θi (deg)	r (m)	H1 (m)	h2 (m)	Pore Pressure ui (kN/m2)	Soil Type	c' (kN/m2)	ϕ' (deg)	qi (kN/m2)	γ (kN/m3)
1	1.324	60.750	18.260	0.000	2.143		1	0.00	38.00		19.50
2	1.500	52.670	18.260	2.143	3.372		1	0.00	38.00		19.50
3	1.500	45.480	18.260	3.372	4.153		1	0.00	38.00		19.50
4	1.500	35.120	18.260	4.153	4.626		1	0.00	38.00		19.50
5	1.500	33.280	18.260	4.626	4.862		2	5.30	23.00		19.50
6	0.954	28.790	18.260	4.862	4.909		2	5.30	23.00		19.50
7	1.500	24.480	18.260	4.909	4.843		3	7.20	20.00		19.50
8	1.500	19.400	18.260	4.843	4.622		3	7.20	20.00		19.50
9	1.500	14.480	18.260	4.622	4.260		3	7.20	20.00		19.50
10	1.500	9.660	18.260	4.260	3.766		3	7.20	20.00		19.50
11	1.500	4.920	18.260	3.766	3.122		3	7.20	20.00		19.50
12	1.500	0.000	18.260	3.122	2.400		3	7.20	20.00		19.50
13	1.500	-4.500	18.260	2.400	1.532		3	7.20	20.00		19.50
14	2.046	-10.120	18.260	1.532	0.143		3	7.20	20.00		19.50
15	0.562	-14.300	18.260	0.143	0.000		3	7.20	20.00		19.50

Table A2.1: Slice Details for Example 1(a)

Example 1(b)

Point	x (m)	y (m)
1	20	25
2	30	25
3	43	29.75
4	50	31.5
5	53	32
6	56	32.25
7	70	32.25

Table A2.2: Coordinates of the phreatic surface for Example 1 (b)

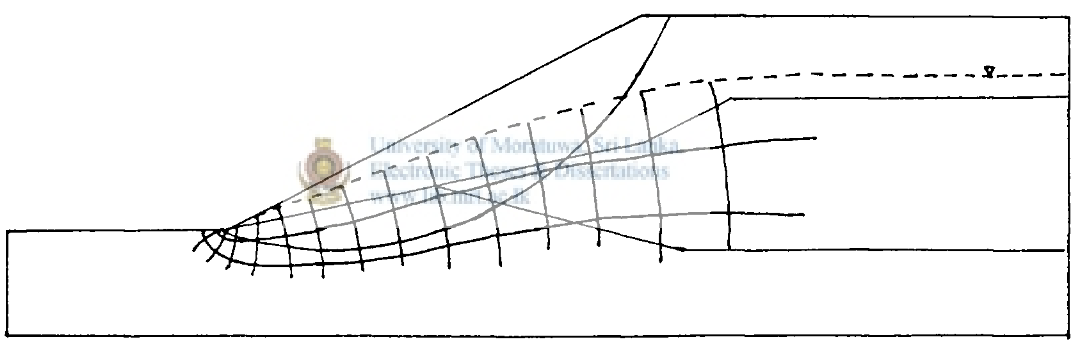

Figure A2.2: Flow Net for Example 1(b)

(Co-ordinates of the Slope Geometry are given in figure 3.9)

Slice	Slice Width Δxi (m)	θi (deg)	r (m)	h1 (m)	h2 (m)	Pore Pressure Ui (kN/m2)	Soil Type	c' (kN/m2)	φ' (deg)	qi (kN/m2)	γ' (kN/m3)
1	1.500	61.960	17.520	0.000	2.870	0.00	1	0.00	38.00		19.50
2	1.930	51.680	17.520	2.870	4.180	3.13	1	0.00	38.00		19.50
3	1.500	43.360	17.520	4.180	4.850	16.28	1	0.00	38.00		19.50
4	1.490	36.960	17.520	4.850	5.230	24.91	2	5.30	23.00		19.50
5	1.500	31.060	17.520	5.230	5.380	30.37	2	5.30	23.00		19.50
6	1.500	25.490	17.520	5.380	5.350	33.86	3	7.20	20.00		19.50
7	1.500	20.160	17.520	5.350	5.060	34.11	3	7.20	20.00		19.50
8	1.500	15.010	17.520	5.060	4.800	32.34	3	7.20	20.00		19.50
9	1.500	9.990	17.520	4.800	4.320	31.16	3	7.20	20.00		19.50
10	1.500	5.040	17.520	4.320	3.700	30.43	3	7.20	20.00		19.50
11	1.500	0.000	17.520	3.700	2.960	25.20	3	7.20	20.00		19.50
12	1.500	-4.780	17.520	2.960	2.080	18.71	3	7.20	20.00		19.50
13	1.500	-9.780	17.520	2.080	1.070	15.20	3	7.20	20.00		19.50
14	1.180	-14.210	17.520	1.070	0.180	9.83	3	7.20	20.00		19.50
15	0.590	-17.220	17.520	0.180	0.000	2.42	3	7.20	20.00		19.50

Table A2.3: Slice Details of Example 1(b)

Example 2

Details of critical failure surface (Non-circular)

Point	x (m)	y (m)
1	42	27.75
2	44	26.5
3	63	27
4	72.5	40

Table A2.4: Failure Surface Coordinates for Example 2

Details of critical failure surface (Circular)

Center = (50.25, 50.25)

Radius = 23.75m

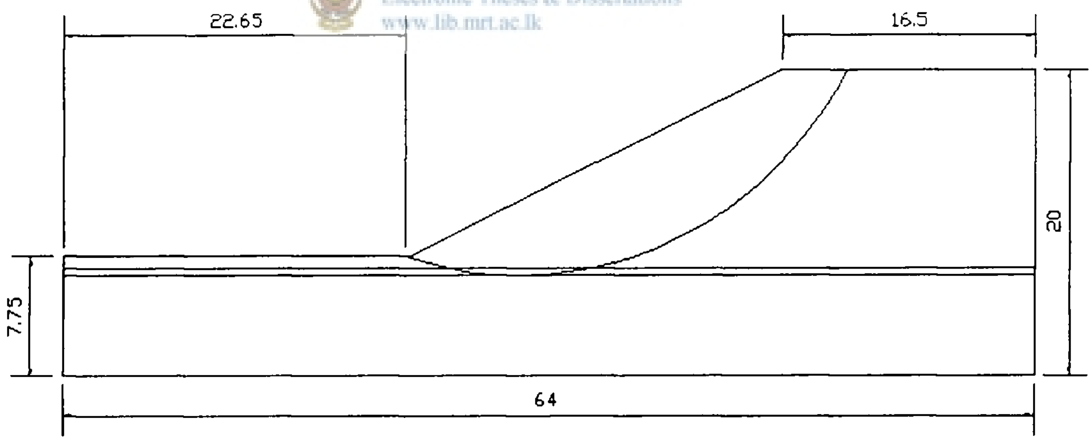

Figure A2.3: Critical Circular Failure Surface for Example 2

(critical Non-circular Failure surface in given in the main text)

Slice	Slice Width Δxi (m)	θi (deg)	H1 (m)	h2 (m)	Pore Pressure ui (kN/m2)	Soil Type	c' (kN/m2)	ϕ' (deg)	qi (kN/m2)	γ (kN/m3)
1	5.000	53.842	0.000	6.842		1	28.50	20.00		18.84
2	4.500	53.842	6.842	10.750		1	28.50	20.00		18.84
3	6.190	1.507	10.750	7.818		2	0.00	10.00		18.84
4	6.215	1.507	7.818	4.874		2	0.00	10.00		18.84
5	6.595	1.507	4.874	1.750		2	0.00	10.00		18.84
6	1.000	-32.005	1.750	0.625		2	0.00	10.00		18.84
7	1.000	-32.005	0.625	0.000		1	28.50	20.00		18.84

Table A2.5: Slice Details for Example 2 (Non Circular Failure Surface)

Slice	Slice Width Δxi (m)	θi (deg)	r (m)	h1 (m)	h2 (m)	Pore Pressure Ui (kN/m2)	Soil Type	c' (kN/m2)	ϕ' (deg)	qi (kN/m2)	γ (kN/m3)
1	2.174	58.900	23.750	0.000	3.660		1	28.50	20.00		18.84
2	2.000	50.200	23.750	3.660	6.075		1	28.50	20.00		18.84
3	2.000	43.200	23.750	6.075	6.957		1	28.50	20.00		18.84
4	2.000	36.900	23.750	6.957	7.460		1	28.50	20.00		18.84
5	2.000	31.100	23.750	7.460	7.667		1	28.50	20.00		18.84
6	2.000	25.600	23.750	7.667	7.625		1	28.50	20.00		18.84
7	2.000	20.300	23.750	7.625	7.366		1	28.50	20.00		18.84
8	2.402	14.800	23.750	7.366	6.913		1	28.50	20.00		18.84
9	1.598	9.800	23.750	6.913	6.277		2	0.00	10.00		18.84
10	2.000	5.400	23.750	6.277	5.467		2	0.00	10.00		18.84
11	2.000	0.600	23.750	5.467	4.488		2	0.00	10.00		18.84
12	2.000	-4.200	23.750	4.488	3.340		2	0.00	10.00		18.84
13	2.000	-9.100	23.750	3.340	2.000		2	0.00	10.00		18.84
14	2.854	-15.100	23.750	2.000	0.000		1	28.50	20.00		18.84

Table A2.6: Slice Details for Example 2 (Circular Failure Surface)

Example 3

Details of Critical Failure Surface (Non-Circular)

Point	x (m)	y (m)
1	43	27.75
2	49.15	26.44
3	77.06	34.86
4	80	40

Table A2.7: Coordinates of the Critical Failure Surface for Example 3

Details of Critical Failure Surface (Circular)

Center = (48.59, 71.30)

Radius = 43.35m

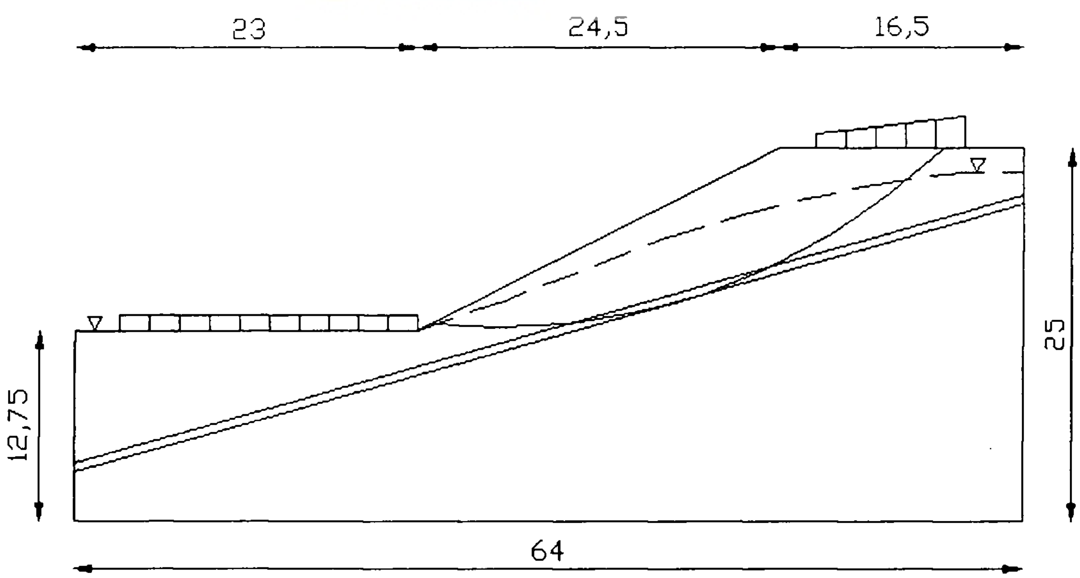

Figure A2.4: Critical Circular Failure Surface for Example 3

Point	x (m)	y (m)
1	20	27.75
2	43	27.75
3	49	29.80
4	60	34.00
5	66	35.80
6	74	37.60
7	80	38.40
8	84	38.40

Table A2.8: Coordinates of Piezometric Surface for Example 3

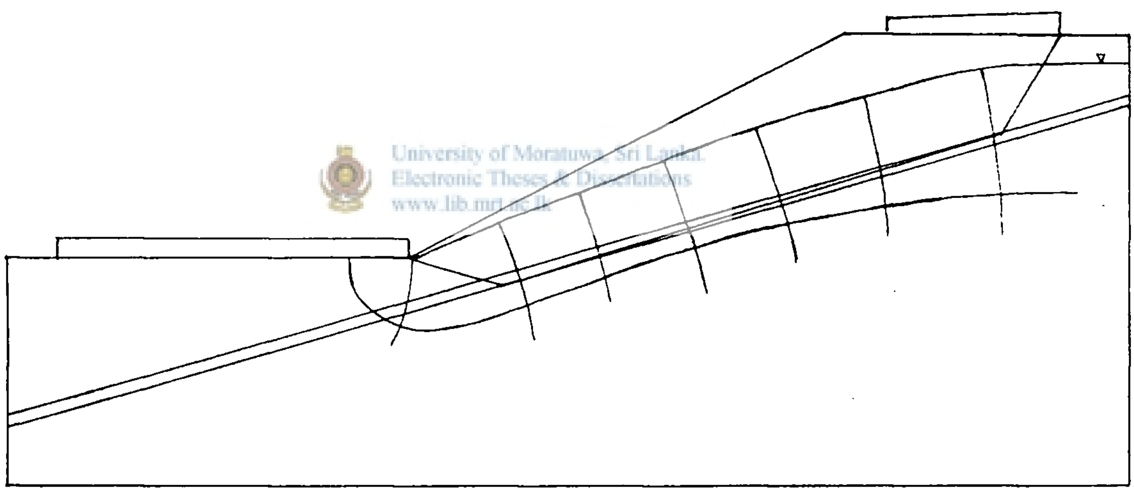

Figure A2.5: Flow Net for Example 3

Slice	Slice Width Δxi (m)	θi (deg)	h1 (m)	h2 (m)	Pore Pressure Ui (kN/m2)	Soil Type	c' (kN/m2)	ϕ' (deg)	qi (kN/m2)	γ (kN/m3)
1	2.800	-12.020	0.000	2.000	8.83	1	28.50	20.00	0.00	18.84
2	2.600	-12.020	2.000	3.850	22.56	1	28.50	20.00	0.00	18.84
3	3.200	16.780	3.850	4.870	31.39	2	0.00	10.00	0.00	18.84
4	2.900	16.780	4.870	5.440	31.39	2	0.00	10.00	0.00	18.84
5	2.900	16.780	5.440	6.020	34.34	2	0.00	10.00	0.00	18.84
6	2.900	16.780	6.020	6.600	37.28	2	0.00	10.00	0.00	18.84
7	2.900	16.780	6.600	7.170	40.22	2	0.00	10.00	0.00	18.84
8	2.900	16.780	7.170	7.750	40.22	2	0.00	10.00	0.00	18.84
9	2.000	16.780	7.750	7.840	40.22	2	0.00	10.00	0.00	18.84
10	1.900	16.780	7.840	7.270	40.22	2	0.00	10.00	0.00	18.84
11	2.750	16.780	7.270	6.440	37.28	2	0.00	10.00	22.28	18.84
12	2.610	16.780	6.440	5.640	34.34	2	0.00	10.00	26.84	18.84
13	2.040	16.780	5.640	4.550	31.39	2	0.00	10.00	31.71	18.84
14	2.60	60.26	4.55	0.000	8.83	1	28.50	20.00	36.86	18.84

Table A2.9: Slice Details for Example 3 (Non Circular Failure Surface)

Slice	Slice Width Δxi (m)	θi (deg)	r (m)	H1 (m)	h2 (m)	Pore Pressure ui (kN/m2)	Soil Type	c' (kN/m2)	ϕ' (deg)	qi (kN/m2)	γ (kN/m3)
1	1.500	61.960	17.520	0.000	2.870	0.00	1	0.00	38.00		19.50
2	1.930	51.680	17.520	2.870	4.180	3.13	1	0.00	38.00		19.50
3	1.500	43.360	17.520	4.180	4.850	16.28	1	0.00	38.00		19.50
4	1.490	36.960	17.520	4.850	5.230	24.91	2	5.30	23.00		19.50
5	1.500	31.060	17.520	5.230	5.380	30.37	2	5.30	23.00		19.50
6	1.500	25.490	17.520	5.380	5.350	33.86	3	7.20	20.00		19.50
7	1.500	20.160	17.520	5.350	5.060	34.11	3	7.20	20.00		19.50
8	1.500	15.010	17.520	5.060	4.800	32.34	3	7.20	20.00		19.50
9	1.500	9.990	17.520	4.800	4.320	31.16	3	7.20	20.00		19.50
10	1.500	5.040	17.520	4.320	3.700	30.43	3	7.20	20.00		19.50
11	1.500	0.000	17.520	3.700	2.960	25.20	3	7.20	20.00		19.50
12	1.500	-4.780	17.520	2.960	2.080	18.71	3	7.20	20.00		19.50
13	1.500	-9.780	17.520	2.080	1.070	15.20	3	7.20	20.00		19.50
14	1.180	-14.210	17.520	1.070	0.180	9.83	3	7.20	20.00		19.50
15	0.590	-17.220	17.520	0.180	0.000	2.42	3	7.20	20.00		19.50

Table A2.10: Slice Details for Example 3 (Circular Failure Surface)

Annex 3

CHART FOR f_0 IN JANBU'S SIMPLIFIED METHOD

Following is the chart given by Janbu regarding the modification factor f_0:

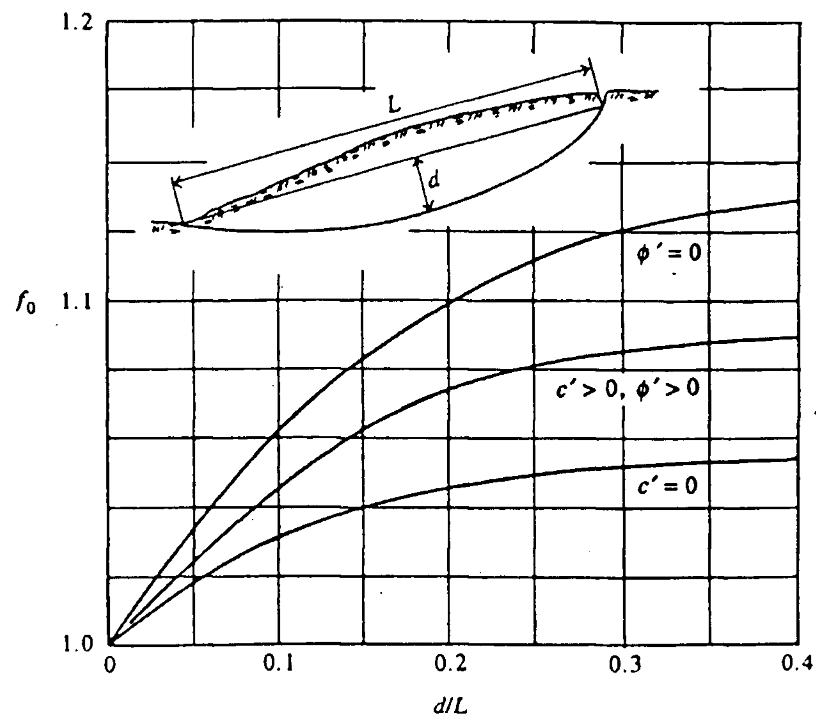

Figure A3.1: Chart for f_0 in Janbu's simplified method

Annex 4

SAMPLE SET OF SPREADSHEETS – MODEL BASED ON BISHOP'S METHOD

{Values correspond to Example 1(b) (FileName: ACAD1C1)}

Spreadsheet: BISHOP – PROB – DIRECT

(COV (u) = based on soil layers)

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

DETERMINISTIC

(Probabilistic calculations are valid upto 5 different soil layers)

												CALCULATION-STAGE 1			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Slice	Slice Width Δxi (m)	θi (deg)	r (m)	h1 (m)	h2 (m)	Pore Pressure ui (kN/m2)	Soil Type	c' (kN/m2)	φ' (deg)	qi (kN/m2)	γ (kN/m3)	{(5)+(6)}/2 hav (m)	(2)*(12)*(13) wi (kN-per m width)	(2)*(11) Qi (kN-per m width)	tan φ'
1	1.500	61.960	17.520	0.000	2.870	0.00	1	0.00	38.00		19.50	1.44	41.97		0.78
2	1.930	51.680	17.520	2.870	4.180	3.13	1	0.00	38.00		19.50	3.53	132.66		0.78
3	1.500	43.360	17.520	4.180	4.850	16.28	1	0.00	38.00		19.50	4.52	132.06		0.78
4	1.490	36.960	17.520	4.850	5.230	24.91	2	5.30	23.00		19.50	5.04	146.44		0.42
5	1.500	31.060	17.520	5.230	5.380	30.37	2	5.30	23.00		19.50	5.31	155.17		0.42
6	1.500	25.490	17.520	5.380	5.350	33.86	3	7.20	20.00		19.50	5.37	156.93		0.36
7	1.500	20.160	17.520	5.350	5.060	34.11	3	7.20	20.00		19.50	5.21	152.25		0.36
8	1.500	15.010	17.520	5.060	4.800	32.34	3	7.20	20.00		19.50	4.93	144.20		0.36
9	1.500	9.990	17.520	4.800	4.320	31.16	3	7.20	20.00		19.50	4.56	133.38		0.36
10	1.500	5.040	17.520	4.320	3.700	30.43	3	7.20	20.00		19.50	4.01	117.29		0.36
11	1.500	0.000	17.520	3.700	2.960	25.20	3	7.20	20.00		19.50	3.33	97.40		0.36
12	1.500	-4.780	17.520	2.960	2.080	18.71	3	7.20	20.00		19.50	2.52	73.71		0.36
13	1.500	-9.780	17.520	2.080	1.070	15.20	3	7.20	20.00		19.50	1.58	46.07		0.36
14	1.180	-14.210	17.520	1.070	0.180	9.83	3	7.20	20.00		19.50	0.63	14.38		0.36
15	0.590	-17.220	17.520	0.180	0.000	2.42	3	7.20	20.00		19.50	0.09	1.04		0.36
16															
												FOS(3)	1.03	FOS(4)	1.03
														FOS	1.03

CALCULATION OF PROBABILITY OF FAILURE OF A SELECTED FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

PROBABILISTIC(First Order Second Moment)

Direct Differentiation

DATA INPUT

Probabilistic Parameters	COV			Mean			c'(kPa)			Φ'(rad)			u (kPa)		
	c'	Φ'	u	c'(kPa)	Φ' (deg)	u (kPa)	Mean	σ	V	Mean	σ	V	Mean	σ	V
Soil 1	0	0.3	0.25	0	38	6.47	0.00	0.0000	0.0000	0.66	0.1990	0.0396	6.47	1.6175	2.6163
Soil 2	0.3	0.4	0.3	5.3	23	27.64	5.30	1.5900	2.5281	0.40	0.1606	0.0258	27.64	8.2920	68.7573
Soil 3	0.2	0.35	0.35	7.2	20	23.33	7.20	1.4400	2.0736	0.35	0.1222	0.0149	23.33	8.1655	66.6754
Soil 4							0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.00	0.0000	0.0000
Soil 5							0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.00	0.0000	0.0000

Xr	(∂F/∂Xr)	(∂F/∂Xr)²	(∂F/∂Xr)² *V(Xr)
c1	0.00716	5E-05	0
c2	0.00493	2E-05	6E-05
c3	0.02418	0.0006	0.001
c4	0.00000	0	0
c5	0.00000	0	0
φ1	0.63840	0.4076	0.016
φ2	0.42615	0.1816	0.005
φ3	1.13383	1.2856	0.019
φ4	0.00000	0	0
φ5	0.00000	0	0
u1	-0.00560	3E-05	0.002
u2	-0.00209	4E-06	3E-04
u3	-0.00880	8E-05	0
u4	0.00000	0	0
u5	0.00000	0	0
			0.044

F			
	V(FOS)	0.044	TAYLOR SERIES
	σ(FOS)	0.209	
	FOS(MLV)	1.03	
	COV(F)	0.203	

(NORMAL DISTRIBUTION)		
RELIABILITY INDEX	0.133	
RELIABILITY	0.553	55.31 %
PROB. FAIL	0.447	44.69 %

(LOGNORMAL DISTRIBUTION)		
$1+[COV(F)]^2$	1.041	
RELIABILITY INDEX	0.036	
RELIABILITY	0.514	51.44 %
PROB. FAIL	0.486	48.56 %

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

CALCULATIONS

												CALCULATION-STAGE 1		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Slice	Slice Width Δxi (m)	θi (deg)	r (m)	h1 (m)	h2 (m)	Pore Pressure ui (kN/m2)	Soil Type	c' (kN/m2)	ϕ' (deg)	qi (kN/m2)	γ (kN/m3)	{(5)+(6)}/2 hav (m)	(2)*(12)*(13) wi (kN-per m width)	(2)*(11) Qi (kN-per m width)
1	1.500	61.960	17.520		2.870		1		38.00		19.50	1.44	41.97	
2	1.930	51.680	17.520	2.870	4.180	3.13	1		38.00		19.50	3.53	132.66	
3	1.500	43.360	17.520	4.180	4.850	16.28	1		38.00		19.50	4.52	132.06	
4	1.490	36.960	17.520	4.850	5.230	24.91	2	5.30	23.00		19.50	5.04	146.44	
5	1.500	31.060	17.520	5.230	5.380	30.37	2	5.30	23.00		19.50	5.31	155.17	
6	1.500	25.490	17.520	5.380	5.350	33.86	3	7.20	20.00		19.50	5.37	156.93	
7	1.500	20.160	17.520	5.350	5.060	34.11	3	7.20	20.00		19.50	5.21	152.25	
8	1.500	15.010	17.520	5.060	4.800	32.34	3	7.20	20.00		19.50	4.93	144.20	
9	1.500	9.990	17.520	4.800	4.320	31.16	3	7.20	20.00		19.50	4.56	133.38	
10	1.500	5.040	17.520	4.320	3.700	30.43	3	7.20	20.00		19.50	4.01	117.29	
11	1.500		17.520	3.700	2.960	25.20	3	7.20	20.00		19.50	3.33	97.40	
12	1.500	-4.780	17.520	2.960	2.080	18.71	3	7.20	20.00		19.50	2.52	73.71	
13	1.500	-9.780	17.520	2.080	1.070	15.20	3	7.20	20.00		19.50	1.58	46.07	
14	1.180	-14.210	17.520	1.070	0.180	9.83	3	7.20	20.00		19.50	0.63	14.38	
15	0.590	-17.220	17.520	0.180		2.42	3	7.20	20.00		19.50	0.09	1.04	
16														

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

CALCULATIONS

	CALCULATION-STAGE 2													
16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
			Ui=				Trial 1	Trial 1	Trial 2	Trial 2	Trial 3	Trial 3	Trial 4	Trial 4
					(20)*(16)	(18)+(21)		(22)/(23)		(22)/(25)		(22)/(27)		(22)/(29)
tan φ'	(wi+Qi) sin θi	c'Δxi	ui*Δxi	(wi+Qi -uiΔxi)	(20)*tanφ'		Mi(θ)		Mi(θ)		Mi(θ)		Mi(θ)	
0.78	37.05			41.97	32.79	32.79	1.09	30.14	1.13	29.02	1.14	28.79	1.14	28.75
0.78	104.08		6.04	126.62	98.93	98.93	1.17	84.60	1.21	81.99	1.21	81.45	1.22	81.34
0.78	90.67		24.42	107.64	84.10	84.10	1.21	69.63	1.24	67.80	1.25	67.43	1.25	67.35
0.42	88.05	7.90	37.12	109.32	46.40	54.30	1.03	52.83	1.04	52.05	1.05	51.88	1.05	51.85
0.42	80.06	7.95	45.56	109.62	46.53	54.48	1.05	51.74	1.07	51.10	1.07	50.96	1.07	50.93
0.36	67.53	10.80	50.79	106.14	38.63	49.43	1.04	47.39	1.05	46.96	1.05	46.87	1.05	46.85
0.36	52.47	10.80	51.17	101.08	36.79	47.59	1.05	45.27	1.06	44.95	1.06	44.88	1.06	44.87
0.36	37.35	10.80	48.51	95.69	34.83	45.63	1.05	43.44	1.06	43.21	1.06	43.16	1.06	43.15
0.36	23.14	10.80	46.74	86.64	31.53	42.33	1.04	40.65	1.05	40.50	1.05	40.47	1.05	40.46
0.36	10.30	10.80	45.65	71.65	26.08	36.88	1.02	35.99	1.03	35.92	1.03	35.90	1.03	35.90
0.36		10.80	37.80	59.60	21.69	32.49	1.00	32.49	1.00	32.49	1.00	32.49	1.00	32.49
0.36	-6.14	10.80	28.07	45.65	16.61	27.41	0.97	28.28	0.97	28.33	0.97	28.35	0.97	28.35
0.36	-7.83	10.80	22.80	23.27	8.47	19.27	0.93	20.72	0.93	20.80	0.93	20.82	0.93	20.82
0.36	-3.53	8.50	11.60	2.78	1.01	9.51	0.89	10.69	0.88	10.76	0.88	10.77	0.88	10.77
0.36	-0.31	4.25	1.43	-0.39	-0.14	4.11	0.86	4.78	0.85	4.82	0.85	4.83	0.85	4.83
							1.00		1.00		1.00		1.00	
	572.90					639.25		598.65		590.69		589.06		588.72
					FOS(ini)	1.116	FOS(1)	1.045	FOS(2)	1.031	FOS(3)	1.028	FOS(4)	1.028
													FOS	1.028

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

CALCULATIONS

CALCULATION-STAGE 3

31	32	33	34	35	36	37	38	39	40	41
Soil 1				**Soil 2**				**Soil 3**		
(2)/(29) Δxi/Mi(θ)	**sec²Φ'**	**(20)*sec²Φ'/Mi(θ)**	**-(2)*(16)/(29) -Δxi*tanΦ'/Mi(θ)**	**Δxi/Mi(θ)**	**sec²Φ'**	**(20)*sec²Φ'/Mi(θ)**	**-(2)*(16)/(29) -Δxi*tanΦ'/Mi(θ)**	**Δxi/Mi(θ)**	**sec²Φ'**	**(20)*sec²Φ'/Mi(θ)**
1.31	1.61	59.25	-1.03							
1.59	1.61	167.66	-1.24							
1.20	1.61	138.82	-0.94							
				1.422744052	1.18017887	123.1950143	-0.60391902			
				1.402366346	1.18017887	120.9464143	-0.595269197			
								1.42180242	1.13247433	113.9305247
								1.41411764	1.13247433	107.9178422
								1.41836159	1.13247433	102.4712351
								1.43369728	1.13247433	93.78060148
								1.46023549	1.13247433	78.98798757
								1.5	1.13247433	67.49830134
								1.55114998	1.13247433	53.45448018
								1.62103018	1.13247433	28.47746079
								1.33709895	1.13247433	3.569797785
								0.69380667	1.13247433	-0.522502636
4.10		365.74	-3.21	2.825110398		244.14	-1.20	13.8513002		649.57
dF/dc Σ(31)/Σ(17)		dF/dΦ' Σ(33)/Σ(17)	dF/du Σ(34)/Σ(17)	dF/dc Σ(35)/Σ(17)		dF/dΦ' Σ(37)/Σ(17)	dF/du Σ(38)/Σ(17)	dF/dc Σ(39)/Σ(17)		dF/dΦ' Σ(41)/Σ(17)
0.00716		0.63840	-0.00560	0.00493		0.42615	-0.00209	0.02418		1.13383

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

CALCULATIONS

42	43	44	45	46	47	48	49	50
	Soil 4				Soil 5			
-(2)*(16)/(29) -Δxi*tanΦ'/Mi(θ)	Δxi/Mi(θ)	$sec^2Φ'$	(20)*$sec^2Φ'$/Mi(θ)	-(2)*(16)/(29) -Δxi*tanΦ'/Mi(θ	Δxi/Mi(θ)	$sec^2Φ'$	(20)*$sec^2Φ'$/Mi(θ)	-(2)*(16)/(29) -Δxi*tanΦ'/Mi(θ)
-0.517493761								
-0.51469673								
-0.516241401								
-0.521823136								
-0.531482254								
-0.545955351								
-0.564572421								
-0.590006735								
-0.486664217								
-0.252524978								
-5.04	0		0.00	0.00	0		0.00	0.00
dF/du Σ(42)/Σ(17)	dF/dc Σ(43)/Σ(17)		dF/dΦ' Σ(45)/Σ(17)	dF/du Σ(46)/Σ(17)	dF/dc Σ(47)/Σ(17)		dF/dΦ' Σ(49)/Σ(17)	dF/du Σ(50)/Σ(17)
-0.00880	0.00000		0.00000	0.00000	0.00000		0.00000	0.00000

Spreadsheet: BISHOP - PROB - DIRECT

(COV(u) = constant for the slope)

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

DETERMINISTIC

(Probabilistic calculations are valid upto 5 different soil layers)

												CALCULATION-STAGE 1			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Slice	Slice Width Δxi (m)	θi (deg)	r (m)	h1 (m)	h2 (m)	Pore Pressure ui (kN/m2)	Soil Type	c' (kN/m2)	ϕ' (deg)	qi (kN/m2)	γ (kN/m3)	{(5)+(6)}/2 hav (m)	(2)*(12)*(13) wi (kN-per m width)	(2)*(11) Qi (kN-per m width)	tan ϕ'
1	1.500	61.960	17.520	0.000	2.870	0.00	1	0.00	38.00		19.50	1.44	41.97		0.78
2	1.930	51.680	17.520	2.870	4.180	3.13	1	0.00	38.00		19.50	3.53	132.66		0.78
3	1.500	43.360	17.520	4.180	4.850	16.28	1	0.00	38.00		19.50	4.52	132.06		0.78
4	1.490	36.960	17.520	4.850	5.230	24.91	2	5.30	23.00		19.50	5.04	146.44		0.42
5	1.500	31.060	17.520	5.230	5.380	30.37	2	5.30	23.00		19.50	5.31	155.17		0.42
6	1.500	25.490	17.520	5.380	5.350	33.86	3	7.20	20.00		19.50	5.37	156.93		0.36
7	1.500	20.160	17.520	5.350	5.060	34.11	3	7.20	20.00		19.50	5.21	152.25		0.36
8	1.500	15.010	17.520	5.060	4.800	32.34	3	7.20	20.00		19.50	4.93	144.20		0.36
9	1.500	9.990	17.520	4.800	4.320	31.16	3	7.20	20.00		19.50	4.56	133.38		0.36
10	1.500	5.040	17.520	4.320	3.700	30.43	3	7.20	20.00		19.50	4.01	117.29		0.36
11	1.500	0.000	17.520	3.700	2.960	25.20	3	7.20	20.00		19.50	3.33	97.40		0.36
12	1.500	-4.780	17.520	2.960	2.080	18.71	3	7.20	20.00		19.50	2.52	73.71		0.36
13	1.500	-9.780	17.520	2.080	1.070	15.20	3	7.20	20.00		19.50	1.58	46.07		0.36
14	1.180	-14.210	17.520	1.070	0.180	9.83	3	7.20	20.00		19.50	0.63	14.38		0.36
15	0.590	-17.220	17.520	0.180	0.000	2.42	3	7.20	20.00		19.50	0.09	1.04		0.36
16															
												FOS(3)	1.03	FOS(4)	1.03
														FOS	1.03

CALCULATION OF PROBABILITY OF FAILURE OF A SELECTED FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

PROBABILISTIC(First Order Second Moment)

Direct Differentiation

DATA INPUT

Probabilistic Parameters	COV		Mean		c'(kPa)			Φ'(rad)		
	c'	Φ'	c'(kPa)	Φ'(deg)	Mean	σ	V	Mean	σ	V
Soil 1	0	0.3	0	38	0.00	0.0000	0.0000	0.66	0.1990	0.0396
Soil 2	0.3	0.4	5.3	23	5.30	1.5900	2.5281	0.40	0.1606	0.0258
Soil 3	0.2	0.35	7.2	20	7.20	1.4400	2.0736	0.35	0.1222	0.0149
Soil 4					0.00	0.0000	0.0000	0.00	0.0000	0.0000
Soil 5					0.00	0.0000	0.0000	0.00	0.0000	0.0000

	Variance
u (kPa)	43.955

Xr	(∂F/∂Xr)	$(\partial F/\partial Xr)^2$	$(\partial F/\partial Xr)^2 * V(Xr)$
c1	0.01	5E-05	0
c2	0.00493	2E-05	6E-05
c3	0.02418	6E-04	0.001
c4	0	0	0
c5	0	0	0
ϕ1	0.64	0.408	0.016
ϕ2	0.42615	0.182	0.005
ϕ3	1.13383	1.286	0.019
ϕ4	0	0	0
ϕ5	0	0	0
u	-0.02	3E-04	0.012
			0.053

F			
	V(FOS)	0.053	TAYLOR SEIRIES
	σ(FOS)	0.231	
	FOS(MLV)	1.028	
	COV(F)	0.224	

(NORMAL DISTRIBUTION)

RELIABILITY INDEX	0.121	
RELIABILITY	0.548	54.81 %
PROB. FAIL	0.452	45.19 %

(LOGNORMAL DISTRIBUTION)

$1+[COV(F)]^2$	1.05	
RELIABILITY INDEX	0.013	
RELIABILITY	0.505	50.53 %
PROB. FAIL	0.495	49.47 %

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

CALCULATIONS

												CALCULATION-STAGE 1		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Slice	Slice Width Δxi (m)	θi (deg)	r (m)	h1 (m)	h2 (m)	Pore Pressure ui (kN/m2)	Soil Type	c' (kN/m2)	ϕ' (deg)	qi (kN/m2)	γ (kN/m3)	{(5)+(6)}/2 hav (m)	(2)*(12)*(13) wi (kN-per m width)	(2)*(11) Qi (kN-per m width)
1	1.500	61.960	17.520		2.870		1		38.00		19.50	1.44	41.97	
2	1.930	51.680	17.520	2.870	4.180	3.13	1		38.00		19.50	3.53	132.66	
3	1.500	43.360	17.520	4.180	4.850	16.28	1		38.00		19.50	4.52	132.06	
4	1.490	36.960	17.520	4.850	5.230	24.91	2	5.30	23.00		19.50	5.04	146.44	
5	1.500	31.060	17.520	5.230	5.380	30.37	2	5.30	23.00		19.50	5.31	155.17	
6	1.500	25.490	17.520	5.380	5.350	33.86	3	7.20	20.00		19.50	5.37	156.93	
7	1.500	20.160	17.520	5.350	5.060	34.11	3	7.20	20.00		19.50	5.21	152.25	
7	1.500	15.010	17.520	5.060	4.800	32.34	3	7.20	20.00		19.50	4.93	144.20	
7	1.500	9.990	17.520	4.800	4.320	31.16	3	7.20	20.00		19.50	4.56	133.38	
7	1.500	5.040	17.520	4.320	3.700	30.43	3	7.20	20.00		19.50	4.01	117.29	
7	1.500		17.520	3.700	2.960	25.20	3	7.20	20.00		19.50	3.33	97.40	
7	1.500	-4.780	17.520	2.960	2.080	18.71	3	7.20	20.00		19.50	2.52	73.71	
7	1.500	-9.780	17.520	2.080	1.070	15.20	3	7.20	20.00		19.50	1.58	46.07	
7	1.180	-14.210	17.520	1.070	0.180	9.83	3	7.20	20.00		19.50	0.63	14.38	
7	0.590	-17.220	17.520	0.180		2.42	3	7.20	20.00		19.50	0.09	1.04	
7														

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

CALCULATIONS

	CALCULATION													
16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
			Ui=				Trial 1	Trial 1	Trial 2	Trial 2	Trial 3	Trial 3	Trial 4	Trial 4
					(20)*(16)	(18)+(21)		(22)/(23)		(22)/(25)		(22)/(27)		(22)/(29)
tan ϕ'	(wi+Qi) sin θi	c'Δxi	ui*Δxi	(wi+Qi -uiΔxi)	(20)*tanϕ'		Mi(0)		Mi(0)		Mi(0)		Mi(θ)	
0.78	37.05			41.97	32.79	32.79	1.09	30.14	1.13	29.02	1.14	28.79	1.14	28.75
0.78	104.08		6.04	126.62	98.93	98.93	1.17	84.60	1.21	81.99	1.21	81.45	1.22	81.34
0.78	90.67		24.42	107.64	84.10	84.10	1.21	69.63	1.24	67.80	1.25	67.43	1.25	67.35
0.42	88.05	7.90	37.12	109.32	46.40	54.30	1.03	52.83	1.04	52.05	1.05	51.88	1.05	51.85
0.42	80.06	7.95	45.56	109.62	46.53	54.48	1.05	51.74	1.07	51.10	1.07	50.96	1.07	50.93
0.36	67.53	10.80	50.79	106.14	38.63	49.43	1.04	47.39	1.05	46.96	1.05	46.87	1.05	46.85
0.36	52.47	10.80	51.17	101.08	36.79	47.59	1.05	45.27	1.06	44.95	1.06	44.88	1.06	44.87
0.36	37.35	10.80	48.51	95.69	34.83	45.63	1.05	43.44	1.06	43.21	1.06	43.16	1.06	43.15
0.36	23.14	10.80	46.74	86.64	31.53	42.33	1.04	40.65	1.05	40.50	1.05	40.47	1.05	40.46
0.36	10.30	10.80	45.65	71.65	26.08	36.88	1.02	35.99	1.03	35.92	1.03	35.90	1.03	35.90
0.36		10.80	37.80	59.60	21.69	32.49	1.00	32.49	1.00	32.49	1.00	32.49	1.00	32.49
0.36	-6.14	10.80	28.07	45.65	16.61	27.41	0.97	28.28	0.97	28.33	0.97	28.35	0.97	28.35
0.36	-7.83	10.80	22.80	23.27	8.47	19.27	0.93	20.72	0.93	20.80	0.93	20.82	0.93	20.82
0.36	-3.53	8.50	11.60	2.78	1.01	9.51	0.89	10.69	0.88	10.76	0.88	10.77	0.88	10.77
0.36	-0.31	4.25	1.43	-0.39	-0.14	4.11	0.86	4.78	0.85	4.82	0.85	4.83	0.85	4.83
							1.00		1.00		1.00		1.00	
	572.90					639.25		598.65		590.69		589.06		588.72
					FOS(ini)	1.12	FOS(1)	1.04	FOS(2)	1.03	FOS(3)	1.03	FOS(4)	1.03
													FOS	1.03

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

CALCULATIONS

31	32	33	34	35	36	37	38	39	40	41	42
Pore Pressure	**Soil 1**			**Soil 2**			**Soil 3**			**Soil 4**	
-(2)*(16)/(29) -Δxi*tanΦ'/Mi(θ)	(2)/(29) Δxi/Mi(θ)	$sec^2Φ'$	(20)*$sec^2Φ'$/Mi(θ)	Δxi/Mi(θ)	$sec^2Φ'$	(20)*$sec^2Φ'$/Mi(θ)	Δxi/Mi(θ)	$sec^2Φ'$	(20)*$sec^2Φ'$/Mi(θ)	Δxi/Mi(θ)	$sec^2Φ'$
-1.03	1.31	1.61	59.25								
-1.24	1.59	1.61	167.66								
-0.94	1.20	1.61	138.82								
-0.60				1.422744052	1.18017887	123.1950143					
-0.60				1.402366346	1.18017887	120.9464143					
-0.52							1.42180242	1.13247433	113.9305247		
-0.51							1.41411764	1.13247433	107.9178422		
-0.52							1.41836159	1.13247433	102.4712351		
-0.52							1.43369728	1.13247433	93.78060148		
-0.53							1.46023549	1.13247433	78.98798757		
-0.55							1.5	1.13247433	67.49830134		
-0.56							1.55114998	1.13247433	53.45448018		
-0.59							1.62103018	1.13247433	28.47746079		
-0.49							1.33709895	1.13247433	3.569797785		
-0.25							0.69380667	1.13247433	-0.522502636		
-9.45	4.10		365.74	2.825110398		244.14	13.8513002		649.57	0	
dF/du Σ(31)/Σ(17)	dF/dc Σ(32)/Σ(17)		dF/dΦ' Σ(34)/Σ(17)	dF/dc Σ(35)/Σ(17)		dF/dΦ' Σ(37)/Σ(17)	dF/dc Σ(38)/Σ(17)		dF/dΦ' Σ(40)/Σ(17)	dF/dc Σ(41)/Σ(17)	
-0.02	0.01		0.64	0.004931285		0.42615359	0.02417771		1.133829554	0	

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

CALCULATIONS

43	44	45	46
	Soil 5		
(20)*$\sec^2\Phi'$/Mi(θ)	Δxi/Mi(θ)	$\sec^2\Phi'$	(20)*$\sec^2\Phi'$/Mi(θ)
0.00	0		0.00
dF/dΦ' Σ(43)/Σ(17)	dF/dc Σ(44)/Σ(17)		dF/dΦ' Σ(46)/Σ(17)
0	0		0

Spreadsheet: BISHOP – PROB – DIRECT – EXACT

(COV (u) = based on soil layers)

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

DETERMINISTIC

(Probabilistic calculations are valid upto 5 different soil layers)

												CALCULATION-STAGE 1			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Slice	Slice Width Δxi (m)	θi (deg)	r (m)	h1 (m)	h2 (m)	Pore Pressure ui (kN/m2)	Soil Type	c' (kN/m2)	φ' (deg)	qi (kN/m2)	γ (kN/m3)	{(5)+(6)}/2 hav (m)	(2)*(12)*(13) wi (kN-per m width)	(2)*(11) Qi (kN-per m width)	tan φ'
1	1.500	61.960	17.520	0.000	2.870	0.00	1	0.00	38.00		19.50	1.44	41.97		0.78
2	1.930	51.680	17.520	2.870	4.180	3.13	1	0.00	38.00		19.50	3.53	132.66		0.78
3	1.500	43.360	17.520	4.180	4.850	16.28	1	0.00	38.00		19.50	4.52	132.06		0.78
4	1.490	36.960	17.520	4.850	5.230	24.91	2	5.30	23.00		19.50	5.04	146.44		0.42
5	1.500	31.060	17.520	5.230	5.380	30.37	2	5.30	23.00		19.50	5.31	155.17		0.42
6	1.500	25.490	17.520	5.380	5.350	33.86	3	7.20	20.00		19.50	5.37	156.93		0.36
7	1.500	20.160	17.520	5.350	5.060	34.11	3	7.20	20.00		19.50	5.21	152.25		0.36
8	1.500	15.010	17.520	5.060	4.800	32.34	3	7.20	20.00		19.50	4.93	144.20		0.36
9	1.500	9.990	17.520	4.800	4.320	31.16	3	7.20	20.00		19.50	4.56	133.38		0.36
10	1.500	5.040	17.520	4.320	3.700	30.43	3	7.20	20.00		19.50	4.01	117.29		0.36
11	1.500	0.000	17.520	3.700	2.960	25.20	3	7.20	20.00		19.50	3.33	97.40		0.36
12	1.500	-4.780	17.520	2.960	2.080	18.71	3	7.20	20.00		19.50	2.52	73.71		0.36
13	1.500	-9.780	17.520	2.080	1.070	15.20	3	7.20	20.00		19.50	1.58	46.07		0.36
14	1.180	-14.210	17.520	1.070	0.180	9.83	3	7.20	20.00		19.50	0.63	14.38		0.36
15	0.590	-17.220	17.520	0.180	0.000	2.42	3	7.20	20.00		19.50	0.09	1.04		0.36
16															
												FOS(3)	1.03	FOS(4)	1.03
														FOS	1.03

CALCULATION OF PROBABILITY OF FAILURE OF A SELECTED FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

PROBABILISTIC(First Order Second Moment)

Direct Differentiation

DATA INPUT

Probabilistic Parameters	COV			Mean			c'(kPa)			Φ'(rad)			u (kPa)		
	c'	Φ	u	c'(kPa)	Φ (deg)	u	Mean	σ	V	Mean	σ	V	Mean	σ	V
Soil 1	0	0.3	0.25	0	38	6.47	0.0000	0.0000	0.0000	0.6632	0.1990	0.0396	6.4700	1.6175	2.6163
Soil 2	0.3	0.4	0.3	5.3	23	27.64	5.3000	1.5900	2.5281	0.4014	0.1606	0.0258	27.6400	8.2920	68.7573
Soil 3	0.2	0.35	0.35	7.2	20	23.33	7.2000	1.4400	2.0736	0.3491	0.1222	0.0149	23.3300	8.1655	66.6754
Soil 4							0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Soil 5							0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Xr	(∂F/∂Xr)	$(\partial F/\partial Xr)^2$	$(\partial F/\partial Xr)^2 * V(Xr)$
c1	0.0072	5E-05	0
c2	0.00493	2E-05	6.1E-05
c3	0.02418	0.0006	0.00121
c4	0	0	0
c5	0	0	0
φ1	0.3328	0.1108	0.00439
φ2	0.3173	0.1007	0.0026
φ3	1.0510	1.1045	0.01649
φ4	0.0000	0	0
φ5	0.0000	0	0
u1	-0.0056	3E-05	8.2E-05
u2	-0.0021	4E-06	0.0003
u3	-0.0088	8E-05	0.00516
u4	0.0000	0	0
u5	0.0000	0	0
			0.03029

F		
	V(FOS)	0.03029 TAYLOR SERIES
	σ(FOS)	0.17403
	FOS(MLV)	1.0279
	COV(F)	0.1693

(NORMAL DISTRIBUTION)

RELIABILITY INDEX	0.16039	
RELIABILITY	0.56371	56.37 %
PROB. FAIL	0.43629	43.63 %

(LOGNORMAL DISTRIBUTION)

$1+[COV(F)]^2$	1.02866	
RELIABILITY INDEX	0.07971	
RELIABILITY	0.53176	53.18 %
PROB. FAIL	0.46824	46.82 %

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

CALCULATIONS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
												CALCULATION-STAGE 1		
Slice	Slice Width Δx_i (m)	θ_i (deg)	r (m)	h1 (m)	h2 (m)	Pore Pressure u_i (kN/m2)	Soil Type	c' (kN/m2)	ϕ' (deg)	q_i (kN/m2)	γ (kN/m3)	{(5)+(6)}/2 hav (m)	(2)*(12)*(13) wi (kN-per m width)	(2)*(11) Qi (kN-per m width)
1	1.5000	61.9600	17.5200		2.8700		1		38.0000		19.5000	1.4350	41.9738	
2	1.9300	51.6800	17.5200	2.8700	4.1800	3.1300	1		38.0000		19.5000	3.5250	132.6634	
3	1.5000	43.3600	17.5200	4.1800	4.8500	16.2800	1		38.0000		19.5000	4.5150	132.0638	
4	1.4900	36.9600	17.5200	4.8500	5.2300	24.9100	2	5.3000	23.0000		19.5000	5.0400	146.4372	
5	1.5000	31.0600	17.5200	5.2300	5.3800	30.3700	2	5.3000	23.0000		19.5000	5.3050	155.1713	
6	1.5000	25.4900	17.5200	5.3800	5.3500	33.8600	3	7.2000	20.0000		19.5000	5.3650	156.9263	
7	1.5000	20.1600	17.5200	5.3500	5.0600	34.1100	3	7.2000	20.0000		19.5000	5.2050	152.2463	
8	1.5000	15.0100	17.5200	5.0600	4.8000	32.3400	3	7.2000	20.0000		19.5000	4.9300	144.2025	
9	1.5000	9.9900	17.5200	4.8000	4.3200	31.1600	3	7.2000	20.0000		19.5000	4.5600	133.3800	
10	1.5000	5.0400	17.5200	4.3200	3.7000	30.4300	3	7.2000	20.0000		19.5000	4.0100	117.2925	
11	1.5000		17.5200	3.7000	2.9600	25.2000	3	7.2000	20.0000		19.5000	3.3300	97.4025	
12	1.5000	-4.7800	17.5200	2.9600	2.0800	18.7100	3	7.2000	20.0000		19.5000	2.5200	73.7100	
13	1.5000	-9.7800	17.5200	2.0800	1.0700	15.2000	3	7.2000	20.0000		19.5000	1.5750	46.0688	
14	1.1800	-14.2100	17.5200	1.0700	0.1800	9.8300	3	7.2000	20.0000		19.5000	0.6250	14.3813	
15	0.5900	-17.2200	17.5200	0.1800		2.4200	3	7.2000	20.0000		19.5000	0.0900	1.0355	
16														

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

CALCULATIONS

	CALCULATION - STAGE 2													
16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
			Ui=				Trial 1	Trial 1	Trial 2	Trial 2	Trial 3	Trial 3	Trial 4	Trial 4
tan φ'	(wi+Qi) sin θi	c'Δxi	ui*Δxi	(wi+Qi -uiΔxi)	(20)*(16) (20)*tanφ'	(18)+(21)	Mi(θ)	(22)/(23)	Mi(θ)	(22)/(25)	Mi(θ)	(22)/(27)	Mi(θ)	(22)/(29)
0.7813	37.0469			41.9738	32.7935	32.7935	1.0881	30.1388	1.1300	29.0209	1.1389	28.7943	1.1407	28.7474
0.7813	104.0824		6.0409	126.6225	98.9283	98.9283	1.1694	84.5984	1.2066	81.9863	1.2145	81.4527	1.2162	81.3421
0.7813	90.6723		24.4200	107.6438	84.1005	84.1005	1.2078	69.6320	1.2404	67.8017	1.2473	67.4257	1.2488	67.3476
0.4245	88.0464	7.8970	37.1159	109.3213	46.4041	54.3011	1.0278	52.8334	1.0433	52.0478	1.0466	51.8842	1.0473	51.8501
0.4245	80.0583	7.9500	45.5550	109.6163	46.5293	54.4793	1.0529	51.7424	1.0662	51.0964	1.0690	50.9615	1.0696	50.9333
0.3640	67.5338	10.8000	50.7900	106.1363	38.6304	49.4304	1.0430	47.3909	1.0526	46.9622	1.0546	46.8723	1.0550	46.8535
0.3640	52.4706	10.8000	51.1650	101.0813	36.7906	47.5906	1.0512	45.2747	1.0588	44.9486	1.0604	44.8801	1.0607	44.8658
0.3640	37.3467	10.8000	48.5100	95.6925	34.8292	45.6292	1.0504	43.4415	1.0561	43.2059	1.0573	43.1562	1.0576	43.1458
0.3640	23.1383	10.8000	46.7400	86.6400	31.5344	42.3344	1.0414	40.6505	1.0453	40.5012	1.0461	40.4697	1.0462	40.4631
0.3640	10.3043	10.8000	45.6450	71.6475	26.0776	36.8776	1.0248	35.9855	1.0267	35.9174	1.0271	35.9030	1.0272	35.8999
0.3640		10.8000	37.8000	59.6025	21.6935	32.4935	1.0000	32.4935	1.0000	32.4935	1.0000	32.4935	1.0000	32.4935
0.3640	-6.1423	10.8000	28.0650	45.6450	16.6134	27.4134	0.9693	28.2805	0.9675	28.3344	0.9671	28.3458	0.9670	28.3482
0.3640	-7.8255	10.8000	22.8000	23.2688	8.4691	19.2691	0.9301	20.7182	0.9263	20.8022	0.9255	20.8201	0.9253	20.8239
0.3640	-3.5303	8.4960	11.5994	2.7819	1.0125	9.5085	0.8893	10.6918	0.8839	10.7574	0.8827	10.7715	0.8825	10.7744
0.3640	-0.3065	4.2480	1.4278	-0.3924	-0.1428	4.1052	0.8586	4.7812	0.8521	4.8180	0.8507	4.8258	0.8504	4.8275
							1.0000		1.0000		1.0000		1.0000	
	572.8954					639.2548		598.6532		590.6940		589.0565		588.7162
					FOS(ini)	1.12	FOS(1)	1.04	FOS(2)	1.03	FOS(3)	1.03	FOS(4)	1.03
													FOS	1.03

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

CALCULATIONS

31	32	33	34	35	36	37	38	39	40	41
		Soil 1						Soil 2		
cos θ	tan θ	(2)/(29) Δxi/Mi(θ)	$sec^2Φ'$	(20)*$sec^2Φ'$/Mi(θ) C=	A*d(1/Miθ)/dϕ D=	C+D=	-(2)*(16)/(29) -Δxi*tanΦ'/Mi(θ)	Δxi/Mi(θ)	$sec^2Φ'$	(20)*$sec^2Φ'$/Mi(θ)
0.4701	1.8776	1.3149	1.6104	59.2549	-34.8467	24.4082	-1.0273			
0.6201	1.2653	1.5869	1.6104	167.6645	-82.2082	85.4562	-1.2398			
0.7271	0.9443	1.2012	1.6104	138.8188	-58.0118	80.8069	-0.9385			
0.7991	0.7525							1.4227	1.1802	123.1950
0.8566	0.6023							1.4024	1.1802	120.9464
0.9027	0.4768									
0.9387	0.3671									
0.9659	0.2681									
0.9848	0.1761									
0.9961	0.0882									
1.0000										
0.9965	-0.0836									
0.9855	-0.1724									
0.9694	-0.2532									
0.9552	-0.3099									
1.0000										
		4.1030				190.6713	-3.2056	2.8251		
		dF/dc Σ(33)/Σ(17)				dF/dΦ' Σ(37)/Σ(17)	dF/du Σ(38)/Σ(17)	dF/dc Σ(39)/Σ(17)		
		0.01				0.33	-0.01	0.004931285		

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

CALCULATIONS

42	43	44	45	46	47	48	49	50	51	52
			Soil 3						Soil 4	
A*d(1/Miθ)/dϕ D=	C+D=	-(2)*(16)/(29) -Δxi*tanΦ'/Mi(θ	Δxi/Mi(θ)	$sec^2Φ'$	(20)*$sec^2Φ'$/Mi(θ)	A*d(1/Miθ)/dϕ D=	C+D=	-(2)*(16)/(29) -Δxi*tanΦ'/Mi(θ)	Δxi/Mi(θ)	$sec^2Φ'$
-34.1776	89.0174	-0.6039								
-28.2072	92.7393	-0.5953								
			1.4218	1.1325	113.9305	-21.0566	92.8739	-0.5175		
			1.4141	1.1325	107.9178	-16.0602	91.8576	-0.5147		
			1.4184	1.1325	102.4712	-11.6409	90.8304	-0.5162		
			1.4337	1.1325	93.7806	-7.3916	86.3890	-0.5218		
			1.4602	1.1325	78.9880	-3.3826	75.6054	-0.5315		
			1.5000	1.1325	67.4983		67.4983	-0.5460		
			1.5511	1.1325	53.4545	2.6913	56.1458	-0.5646		
			1.6210	1.1325	28.4775	4.2115	32.6890	-0.5900		
			1.3371	1.1325	3.5698	3.3019	6.8717	-0.4867		
			0.6938	1.1325	-0.5225	1.8515	1.3290	-0.2525		
	181.7566	-1.1992	13.8513				602.0901	-5.0415	0.0000	
	dF/dΦ' Σ(43)/Σ(17)	dF/du Σ(44)/Σ(17)	dF/dc Σ(45)/Σ(17)				dF/dΦ' Σ(49)/Σ(17)	dF/du Σ(50)/Σ(17)	dF/dc Σ(51)/Σ(17)	
	0.32	0.00	0.02417771				1.05	-0.01	0	

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

CALCULATIONS

53	54	55	56	57	58	59	60	61	62
				Soil 5					
(20)*$\sec^2\Phi'/Mi(\theta)$	A*d(1/Miθ)/dϕ D=	C+D=	-(2)*(16)/(29) -Δxi*tanΦ'/Mi(θ)	Δxi/Mi(θ)	$\sec^2\Phi'$	(20)*$\sec^2\Phi'/Mi(\theta)$	A*d(1/Miθ)/dϕ D=	C+D=	-(2)*(16)/(29) -Δxi*tanΦ'/Mi(θ)
		0.0000	0.0000	0.0000				0.0000	0.0000
		dF/dΦ' Σ(55)/Σ(17)	dF/du Σ(56)/Σ(17)	dF/dc Σ(57)/Σ(17)				dF/dΦ' Σ(61)/Σ(17)	dF/du Σ(62)/Σ(17)
		0.00	0.00	0				0.00	0.00

Spreadsheet: BISHOP – PROB – SMALLINCREMENT

(COV (u) = based on soil layers)

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

DETERMINISTIC

												CALCULATION-STAGE 1	
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Slice	Slice Width Δxi (m)	θi (deg)	r (m)	h1 (m)	h2 (m)	Pore Pressure ui (kN/m2)	Soil Type	c' (kN/m2)	ϕ' (deg)	qi (kN/m2)	γ (kN/m3)	{(5)+(6)}/2 hav (m)	(2)*(12)*(13) wi (kN-per m width)
1	1.500	61.960	17.520	0.000	2.870	0.00	1	0.00	38.00		19.50	1.4350	41.9738
2	1.930	51.680	17.520	2.870	4.180	3.13	1	0.00	38.00		19.50	3.5250	132.6634
3	1.500	43.360	17.520	4.180	4.850	16.28	1	0.00	38.00		19.50	4.5150	132.0638
4	1.490	36.960	17.520	4.850	5.230	24.91	2	5.30	23.00		19.50	5.0400	146.4372
5	1.500	31.060	17.520	5.230	5.380	30.37	2	5.30	23.00		19.50	5.3050	155.1713
6	1.500	25.490	17.520	5.380	5.350	33.86	3	7.20	20.00		19.50	5.3650	156.9263
7	1.500	20.160	17.520	5.350	5.060	34.11	3	7.20	20.00		19.50	5.2050	152.2463
8	1.500	15.010	17.520	5.060	4.800	32.34	3	7.20	20.00		19.50	4.9300	144.2025
9	1.500	9.990	17.520	4.800	4.320	31.16	3	7.20	20.00		19.50	4.5600	133.3800
10	1.500	5.040	17.520	4.320	3.700	30.43	3	7.20	20.00		19.50	4.0100	117.2925
11	1.500	0.000	17.520	3.700	2.960	25.20	3	7.20	20.00		19.50	3.3300	97.4025
12	1.500	-4.780	17.520	2.960	2.080	18.71	3	7.20	20.00		19.50	2.5200	73.7100
13	1.500	-9.780	17.520	2.080	1.070	15.20	3	7.20	20.00		19.50	1.5750	46.0688
14	1.180	-14.210	17.520	1.070	0.180	9.83	3	7.20	20.00		19.50	0.6250	14.3813
15	0.590	-17.220	17.520	0.180	0.000	2.42	3	7.20	20.00		19.50	0.0900	1.0355
16													

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

CALCULATIONS

CALCULATION												
15	16	17	18	19	20	21	22	23	24	25	26	27
				Ui=				Trial 1	Trial 1	Trial 2	Trial 2	Trial 3
(2)*(11) Qi (kN-per m width)	tan ϕ'	(wi+Qi) sin θi	c'Δxi	ui*Δxi	(wi+Qi -uiΔxi)	(20)*(16) (20)*tanϕ'	(18)+(21)	Mi(θ)	(22)/(23)	Mi(θ)	(22)/(25)	Mi(θ)
	0.7813	37.0469			41.9738	32.7935	32.7935	1.0881	30.1388	1.1300	29.0209	1.1389
	0.7813	104.0824		6.0409	126.6225	98.9283	98.9283	1.1694	84.5984	1.2066	81.9863	1.2145
	0.7813	90.6723		24.4200	107.6438	84.1005	84.1005	1.2078	69.6320	1.2404	67.8017	1.2473
	0.4245	88.0464	7.8970	37.1159	109.3213	46.4041	54.3011	1.0278	52.8334	1.0433	52.0478	1.0466
	0.4245	80.0583	7.9500	45.5550	109.6163	46.5293	54.4793	1.0529	51.7424	1.0662	51.0964	1.0690
	0.3640	67.5338	10.8000	50.7900	106.1363	38.6304	49.4304	1.0430	47.3909	1.0526	46.9622	1.0546
	0.3640	52.4706	10.8000	51.1650	101.0813	36.7906	47.5906	1.0512	45.2747	1.0588	44.9486	1.0604
	0.3640	37.3467	10.8000	48.5100	95.6925	34.8292	45.6292	1.0504	43.4415	1.0561	43.2059	1.0573
	0.3640	23.1383	10.8000	46.7400	86.6400	31.5344	42.3344	1.0414	40.6505	1.0453	40.5012	1.0461
	0.3640	10.3043	10.8000	45.6450	71.6475	26.0776	36.8776	1.0248	35.9855	1.0267	35.9174	1.0271
	0.3640		10.8000	37.8000	59.6025	21.6935	32.4935	1.0000	32.4935	1.0000	32.4935	1.0000
	0.3640	-6.1423	10.8000	28.0650	45.6450	16.6134	27.4134	0.9693	28.2805	0.9675	28.3344	0.9671
	0.3640	-7.8255	10.8000	22.8000	23.2688	8.4691	19.2691	0.9301	20.7182	0.9263	20.8022	0.9255
	0.3640	-3.5303	8.4960	11.5994	2.7819	1.0125	9.5085	0.8893	10.6918	0.8839	10.7574	0.8827
	0.3640	-0.3065	4.2480	1.4278	-0.3924	-0.1428	4.1052	0.8586	4.7812	0.8521	4.8180	0.8507
								1.0000		1.0000		1.0000
		572.8954					639.2548		598.6532		590.6940	
						FOS(ini)	1.1158	FOS(1)	1.0450	FOS(2)	1.0311	FOS(3)

28	29	30
Trial 3	**Trial 4**	**Trial 4**
(22)/(27)	Mi(θ)	(22)/(29)
28.7943	1.1407	28.7474
81.4527	1.2162	81.3421
67.4257	1.2488	67.3476
51.8842	1.0473	51.8501
50.9615	1.0696	50.9333
46.8723	1.0550	46.8535
44.8801	1.0607	44.8658
43.1562	1.0576	43.1458
40.4697	1.0462	40.4631
35.9030	1.0272	35.8999
32.4935	1.0000	32.4935
28.3458	0.9670	28.3482
20.8201	0.9253	20.8239
10.7715	0.8825	10.7744
4.8258	0.8504	4.8275
	1.0000	
589.0565		588.7162
1.0282	FOS(4)	1.0276
	FOS	1.0279

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

PROBABILISTIC(First Order Second Moment - small increment)

	c					ϕ								u				
						(DEG)				(RAD)								
Soil T	Mean	COV	Del C	s	V	Mean	COV	Del C	s	Mean	del fi rad	s	V	Mean	COV	Del C	s	V
1	0	0	0	0	0	38	0.3	11.4	11.4	0.663225	0.198968	0.199	0.039588	6.47	0.25	1.6175	1.6175	2.616306
2	5.3	0.3	1.59	1.59	2.5281	23	0.4	9.2	9.2	0.401426	0.16057	0.1606	0.025783	27.64	0.3	8.292	8.292	68.75726
3	7.2	0.2	1.44	1.44	2.0736	20	0.35	7	7	0.349066	0.122173	0.1222	0.014926	23.33	0.35	8.1655	8.1655	66.67539
4				0	0				0	0	0	0	0				0	0
5				0	0				0	0	0	0	0				0	0

OUTPUT

F						
F_{MLV}	1.0279					
FC1+	1.0279	Fϕ1+	1.1167	Fu1+	1.0165	
FC1--	1.0279	Fϕ1--	0.9444	Fu1--	1.0357	
FC2+	1.0378	Fϕ2+	1.0926	Fu2+	1.0060	
FC2--	1.0180	Fϕ2--	0.9621	Fu2--	1.0498	
Fc3+	1.0715	Fϕ3+	1.1941	Fu3+	0.9362	
Fc3--	0.9838	Fϕ3--	0.8675	Fu3--	1.1144	
Fc4+	1.0279	Fϕ4+	1.0279	Fu4+	1.0279	
Fc4--	1.0279	Fϕ4--	1.0279	Fu4--	1.0279	
Fc5+	1.0279	Fϕ5+	1.0279	Fu5+	1.0279	
Fc5--	1.0279	Fϕ5--	1.0279	Fu5--	1.0279	

CENTRAL DIFFERENCES

F0					
Δ Fc1	0.0000	Δ Fϕ1	0.1723	Δ Fu1	-0.0192
Δ Fc2	0.0198	Δ Fϕ2	0.1305	Δ Fu2	-0.0438
Δ Fc3	0.0877	Δ Fϕ3	0.3266	Δ Fu3	-0.1781
Δ Fc4	0.0000	Δ Fϕ4	0.0000	Δ Fu4	0.0000
Δ Fc5	0.0000	Δ Fϕ5	0.0000	Δ Fu5	0.0000

A					
Fc1/2Δ c1	0	Δ Fϕ1/2Δ Ff1	0.43300757	Δ Fu1/2Δ u1	-0.0059
Fc2/2Δ c2	0.00622	Δ Fϕ2/2Δ Ff2	0.40633596	Δ Fu2/2Δ u2	-0.0026
Fc3/2Δ c3	0.03047	Δ Fϕ3/2Δ Ff3	1.33649009	Δ Fu3/2Δ u3	-0.0109
Fc4/2Δ c4	0	Δ Fϕ4/2Δ Ff4	0	Δ Fu4/2Δ u4	0
Fc5/2Δ c5	0	Δ Fϕ5/2Δ Ff5	0	Δ Fu5/2Δ u5	0

FORWARD DIFFERENCES

F0					
Δ Fc1	0.0000	Δ Fϕ1	0.0888	Δ Fu1	-0.0114
Δ Fc2	0.0099	Δ Fϕ2	0.0647	Δ Fu2	-0.0219
Δ Fc3	0.0436	Δ Fϕ3	0.1662	Δ Fu3	-0.0917
Δ Fc4	0.0000	Δ Fϕ4	0.0000	Δ Fu4	0.0000
Δ Fc5	0.0000	Δ Fϕ5	0.0000	Δ Fu5	0.0000

A					
Δ Fc1/Δ c1	0	Δ Fϕ1/2Δ Ff1	0.44635547	Δ Fu1/Δ u1	-0.0070439
Δ Fc2/Δ c2	0.00622325	Δ Fϕ2/2Δ Ff2	0.40301968	Δ Fu2/Δ u2	-0.0026366
Δ Fc3/Δ c3	0.0302916	Δ Fϕ3/2Δ Ff3	1.3600159	Δ Fu3/Δ u3	-0.0112281
Δ Fc4/Δ c4	0	Δ Fϕ4/2Δ Ff4	0	Δ Fu4/Δ u4	0
Δ Fc5/Δ c5	0	Δ Fϕ5/2Δ Ff5	0	Δ Fu5/Δ u5	0

Λ*sigma		
	c	0
	2	0.00989
	3	0.04387
	4	0
	5	0

φ	0.08615445
2	0.06524548
3	0.16328307
4	0
5	0

u	-0.0096
2	-0.0219
3	-0.0891
4	0
5	0

F			
	V(FOS)	0.04887	
	σ(FOS)	0.22106	TAYLOR SERIES
	FOS(ML	1.0279	
	COV(F)	0.21506	

(NORMAL DISTRIBUTION)		
RELIABILITY INDEX	0.1263	
RELIABILITY	0.5502	55.02 %
PROB. FAIL	0.4498	44.98 %

(LOGNORMAL DISTRIBUTION)		
$1+[COV(F)]^2$	1.0462	
RELIABILITY INDEX	0.0232	
RELIAB	0.5092	50.92 %
PROB. F	0.4908	49.08 %

Λ*sigma		
	c	0
	2	0.00989497
	3	0.04361991
	4	0
	5	0

φ	0.08881025
2	0.06471299
3	0.16615729
4	0
5	0

u	-0.0113935
2	-0.021863
3	-0.0916827
4	0
5	0

F			
	V(FOS)	0.0506974	
	σ(FOS)	0.22516083	TAYLOR SERIES
	FOS(MLV)	1.0279	
	COV(F)	0.21904668	

(NORMAL DISTRIBUTION)		
RELIABILITY INDEX	0.1239671	
RELIABILITY	0.54932938	54.93 %
PROB. FAIL	0.45067062	45.07 %

(LOGNORMAL DISTRIBUTION)		
$1+[COV(F)]^2$	1.04798145	
RELIABILITY INDEX	0.01892571	
RELIABILI	0.50754985	50.75 %
PROB. FAI	0.49245015	49.25 %

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

Fc1+

												CALCULATION-STAGE 1	
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Slice	Slice Width Δxi (m)	θi (deg)	r (m)	h1 (m)	h2 (m)	Pore Pressure ui (kN/m2)	Soil Type	c' (kN/m2)	ϕ' (deg)	qi (kN/m2)	γ (kN/m3)	{(5)+(6)}/2 hav (m)	(2)*(12)*(13) wi (kN-per m width)
1	1.500	61.960	17.520		2.870		1		38.000		19.500	1.44	41.97
2	1.930	51.680	17.520	2.870	4.180	3.130	1		38.000		19.500	3.53	132.66
3	1.500	43.360	17.520	4.180	4.850	16.280	1		38.000		19.500	4.52	132.06
4	1.490	36.960	17.520	4.850	5.230	24.910	2	5.300	23.000		19.500	5.04	146.44
5	1.500	31.060	17.520	5.230	5.380	30.370	2	5.300	23.000		19.500	5.31	155.17
6	1.500	25.490	17.520	5.380	5.350	33.860	3	7.200	20.000		19.500	5.37	156.93
7	1.500	20.160	17.520	5.350	5.060	34.110	3	7.200	20.000		19.500	5.21	152.25
8	1.500	15.010	17.520	5.060	4.800	32.340	3	7.200	20.000		19.500	4.93	144.20
9	1.500	9.990	17.520	4.800	4.320	31.160	3	7.200	20.000		19.500	4.56	133.38
10	1.500	5.040	17.520	4.320	3.700	30.430	3	7.200	20.000		19.500	4.01	117.29
11	1.500		17.520	3.700	2.960	25.200	3	7.200	20.000		19.500	3.33	97.40
12	1.500	-4.780	17.520	2.960	2.080	18.710	3	7.200	20.000		19.500	2.52	73.71
13	1.500	-9.780	17.520	2.080	1.070	15.200	3	7.200	20.000		19.500	1.58	46.07
14	1.180	-14.210	17.520	1.070	0.180	9.830	3	7.200	20.000		19.500	0.63	14.38
15	0.590	-17.220	17.520	0.180		2.420	3	7.200	20.000		19.500	0.09	1.04
16													

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

Fc1+

		CALCULATION											
15	16	17	18	19	20	21	22	23	24	25	26	27	28
				Ui=				Trial 1	Trial 1	Trial 2	Trial 2	Trial 3	Trial 3
(2)*(11) Qi (kN-per m width)	tan ϕ'	(wi+Qi) sin θi	c'Δxi	ui*Δxi	(wi+Qi -uiΔxi)	(20)*(16) (20)*tanϕ'	(18)+(21)	Mi(θ)	(22)/(23)	Mi(θ)	(22)/(25)	Mi(θ)	(22)/(27)
	0.78	37.05			41.97	32.79	32.79	1.09	30.14	1.13	29.02	1.14	28.79
	0.78	104.08		6.04	126.62	98.93	98.93	1.17	84.60	1.21	81.99	1.21	81.45
	0.78	90.67		24.42	107.64	84.10	84.10	1.21	69.63	1.24	67.80	1.25	67.43
	0.42	88.05	7.90	37.12	109.32	46.40	54.30	1.03	52.83	1.04	52.05	1.05	51.88
	0.42	80.06	7.95	45.56	109.62	46.53	54.48	1.05	51.74	1.07	51.10	1.07	50.96
	0.36	67.53	10.80	50.79	106.14	38.63	49.43	1.04	47.39	1.05	46.96	1.05	46.87
	0.36	52.47	10.80	51.17	101.08	36.79	47.59	1.05	45.27	1.06	44.95	1.06	44.88
	0.36	37.35	10.80	48.51	95.69	34.83	45.63	1.05	43.44	1.06	43.21	1.06	43.16
	0.36	23.14	10.80	46.74	86.64	31.53	42.33	1.04	40.65	1.05	40.50	1.05	40.47
	0.36	10.30	10.80	45.65	71.65	26.08	36.88	1.02	35.99	1.03	35.92	1.03	35.90
	0.36		10.80	37.80	59.60	21.69	32.49	1.00	32.49	1.00	32.49	1.00	32.49
	0.36	-6.14	10.80	28.07	45.65	16.61	27.41	0.97	28.28	0.97	28.33	0.97	28.35
	0.36	-7.83	10.80	22.80	23.27	8.47	19.27	0.93	20.72	0.93	20.80	0.93	20.82
	0.36	-3.53	8.50	11.60	2.78	1.01	9.51	0.89	10.69	0.88	10.76	0.88	10.77
	0.36	-0.31	4.25	1.43	-0.39	-0.14	4.11	0.86	4.78	0.85	4.82	0.85	4.83
								1.00		1.00		1.00	
		572.90					639.25		598.65		590.69		589.06
						FOS(m)	1.12	FOS(1)	1.04	FOS(2)	1.03	FOS(3)	1.03

29	30
Trial 4	Trial 4
Mi(0)	(22)/(29)
1.14	28.75
1.22	81.34
1.25	67.35
1.05	51.85
1.07	50.93
1.05	46.85
1.06	44.87
1.06	43.15
1.05	40.46
1.03	35.90
1.00	32.49
0.97	28.35
0.93	20.82
0.88	10.77
0.85	4.83
1.00	
	588.72

FOS(4)	1.03

FOS	1.03

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

Fc1-

												CALCULATION-STAGE 1	
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Slice	Slice Width Δxi (m)	θi (deg)	r (m)	h1 (m)	h2 (m)	Pore Pressure ui (kN/m2)	Soil Type	c' (kN/m2)	ϕ' (deg)	qi (kN/m2)	γ (kN/m3)	{(5)+(6)}/2 hav (m)	(2)*(12)*(13) wi (kN-per m width)
1	1.500	61.960	17.520		2.870		1		38.000		19.500	1.44	41.97
2	1.930	51.680	17.520	2.870	4.180	3.130	1		38.000		19.500	3.53	132.66
3	1.500	43.360	17.520	4.180	4.850	16.280	1		38.000		19.500	4.52	132.06
4	1.490	36.960	17.520	4.850	5.230	24.910	2	5.300	23.000		19.500	5.04	146.44
5	1.500	31.060	17.520	5.230	5.380	30.370	2	5.300	23.000		19.500	5.31	155.17
6	1.500	25.490	17.520	5.380	5.350	33.860	3	7.200	20.000		19.500	5.37	156.93
7	1.500	20.160	17.520	5.350	5.060	34.110	3	7.200	20.000		19.500	5.21	152.25
8	1.500	15.010	17.520	5.060	4.800	32.340	3	7.200	20.000		19.500	4.93	144.20
9	1.500	9.990	17.520	4.800	4.320	31.160	3	7.200	20.000		19.500	4.56	133.38
10	1.500	5.040	17.520	4.320	3.700	30.430	3	7.200	20.000		19.500	4.01	117.29
11	1.500		17.520	3.700	2.960	25.200	3	7.200	20.000		19.500	3.33	97.40
12	1.500	-4.780	17.520	2.960	2.080	18.710	3	7.200	20.000		19.500	2.52	73.71
13	1.500	-9.780	17.520	2.080	1.070	15.200	3	7.200	20.000		19.500	1.58	46.07
14	1.180	-14.210	17.520	1.070	0.180	9.830	3	7.200	20.000		19.500	0.63	14.38
15	0.590	-17.220	17.520	0.180		2.420	3	7.200	20.000		19.500	0.09	1.04
16													

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

Fc1+

		CALCULATION											
15	16	17	18	19	20	21	22	23	24	25	26	27	28
				Ui=				Trial 1	Trial 1	Trial 2	Trial 2	Trial 3	Trial 3
(2)*(11) Qi (kN-per m width)	tan φ'	(wi+Qi) sin θi	c'Δxi	ui*Δxi	(wi+Qi -uiΔxi)	(20)*(16) (20)*tanφ'	(18)+(21)	Mi(θ)	(22)/(23)	Mi(θ)	(22)/(25)	Mi(θ)	(22)/(27)
	0.78	37.05			41.97	32.79	32.79	1.09	30.14	1.13	29.02	1.14	28.79
	0.78	104.08		6.04	126.62	98.93	98.93	1.17	84.60	1.21	81.99	1.21	81.45
	0.78	90.67		24.42	107.64	84.10	84.10	1.21	69.63	1.24	67.80	1.25	67.43
	0.42	88.05	7.90	37.12	109.32	46.40	54.30	1.03	52.83	1.04	52.05	1.05	51.88
	0.42	80.06	7.95	45.56	109.62	46.53	54.48	1.05	51.74	1.07	51.10	1.07	50.96
	0.36	67.53	10.80	50.79	106.14	38.63	49.43	1.04	47.39	1.05	46.96	1.05	46.87
	0.36	52.47	10.80	51.17	101.08	36.79	47.59	1.05	45.27	1.06	44.95	1.06	44.88
	0.36	37.35	10.80	48.51	95.69	34.83	45.63	1.05	43.44	1.06	43.21	1.06	43.16
	0.36	23.14	10.80	46.74	86.64	31.53	42.33	1.04	40.65	1.05	40.50	1.05	40.47
	0.36	10.30	10.80	45.65	71.65	26.08	36.88	1.02	35.99	1.03	35.92	1.03	35.90
	0.36		10.80	37.80	59.60	21.69	32.49	1.00	32.49	1.00	32.49	1.00	32.49
	0.36	-6.14	10.80	28.07	45.65	16.61	27.41	0.97	28.28	0.97	28.33	0.97	28.35
	0.36	-7.83	10.80	22.80	23.27	8.47	19.27	0.93	20.72	0.93	20.80	0.93	20.82
	0.36	-3.53	8.50	11.60	2.78	1.01	9.51	0.89	10.69	0.88	10.76	0.88	10.77
	0.36	-0.31	4.25	1.43	-0.39	-0.14	4.11	0.86	4.78	0.85	4.82	0.85	4.83
								1.00		1.00		1.00	
		572.90					639.25		598.65		590.69		589.06

FOS(ini)	1.12	FOS(1)	1.04	FOS(2)	1.03	FOS(3)	1.03

29	30
Trial 4	**Trial 4**
Mi(θ)	**(22)/(29)**
1.14	28.75
1.22	81.34
1.25	67.35
1.05	51.85
1.07	50.93
1.05	46.85
1.06	44.87
1.06	43.15
1.05	40.46
1.03	35.90
1.00	32.49
0.97	28.35
0.93	20.82
0.88	10.77
0.85	4.83
1.00	
	588.72

FOS(4)	1.03

FOS	1.03

Annex 5

SAMPLE SET OF SPREADSHEETS – MODEL BASED ON JANBU'S SIMPLIFIED METHOD

{Data correspond to Example 3 (FileName:ACAD4)}

Spreadsheet: Janbu – Prob – Direct

(COV (u) = based on soil layers)

CALCULATION OF FACTOR OF SAFETY OF A SELECTED FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD

DETERMINISTIC

Note: Enter Values only in yellow cells (Probabilistic Calculations are valid upto 5 different soil layers)

	INPUTS										CALCULATION-STAGE 1			
1	2	3	4	5	6		7	8	9	10	11	12	13	14
Slice	Slice Width Δxi (m)	θi (deg)	h1 (m)	h2 (m)	Pore Pressure ui (kN/m2)	Soil Type	c' (kN/m2)	ϕ' (deg)	qi (kN/m2)	γ (kN/m3)	{(4)+(5)}/2 hav (m)	(2)*(10)*(11) wi (kN-per m width)	(9)*(2) Qi (kN-per m width)	tan ϕ
1	2.800	-12.020	0.000	2.000	8.83	1	28.50	20.00	0.00	18.84	1.00	52.75		0.36
2	2.600	-12.020	2.000	3.850	22.56	1	28.50	20.00	0.00	18.84	2.93	143.28		0.36
3	3.200	16.780	3.850	4.870	31.39	2	0.00	10.00	0.00	18.84	4.36	262.86		0.18
4	2.900	16.780	4.870	5.440	31.39	2	0.00	10.00	0.00	18.84	5.16	281.65		0.18
5	2.900	16.780	5.440	6.020	34.34	2	0.00	10.00	0.00	18.84	5.73	313.06		0.18
6	2.900	16.780	6.020	6.600	37.28	2	0.00	10.00	0.00	18.84	6.31	344.75		0.18
7	2.900	16.780	6.600	7.170	40.22	2	0.00	10.00	0.00	18.84	6.89	376.17		0.18
8	2.900	16.780	7.170	7.750	40.22	2	0.00	10.00	0.00	18.84	7.46	407.58		0.18
9	2.000	16.780	7.750	7.840	40.22	2	0.00	10.00	0.00	18.84	7.80	293.72		0.18
10	1.900	16.780	7.840	7.270	40.22	2	0.00	10.00	0.00	18.84	7.56	270.44		0.18
11	2.750	16.780	7.270	6.440	37.28	2	0.00	10.00	22.28	18.84	6.86	355.16	61.27	0.18
12	2.610	16.780	6.440	5.640	34.34	2	0.00	10.00	26.84	18.84	6.04	297.00	70.05	0.18
13	2.040	16.780	5.640	4.550	31.39	2	0.00	10.00	31.71	18.84	5.10	195.82	64.69	0.18
14	2.60	60.26	4.55	0.000	8.83	1	28.50	20.00	36.86	18.84	2.28	111.44	95.84	0.36
15														
16														

f0	1.05

FOS(4)	0.70	FOS(5)	0.70
		F0S(F0)	0.70
		FOS	0.73

CALCULATION OF PROBABILITY OF FAILURE OF A SELECTED FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD

PROBABILISTIC(First Order Second Moment)

Direct Differentiation

DATA INPUT

Probabilistic Parameters	COV			Mean			c'(kPa)			Φ'(rad)			u (kPa)		
	c'	Φ'	u	c'(kPa)	Φ'(deg)	u	Mean	σ	V	Mean	σ	V	Mean	σ	V
Soil 1	0.2	0.3	0.3	28.5	20	13.29	28.50	5.7000	32.4900	0.35	0.1047	0.0110	13.29	3.9870	15.8962
Soil 2	0	0.2	0.2	0	10	36.05	0.00	0.0000	0.0000	0.17	0.0349	0.0012	36.05	7.2100	51.9841
Soil 3							0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.00	0.0000	0.0000
Soil 4							0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.00	0.0000	0.0000
Soil 5							0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.00	0.0000	0.0000

Xr	$(\partial F/\partial X_r)$	$(\partial F/\partial X_r)^2$	$(\partial F/\partial X_r)^2 * V(X_r)$
c1	0.0085	7E-05	0.002
c2	0.0209	4E-04	0
c3	0	0	0
c4	0	0	0
c5	0	0	0
ϕ1	0.4231	0.179	0.002
ϕ2	1.8969	3.598	0.004
ϕ3	0	0	0
ϕ4	0	0	0
ϕ5	0	0	0
u1	-0.0031	9E-06	2E-04
u2	-0.0037	1E-05	7E-04
u3	0	0	0
u4	0	0	0
u5	0	0	0
			0.01

F0	V(FOS)				0.0095	TAYLOR SERIES
	σ(FOS)				0.0976	
	FOS(MLV)				0.7014	
	COV(F)				0.1392	

	f0				1.0450	
F	V(FOS)				0.0104	$=f_0^2*V(F_0)$
	σ(FOS)				0.1020	

	FOS(MLV)				0.7330
	COV(F)				0.1392

(NORMAL DISTRIBUTION)		
RELIABILITY INDEX	-2.617	
RELIABILITY	0.004	0.44 %
PROB. FAIL	0.996	99.56 %

(LOGNORMAL DISTRIBUTION)		
$1+[COV(F)]^2$	1.019	
RELIABILITY INDEX	-2.312	
RELIABILITY	0.01	1.04 %
PROB. FAIL	0.99	98.96 %

JANBU'S SIMPLIFIED METHOD

DETERMINISTIC/ PROBABILISTIC

Calculations

	INPUTS									CALCULATION-STAGE 1				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Slice	Slice Width			Pore Pressure						{(4)+(5)}/2	(2)*(10)*(11)	(9)*(2)		
	Δxi	θi	h1	h2	ui	c'	ϕ'	qi	γ	hav	wi	Qi	tan ϕ	(wi+Qi) tan θi
	(m)	(deg)	(m)	(m)	(kN/m2)	(kN/m2)	(deg)	(kN/m2)	(kN/m3)	(m)	kN-per m width	kN-per m width)		
1	2.8000	-12.0200		2.0000	8.8300	28.5000	20.0000		18.8400	1.0000	52.7520		0.3640	-11.2320
2	2.6000	-12.0200	2.0000	3.8500	22.5600	28.5000	20.0000		18.8400	2.9250	143.2782		0.3640	-30.5070
3	3.2000	16.7800	3.8500	4.8700	31.3900		10.0000		18.8400	4.3600	262.8557		0.1763	79.2607
4	2.9000	16.7800	4.8700	5.4400	31.3900		10.0000		18.8400	5.1550	281.6486		0.1763	84.9275
5	2.9000	16.7800	5.4400	6.0200	34.3400		10.0000		18.8400	5.7300	313.0643		0.1763	94.4004
6	2.9000	16.7800	6.0200	6.6000	37.2800		10.0000		18.8400	6.3100	344.7532		0.1763	103.9558
7	2.9000	16.7800	6.6000	7.1700	40.2200		10.0000		18.8400	6.8850	376.1689		0.1763	113.4288
8	2.9000	16.7800	7.1700	7.7500	40.2200		10.0000		18.8400	7.4600	407.5846		0.1763	122.9018
9	2.0000	16.7800	7.7500	7.8400	40.2200		10.0000		18.8400	7.7950	293.7156		0.1763	88.5661
10	1.9000	16.7800	7.8400	7.2700	40.2200		10.0000		18.8400	7.5550	270.4388		0.1763	81.5473
11	2.7500	16.7800	7.2700	6.4400	37.2800		10.0000	22.2800	18.8400	6.8550	355.1576	61.2700	0.1763	125.5683
12	2.6100	16.7800	6.4400	5.6400	34.3400		10.0000	26.8400	18.8400	6.0400	297.0013	70.0524	0.1763	110.6803
13	2.0400	16.7800	5.6400	4.5500	31.3900		10.0000	31.7100	18.8400	5.0950	195.8192	64.6884	0.1763	78.5527
14	2.6000	60.2600	4.5500		8.8300	28.5000	20.0000	36.8600	18.8400	2.2750	111.4386	95.8360	0.3640	362.8023
15														
16														
														1404.8529

f0	1.0450

JANBU'S SIMPLIFIED METHOD

DETERMINISTIC/ PROBABILISTIC

Calculations

CALCULATION - STAGE 2

16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	32
	Ui=				Trial 1	Trial 1	Trial 2	Trial 2	Trial 3	Trial 3	Trial 4	Trial 4	Trial 5	Trial 5	
				(16)+(19)		(20)/(21)		(20)/(23)		(20)/(25)		(20)/(27)		(20)/(29)	(2)/(23)
c'Δxi	ui*Δxi	(wi+Qi -uiΔxi)	(18)*tanφ'		ni(θ)		ni(θ)		ni(θ)		ni(θ)		ni(θ)		Δxi/ni(θ)
79.8000	24.7240	28.0280	10.2014	90.0014	0.8240	109.2198	0.8473	106.2246	0.8504	105.8339	0.8509	105.7768	0.8509	105.7683	3.2905
74.1000	58.6560	84.6222	30.8000	104.9000	0.8240	127.2998	0.8473	123.8087	0.8504	123.3534	0.8509	123.2868	0.8509	123.2770	3.0555
	100.4480	162.4077	28.6369	28.6369	1.0038	28.5279	0.9885	28.9687	0.9865	29.0291	0.9862	29.0379	0.9861	29.0393	
	91.0310	190.6176	33.6110	33.6110	1.0038	33.4831	0.9885	34.0005	0.9865	34.0713	0.9862	34.0818	0.9861	34.0833	
	99.5860	213.4783	37.6420	37.6420	1.0038	37.4987	0.9885	38.0782	0.9865	38.1575	0.9862	38.1692	0.9861	38.1709	
	108.1120	236.6412	41.7262	41.7262	1.0038	41.5674	0.9885	42.2097	0.9865	42.2977	0.9862	42.3106	0.9861	42.3126	
	116.6380	259.5309	45.7623	45.7623	1.0038	45.5881	0.9885	46.2926	0.9865	46.3890	0.9862	46.4032	0.9861	46.4053	
	116.6380	290.9466	51.3017	51.3017	1.0038	51.1065	0.9885	51.8962	0.9865	52.0043	0.9862	52.0203	0.9861	52.0226	
	80.4400	213.2756	37.6062	37.6062	1.0038	37.4631	0.9885	38.0420	0.9865	38.1213	0.9862	38.1330	0.9861	38.1347	
	76.4180	194.0208	34.2111	34.2111	1.0038	34.0809	0.9885	34.6075	0.9865	34.6796	0.9862	34.6903	0.9861	34.6918	
	102.5200	313.9076	55.3504	55.3504	1.0038	55.1397	0.9885	55.9917	0.9865	56.1084	0.9862	56.1256	0.9861	56.1282	
	89.6274	277.4263	48.9177	48.9177	1.0038	48.7316	0.9885	49.4846	0.9865	49.5877	0.9862	49.6029	0.9861	49.6051	
	64.0356	196.4720	34.6433	34.6433	1.0038	34.5115	0.9885	35.0447	0.9865	35.1178	0.9862	35.1285	0.9861	35.1301	
74.1000	22.9580	184.3166	67.0858	141.1858	0.5265	268.1770	0.4773	295.7823	0.4707	299.9377	0.4697	300.5578	0.4696	300.6501	5.5366
					1.0000		1.0000		1.0000		1.0000		1.0000		
					1.0000		1.0000		1.0000		1.0000		1.0000		
				785.4959		952.3949		980.4320		984.6888		985.3247		985.4194	11.8826

FOS(ini)	0.5591	FOS(1)	0.6779	FOS(2)	0.6979	FOS(3)	0.7009	FOS(4)	0.7014	FOS(5)	0.7014	dF0/dc1
										FOS(F0)	0.7014	Σ(32)/Σ(15)
										FOS	0.7330	0.0085

33	34		35	36	37		38	39	40		41	42
Soil 1			Soil 2					Soil 3				
sec²Φ'	(18)*(33)/(23) (18)*sec²Φ'/ni(θ)	-(2)*(14)/(23) -Δxi*tanΦ'/ni(θ	(2)/(23) Δxi/ni(θ)	sec²Φ'	(18)*(36)/(23) (18)*sec²Φ'/ni(θ)	-(2)*(14)/(23) -Δxi*tanΦ'/ni(θ	(2)/(23) Δxi/ni(θ)	sec²Φ'	(18)*(39)/(23) (18)*sec²Φ'/ni(θ	-(2)*(14)/(23) -Δxi*tanΦ'/ni(	(2)/(23) Δxi/ni(θ)	sec²Φ'
1.1325	37.3016	-1.1977										
1.1325	112.6210	-1.1121										
			3.2450	1.0311	169.8102	-0.5722						
			2.9408	1.0311	199.3060	-0.5185						
			2.9408	1.0311	223.2086	-0.5185						
			2.9408	1.0311	247.4273	-0.5185						
			2.9408	1.0311	271.3603	-0.5185						
			2.9408	1.0311	304.2079	-0.5185						
			2.0281	1.0311	222.9967	-0.3576						
			1.9267	1.0311	202.8643	-0.3397						
			2.7886	1.0311	328.2155	-0.4917						
			2.6467	1.0311	290.0714	-0.4667						
			2.0687	1.0311	205.4272	-0.3648						
1.1325	444.4914	-2.0152										
	594.4139	-4.3249	29.4075		2664.8955	-5.1853	0.0000		0.0000	0.0000	0.0000	
	dF0/dϕ1 Σ(34)/Σ(15)	dF0/du1 Σ(00)/Σ(15)	dF0/dc2 Σ(35)/Σ(15)		dF0/dϕ2 Σ(37)/Σ(15)	dF0/du2 Σ(00)/Σ(15)	dF0/dc3 Σ(38)/Σ(15)		dF0/dϕ3 Σ(40)/Σ(15)	dF0/du3 Σ(00)/Σ(15)	dF0/dc4 Σ(41)/Σ(15)	
	0.4231	-0.0031	0.0209		1.8969	-0.0037	0.0000		0.0000	0.0000	0.0000	

43		44	45	46	
Soil 4		**Soil 5**			
(18)*(42)/(23) **(18)*sec^{2}Φ'/ni(θ)**	**-(2)*(14)/(23)** **-Δxi*tanΦ'/ni(θ**	**(2)/(23)** **Δxi/ni(θ)**	**sec^{2}Φ'**	**(18)*(45)/(23)** **(18)*sec^{2}Φ'/ni(θ)**	**-(2)*(14)/(23)** **-Δxi*tanΦ'/ni(θ)**
0.0000	0.0000	0.0000		0.0000	0.0000

dF0/dφ4	dF0/du4	dF0/dc5		dF0/dφ5	dF0/du5
Σ(43)/Σ(15)	Σ(00)/Σ(15)	Σ(44)/Σ(15)		Σ(46)/Σ(15)	Σ(00)/Σ(15)
0.0000	0.0000	0.0000		0.0000	0.0000

Spreadsheet: BISHOP – PROB – DIRECT

(COV (u) = constant for the slope)

CALCULATION OF FACTOR OF SAFETY OF A SELECTED FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD

DETERMINISTIC

Note: Enter Values only in yellow cells (Probabilistic Calculations are valid upto 5 different soil layers)

	INPUTS										CALCULATION-STAGE 1			
1	2	3	4	5	6		7	8	9	10	11	12	13	14
Slice	Slice Width				Pore Pressure	Soil Type					{(4)+(5)}/2	(2)*(10)*(11)	(9)*(2)	
	Δxi (m)	θi (deg)	h1 (m)	h2 (m)	ui (kN/m2)		c' (kN/m2)	ϕ' (deg)	qi (kN/m2)	γ (kN/m3)	hav (m)	wi (kN-per m width)	Qi (kN-per m width)	tan ϕ
1	2.800	-12.020	0.000	2.000	8.83	1	28.50	20.00	0.00	18.84	1.00	52.75		0.36
2	2.600	-12.020	2.000	3.850	22.56	1	28.50	20.00	0.00	18.84	2.93	143.28		0.36
3	3.200	16.780	3.850	4.870	31.39	2	0.00	10.00	0.00	18.84	4.36	262.86		0.18
4	2.900	16.780	4.870	5.440	31.39	2	0.00	10.00	0.00	18.84	5.16	281.65		0.18
5	2.900	16.780	5.440	6.020	34.34	2	0.00	10.00	0.00	18.84	5.73	313.06		0.18
6	2.900	16.780	6.020	6.600	37.28	2	0.00	10.00	0.00	18.84	6.31	344.75		0.18
7	2.900	16.780	6.600	7.170	40.22	2	0.00	10.00	0.00	18.84	6.89	376.17		0.18
8	2.900	16.780	7.170	7.750	40.22	2	0.00	10.00	0.00	18.84	7.46	407.58		0.18
9	2.000	16.780	7.750	7.840	40.22	2	0.00	10.00	0.00	18.84	7.80	293.72		0.18
10	1.900	16.780	7.840	7.270	40.22	2	0.00	10.00	0.00	18.84	7.56	270.44		0.18
11	2.750	16.780	7.270	6.440	37.28	2	0.00	10.00	22.28	18.84	6.86	355.16	61.27	0.18
12	2.610	16.780	6.440	5.640	34.34	2	0.00	10.00	26.84	18.84	6.04	297.00	70.05	0.18
13	2.040	16.780	5.640	4.550	31.39	2	0.00	10.00	31.71	18.84	5.10	195.82	64.69	0.18
14	2.60	60.26	4.55	0.000	8.83	1	28.50	20.00	36.86	18.84	2.28	111.44	95.84	0.36
15														
16														

f0	1.05

FOS(4)	0.70	FOS(5)	0.70
		F0S(F0)	0.70
		FOS	0.73

CALCULATION OF PROBABILITY OF FAILURE OF A SELECTED FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD

PROBABILISTIC(First Order Second Moment)

Direct Differentiation

DATA INPUT

Probabilistic Parameters	COV		Mean		c'(kPa)			Φ'(rad)		
	c'	Φ'	c'(kPa)	Φ'(deg)	Mean	σ	V	Mean	σ	V
Soil 1	0.2	0.3	28.5	20	28.50	5.7000	32.4900	0.35	0.1047	0.0110
Soil 2	0	0.2	0	10	0.00	0.0000	0.0000	0.17	0.0349	0.0012
Soil 3	0	0	0	0	0.00	0.0000	0.0000	0.00	0.0000	0.0000
Soil 4	0	0	0	0	0.00	0.0000	0.0000	0.00	0.0000	0.0000
Soil 5	0	0	0	0	0.00	0.0000	0.0000	0.00	0.0000	0.0000

	Variance
u (kPa)	42.38

Xr	$(\partial F/\partial Xr)$	$(\partial F/\partial Xr)^2$	$(\partial F/\partial Xr)^2 * V(Xr)$
c1	0.0085	7E-05	0.002
c2	0.0209	4E-04	0
c3	0	0	0
c4	0	0	0
c5	0	0	0
ϕ1	0.4231	0.179	0.002
ϕ2	1.8969	3.598	0.004
ϕ3	0	0	0
ϕ4	0	0	0
ϕ5	0	0	0
u	-0.0068	5E-05	0.002
			0.011

F0	V(FOS)	0.0106	TAYLOR SEIRIES
	σ(FOS)	0.1030	
	FOS(MLV)	0.7014	
	COV(F)	0.1469	

	f0	1.0450	
F	V(FOS)	0.0116	$=f_0^{-2} * V(F_0)$
	σ(FOS)	0.1077	
	FOS(MLV)	0.7330	
	COV(F)	0.1469	

(NORMAL DISTRIBUTION)		
RELIABILITY INDEX	-2.48	
RELIABILITY	0.007	0.66 %
PROB. FAIL	0.993	99.34 %

(LOGNORMAL DISTRIBUTION)		
$1+[COV(F)]^2$	1.022	
RELIABILITY INDEX	-2.199	
RELIABILITY	0.014	1.39 %
PROB. FAIL	0.986	98.61 %

<u>JANBU'S SIMPLIFIED METHOD</u>

DETERMINISTIC/ PROBABILISTIC

Calculations

INPUTS										CALCULATION-STAGE 1				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Slice	Slice Width Δxi (m)	θi (deg)	h1 (m)	Pore Pressure h2 (m)	ui (kN/m2)	c' (kN/m2)	ϕ' (deg)	qi (kN/m2)	γ (kN/m3)	{(4)+(5)}/2 hav (m)	(2)*(10)*(11) wi (kN-per m width)	(9)*(2) Qi (kN-per m width)	tan ϕ	(wi+Qi) tan θi
1	2.8000	-12.0200		2.0000	8.8300	28.5000	20.0000		18.8400	1.0000	52.7520		0.3640	-11.2320
2	2.6000	-12.0200	2.0000	3.8500	22.5600	28.5000	20.0000		18.8400	2.9250	143.2782		0.3640	-30.5070
3	3.2000	16.7800	3.8500	4.8700	31.3900		10.0000		18.8400	4.3600	262.8557		0.1763	79.2607
4	2.9000	16.7800	4.8700	5.4400	31.3900		10.0000		18.8400	5.1550	281.6486		0.1763	84.9275
5	2.9000	16.7800	5.4400	6.0200	34.3400		10.0000		18.8400	5.7300	313.0643		0.1763	94.4004
6	2.9000	16.7800	6.0200	6.6000	37.2800		10.0000		18.8400	6.3100	344.7532		0.1763	103.9558
7	2.9000	16.7800	6.6000	7.1700	40.2200		10.0000		18.8400	6.8850	376.1689		0.1763	113.4288
8	2.9000	16.7800	7.1700	7.7500	40.2200		10.0000		18.8400	7.4600	407.5846		0.1763	122.9018
9	2.0000	16.7800	7.7500	7.8400	40.2200		10.0000		18.8400	7.7950	293.7156		0.1763	88.5661
10	1.9000	16.7800	7.8400	7.2700	40.2200		10.0000		18.8400	7.5550	270.4388		0.1763	81.5473
11	2.7500	16.7800	7.2700	6.4400	37.2800		10.0000	22.2800	18.8400	6.8550	355.1576	61.2700	0.1763	125.5683
12	2.6100	16.7800	6.4400	5.6400	34.3400		10.0000	26.8400	18.8400	6.0400	297.0013	70.0524	0.1763	110.6803
13	2.0400	16.7800	5.6400	4.5500	31.3900		10.0000	31.7100	18.8400	5.0950	195.8192	64.6884	0.1763	78.5527
14	2.6000	60.2600	4.5500		8.8300	28.5000	20.0000	36.8600	18.8400	2.2750	111.4386	95.8360	0.3640	362.8023
15														
16														
														1404.8529

f0	1.0450

JANBU'S SIMPLIFIED METHOD

DETERMINISTIC/ PROBABILISTIC

Calculations

CALCULATION - STAGE 2															CALULATIONS -
16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Ui=				**Trial 1**	**Trial 1**	**Trial 2**	**Trial 2**	**Trial 3**	**Trial 3**	**Trial 4**	**Trial 4**	**Trial 5**	**Trial 5**	**Pore Pressure**
c'Δxi	**ui*Δxi**	(wi+Qi -uiΔxi)	(18)*tanϕ'	(16)+(19)	**ni(θ)**	(20)/(21)	**ni(θ)**	(20)/(23)	**ni(θ)**	(20)/(25)	**ni(θ)**	(20)/(27)	**ni(θ)**	(20)/(29)	**-(2)*(14)/(23) -Δxi*tanΦ'/ni(θ)**
79.8000	24.7240	28.0280	10.2014	90.0014	0.8240	109.2198	0.8473	106.2246	0.8504	105.8339	0.8509	105.7768	0.8509	105.7683	-1.1977
74.1000	58.6560	84.6222	30.8000	104.9000	0.8240	127.2998	0.8473	123.8087	0.8504	123.3534	0.8509	123.2868	0.8509	123.2770	-1.1121
	100.4480	162.4077	28.6369	28.6369	1.0038	28.5279	0.9885	28.9687	0.9865	29.0291	0.9862	29.0379	0.9861	29.0393	-0.5722
	91.0310	190.6176	33.6110	33.6110	1.0038	33.4831	0.9885	34.0005	0.9865	34.0713	0.9862	34.0818	0.9861	34.0833	-0.5185
	99.5860	213.4783	37.6420	37.6420	1.0038	37.4987	0.9885	38.0782	0.9865	38.1575	0.9862	38.1692	0.9861	38.1709	-0.5185
	108.1120	236.6412	41.7262	41.7262	1.0038	41.5674	0.9885	42.2097	0.9865	42.2977	0.9862	42.3106	0.9861	42.3126	-0.5185
	116.6380	259.5309	45.7623	45.7623	1.0038	45.5881	0.9885	46.2926	0.9865	46.3890	0.9862	46.4032	0.9861	46.4053	-0.5185
	116.6380	290.9466	51.3017	51.3017	1.0038	51.1065	0.9885	51.8962	0.9865	52.0043	0.9862	52.0203	0.9861	52.0226	-0.5185
	80.4400	213.2756	37.6062	37.6062	1.0038	37.4631	0.9885	38.0420	0.9865	38.1213	0.9862	38.1330	0.9861	38.1347	-0.3576
	76.4180	194.0208	34.2111	34.2111	1.0038	34.0809	0.9885	34.6075	0.9865	34.6796	0.9862	34.6903	0.9861	34.6918	-0.3397
	102.5200	313.9076	55.3504	55.3504	1.0038	55.1397	0.9885	55.9917	0.9865	56.1084	0.9862	56.1256	0.9861	56.1282	-0.4917
	89.6274	277.4263	48.9177	48.9177	1.0038	48.7316	0.9885	49.4846	0.9865	49.5877	0.9862	49.6029	0.9861	49.6051	-0.4667
	64.0356	196.4720	34.6433	34.6433	1.0038	34.5115	0.9885	35.0447	0.9865	35.1178	0.9862	35.1285	0.9861	35.1301	-0.3648
74.1000	22.9580	184.3166	67.0858	141.1858	0.5265	268.1770	0.4773	295.7823	0.4707	299.9377	0.4697	300.5578	0.4696	300.6501	-2.0152
					1.0000		1.0000		1.0000		1.0000		1.0000		
					1.0000		1.0000		1.0000		1.0000		1.0000		
				785.4959		952.3949		980.4320		984.6888		985.3247		985.4194	-9.5103

FOS(ini) 0.5591	FOS(1) 0.6779	FOS(2) 0.6979	FOS(3) 0.7009	FOS(4) 0.7014	FOS(5)	0.7014	dF0/du
					FOS(F0)	0.7014	Σ(31)/Σ(15)
					FOS	0.7330	-0.0068

- STAGE 3

32	33	34	35	36	37	38	39	40	41	42	43	44
Soil 1			**Soil 2**			**Soil 3**			**Soil 4**			
(2)/(23) Δxi/ni(θ)	**$sec^2Φ'$**	**(18)*(33)/(23) (18)*$sec^2Φ'$/ni(θ)**	**(2)/(23) Δxi/ni(θ)**	**$sec^2Φ'$**	**(18)*(36)/(23) (18)*$sec^2Φ'$/ni(θ)**	**(2)/(23) Δxi/ni(θ)**	**$sec^2Φ'$**	**(18)*(39)/(23) (18)*$sec^2Φ'$/ni(θ)**	**(2)/(23) Δxi/ni(θ)**	**$sec^2Φ'$**	**(18)*(42)/(23) (18)*$sec^2Φ'$/ni(θ)**	**(2)/(23) Δxi/ni(θ)**
3.2905	1.1325	37.3016										
3.0555	1.1325	112.6210										
			3.2450	1.0311	169.8102							
			2.9408	1.0311	199.3060							
			2.9408	1.0311	223.2086							
			2.9408	1.0311	247.4273							
			2.9408	1.0311	271.3603							
			2.9408	1.0311	304.2079							
			2.0281	1.0311	222.9967							
			1.9267	1.0311	202.8643							
			2.7886	1.0311	328.2155							
			2.6467	1.0311	290.0714							
			2.0687	1.0311	205.4272							
5.5366	1.1325	444.4914										
11.8826		594.4139	29.4075		2664.8955	0.0000		0.0000	0.0000		0.0000	0.0000
dF0/dc1		dF0/dφ1	dF0/dc2		dF0/dφ2	dF0/dc3		dF0/dφ3	dF0/dc4		dF0/dφ4	dF0/dc5
Σ(32)/Σ(15)		Σ(34)/Σ(15)	Σ(35)/Σ(15)		Σ(37)/Σ(15)	Σ(38)/Σ(15)		Σ(40)/Σ(15)	Σ(41)/Σ(15)		Σ(43)/Σ(15)	Σ(44)/Σ(15)
0.0085		0.4231	0.0209		1.8969	0.0000		0.0000	0.0000		0.0000	0.0000

45	46
Soil 5	
$sec^2\Phi'$	(18)*(45)/(23) (18)*$sec^2\Phi'$/ni(θ)
	0.0000
	dF0/dϕ5 Σ(46)/Σ(15)
	0.0000

Spreadsheet: Janbu – Prob – Direct – Exact

(COV (u) = Based on soil layers)

CALCULATION OF FACTOR OF SAFETY OF A SELECTED FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD

DETERMINISTIC

Note: Enter Values only in yellow cells (Probabilistic Calculations are valid upto 5 different soil layers)

	INPUTS									CALCULATION-STAGE 1			
1	2	3	4	5	6		7	8	9	10	11	12	13	14
Slice	Slice Width Δxi (m)	θi (deg)	h1 (m)	h2 (m)	Pore Pressure ui (kN/m2)	Soil Type	c' (kN/m2)	ϕ' (deg)	qi (kN/m2)	γ (kN/m3)	{(4)+(5)}/2 hav (m)	(2)*(10)*(11) wi (kN-per m width)	(9)*(2) Qi (kN-per m width)	tan ϕ
1	2.800	-12.020	0.000	2.000	8.83	1	28.50	20.00	0.00	18.84	1.00	52.75		0.36
2	2.600	-12.020	2.000	3.850	22.56	1	28.50	20.00	0.00	18.84	2.93	143.28		0.36
3	3.200	16.780	3.850	4.870	31.39	2	0.00	10.00	0.00	18.84	4.36	262.86		0.18
4	2.900	16.780	4.870	5.440	31.39	2	0.00	10.00	0.00	18.84	5.16	281.65		0.18
5	2.900	16.780	5.440	6.020	34.34	2	0.00	10.00	0.00	18.84	5.73	313.06		0.18
6	2.900	16.780	6.020	6.600	37.28	2	0.00	10.00	0.00	18.84	6.31	344.75		0.18
7	2.900	16.780	6.600	7.170	40.22	2	0.00	10.00	0.00	18.84	6.89	376.17		0.18
8	2.900	16.780	7.170	7.750	40.22	2	0.00	10.00	0.00	18.84	7.46	407.58		0.18
9	2.000	16.78	7.750	7.840	40.22	2	0.00	10.00	0.00	18.84	7.80	293.72		0.18
10	1.900	16.78	7.840	7.270	40.22	2	0.00	10.00	0.00	18.84	7.56	270.44		0.18
11	2.75	16.78	7.27	6.440	37.28	2		10.00	22.28	18.84	6.86	355.16	61.27	0.18
12	2.61	16.78	6.44	5.640	34.34	2		10.00	26.84	18.84	6.04	297.00	70.05	0.18
13	2.04	16.78	5.64	4.550	31.39	2		10.00	31.71	18.84	5.10	195.82	64.69	0.18
14	2.60	60.26	4.55		8.83	1	28.50	20.00	36.86	18.84	2.28	111.44	95.84	0.36
15														
16														

f0	1.05

FOS(4)	0.70	FOS(5)	0.70
		F0S(F0)	0.70
		FOS	0.73

CALCULATION OF PROBABILITY OF FAILURE OF A SELECTED FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD

PROBABILISTIC(First Order Second Moment)

Direct Differentiation

DATA INPUT

Probabilistic Parameters	COV			Mean			c'(kPa)			Φ'(rad)			u(kPa)		
	c'	Φ	u	c'(kPa)	Φ'(deg)	u	Mean	σ	V	Mean	σ	V	Mean	σ	V
Soil 1	0.2	0.3	0.3	28.5	20	13.29	28.50	5.7000	32.4900	0.35	0.1047	0.0110	13.29	3.9870	15.8962
Soil 2	0	0.2	0.2	0	10	36.05	0.00	0.0000	0.0000	0.17	0.0349	0.0012	36.05	7.2100	51.9841
Soil 3	0	0		0	0		0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.00	0.0000	0.0000
Soil 4	0	0		0	0		0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.00	0.0000	0.0000
Soil 5	0	0		0	0		0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.00	0.0000	0.0000

Xr	$(\partial F/\partial Xr)$	$(\partial F/\partial Xr)^2$	$(\partial F/\partial Xr)^2 * V(Xr)$
c1	0.0085	7E-05	0.002
c2	0.0209	4E-04	0
c3	0	0	0
c4	0	0	0
c5	0	0	0
ϕ1	0.1692	0.029	3E-04
ϕ2	1.7633	3.109	0.004
ϕ3	0	0	0
ϕ4	0	0	0
ϕ5	0	0	0
u1	-0.0031	9E-06	2E-04
u2	-0.0037	1E-05	7E-04
u3	0	0	0
u4	0	0	0
u5	0	0	0
			0.007

F0						
	V(FOS)				0.007	TAYLOR SERIES
	σ(FOS)				0.085	
	FOS(MLV)				0.70	
	COV(F)				0.122	

F	f0					1.05	
	V(FOS)					0.008	$=f_0^{-2} \cdot V(F_0)$
	σ(FOS)					0.089	
	FOS(MLV)					0.73	
	COV(F)					0.122	

(NORMAL DISTRIBUTION)		
RELIABILITY INDEX	-2.994	
RELIABILITY	0.001	0.14 %
PROB. FAIL	0.999	99.86 %

(LOGNORMAL DISTRIBUTION)		
$1+[COV(F)]^2$	1.015	
RELIABILITY INDEX	-2.623	
RELIABILITY	0.004	0.44 %
PROB. FAIL	0.996	99.56 %

JANBU'S SIMPLIFIED METHOD

DETERMINISTIC/ PROBABILISTIC

Calculations

	INPUTS									CALCULATION-STAGE 1				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Slice	Slice Width				Pore Pressure					{(4)+(5)}/2	(2)*(10)*(11)	(9)*(2)		B=
	Δxi	θi	h1	h2	ui	c'	ϕ'	qi	γ	hav	wi	Qi	tan ϕ	(wi+Qi) tan θi
	(m)	(deg)	(m)	(m)	(kN/m2)	(kN/m2)	(deg)	(kN/m2)	(kN/m3)	(m)	(kN-per m width)	(kN-per m width)		
1	2.8000	-12.0200		2.0000	8.8300	28.5000	20.0000		18.8400	1.0000	52.7520		0.3640	-11.2320
2	2.6000	-12.0200	2.0000	3.8500	22.5600	28.5000	20.0000		18.8400	2.9250	143.2782		0.3640	-30.5070
3	3.2000	16.7800	3.8500	4.8700	31.3900		10.0000		18.8400	4.3600	262.8557		0.1763	79.2607
4	2.9000	16.7800	4.8700	5.4400	31.3900		10.0000		18.8400	5.1550	281.6486		0.1763	84.9275
5	2.9000	16.7800	5.4400	6.0200	34.3400		10.0000		18.8400	5.7300	313.0643		0.1763	94.4004
6	2.9000	16.7800	6.0200	6.6000	37.2800		10.0000		18.8400	6.3100	344.7532		0.1763	103.9558
7	2.9000	16.7800	6.6000	7.1700	40.2200		10.0000		18.8400	6.8850	376.1689		0.1763	113.4288
8	2.9000	16.7800	7.1700	7.7500	40.2200		10.0000		18.8400	7.4600	407.5846		0.1763	122.9018
9	2.0000	16.7800	7.7500	7.8400	40.2200		10.0000		18.8400	7.7950	293.7156		0.1763	88.5661
10	1.9000	16.7800	7.8400	7.2700	40.2200		10.0000		18.8400	7.5550	270.4388		0.1763	81.5473
11	2.7500	16.7800	7.2700	6.4400	37.2800		10.0000	22.2800	18.8400	6.8550	355.1576	61.2700	0.1763	125.5683
12	2.6100	16.7800	6.4400	5.6400	34.3400		10.0000	26.8400	18.8400	6.0400	297.0013	70.0524	0.1763	110.6803
13	2.0400	16.7800	5.6400	4.5500	31.3900		10.0000	31.7100	18.8400	5.0950	195.8192	64.6884	0.1763	78.5527
14	2.6000	60.2600	4.5500		8.8300	28.5000	20.0000	36.8600	18.8400	2.2750	111.4386	95.8360	0.3640	362.8023
15														
16														
														1404.8529
f0	1.0450													

JANBU'S SIMPLIFIED METHOD

DETERMINISTIC/ PROBABILISTIC

Calculations

CALCULATION - STAGE 2

16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	Ui=			A=	Trial 1	Trial 1	Trial 2	Trial 2	Trial 3	Trial 3	Trial 4	Trial 4	Trial 5	Trial 5	
				(16)+(19)		(20)/(21)		(20)/(23)		(20)/(25)		(20)/(27)		(20)/(29)	
c'Δxi	ui*Δxi	(wi+Qi -uiΔxi)	(18)*tanϕ'		ni(θ)		ni(θ)		ni(θ)		ni(θ)		ni(θ)		cos θ
79.8000	24.7240	28.0280	10.2014	90.0014	0.8240	109.2198	0.8473	106.2246	0.8504	105.8339	0.8509	105.7768	0.8509	105.7683	0.9781
74.1000	58.6560	84.6222	30.8000	104.9000	0.8240	127.2998	0.8473	123.8087	0.8504	123.3534	0.8509	123.2868	0.8509	123.2770	0.9781
	100.4480	162.4077	28.6369	28.6369	1.0038	28.5279	0.9885	28.9687	0.9865	29.0291	0.9862	29.0379	0.9861	29.0393	0.9574
	91.0310	190.6176	33.6110	33.6110	1.0038	33.4831	0.9885	34.0005	0.9865	34.0713	0.9862	34.0818	0.9861	34.0833	0.9574
	99.5860	213.4783	37.6420	37.6420	1.0038	37.4987	0.9885	38.0782	0.9865	38.1575	0.9862	38.1692	0.9861	38.1709	0.9574
	108.1120	236.6412	41.7262	41.7262	1.0038	41.5674	0.9885	42.2097	0.9865	42.2977	0.9862	42.3106	0.9861	42.3126	0.9574
	116.6380	259.5309	45.7623	45.7623	1.0038	45.5881	0.9885	46.2926	0.9865	46.3890	0.9862	46.4032	0.9861	46.4053	0.9574
	116.6380	290.9466	51.3017	51.3017	1.0038	51.1065	0.9885	51.8962	0.9865	52.0043	0.9862	52.0203	0.9861	52.0226	0.9574
	80.4400	213.2756	37.6062	37.6062	1.0038	37.4631	0.9885	38.0420	0.9865	38.1213	0.9862	38.1330	0.9861	38.1347	0.9574
	76.4180	194.0208	34.2111	34.2111	1.0038	34.0809	0.9885	34.6075	0.9865	34.6796	0.9862	34.6903	0.9861	34.6918	0.9574
	102.5200	313.9076	55.3504	55.3504	1.0038	55.1397	0.9885	55.9917	0.9865	56.1084	0.9862	56.1256	0.9861	56.1282	0.9574
	89.6274	277.4263	48.9177	48.9177	1.0038	48.7316	0.9885	49.4846	0.9865	49.5877	0.9862	49.6029	0.9861	49.6051	0.9574
	64.0356	196.4720	34.6433	34.6433	1.0038	34.5115	0.9885	35.0447	0.9865	35.1178	0.9862	35.1285	0.9861	35.1301	0.9574
74.1000	22.9580	184.3166	67.0858	141.1858	0.5265	268.1770	0.4773	295.7823	0.4707	299.9377	0.4697	300.5578	0.4696	300.6501	0.4961
					1.0000		1.0000		1.0000		1.0000		1.0000		1.0000
					1.0000		1.0000		1.0000		1.0000		1.0000		1.0000
				785.4959		952.3949		980.4320		984.6888		985.3247		985.4194	

FOS(ini)	0.5591	FOS(1)	0.6779	FOS(2)	0.6979	FOS(3)	0.7009	FOS(4)	0.7014	FOS(5)	0.7014
										FOS(F0)	0.7014
										FOS	0.7330

32	34	35	36	37	38		39	40	41	42	43	
	Soil 1						Soil 2					
tan θ	(2)/(23) Δxi/ni(θ)	$sec^2\Phi'$	(18)*(35)/(23) (18)*$sec^2\Phi'$/ni(θ) C=	A*d(1/niθ)/dφ D=	C+D=	-(2)*(14)/(23) -Δxi*tanΦ'/n	(2)/(23) Δxi/ni(θ)	$sec^2\Phi'$	(18)*(40)/(23) (18)*$sec^2\Phi'$/ni(θ) C=	A*d(1/niθ)/dφ D=	C+D=	-(2)*(14)/(23) -Δxi*tanΦ'/ni
-0.2129	3.2905	1.1325	37.3016	40.8776	78.1791	-1.1977						
-0.2129	3.0555	1.1325	112.6210	47.6443	160.2653	-1.1121						
0.3015							3.2450	1.0311	169.8102	-11.9652	157.8451	-0.5722
0.3015							2.9408	1.0311	199.3060	-14.0435	185.2624	-0.5185
0.3015							2.9408	1.0311	223.2086	-15.7277	207.4809	-0.5185
0.3015							2.9408	1.0311	247.4273	-17.4342	229.9931	-0.5185
0.3015							2.9408	1.0311	271.3603	-19.1206	252.2397	-0.5185
0.3015							2.9408	1.0311	304.2079	-21.4351	282.7728	-0.5185
0.3015							2.0281	1.0311	222.9967	-15.7128	207.2839	-0.3576
0.3015							1.9267	1.0311	202.8643	-14.2942	188.5700	-0.3397
0.3015							2.7886	1.0311	328.2155	-23.1267	305.0887	-0.4917
0.3015							2.6467	1.0311	290.0714	-20.4390	269.6324	-0.4667
0.3015							2.0687	1.0311	205.4272	-14.4748	190.9524	-0.3648
1.7503	5.5366	1.1325	444.4914	-445.2378	-0.7464	-2.0152						
	11.8826				237.6980	-4.3249	29.4075				2477.1214	-5.1853
	dF0/dc1 Σ(34)/Σ(15)				dF0/dφ1 Σ(38)/Σ(15)	dF0/du1 Σ(00)/Σ(15)	dF0/dc2 Σ(39)/Σ(15)				dF0/dφ2 Σ(43)/Σ(15)	dF0/du2 Σ(00)/Σ(15)
	0.0085				0.1692	-0.0031	0.0209				1.7633	-0.0037

44	45	46	47	48		49	50	51	52	53		54	55
Soil 3						Soil 4							
(2)/(23)		(18)*(45)/(23)			-(2)*(14)/(23	(2)/(23)		(18)*(50)/(23)			-(2)*(14)/(23)	(2)/(23)	
Δxi/ni(θ)	sec²Φ'	(18)*sec²Φ'/ni(θ)	A*d(1/niθ)/dϕ		-Δxi*tanΦ'/	Δxi/ni(θ)	sec²Φ'	(18)*sec²Φ'/ni(θ)	A*d(1/niθ)/dϕ		-Δxi*tanΦ'/r	Δxi/ni(θ)	sec²Φ'
		C=	D=	C+D=				C=	D=	C+D=			
0.0000				0.0000	0.0000	0.0000				0.0000	0.0000	0.0000	
dF0/dc3				dF0/dϕ3	dF0/du3	dF0/dc4				dF0/dϕ4	dF0/du4	dF0/dc5	
Σ(44)/Σ(15)				Σ(48)/Σ(15	Σ(00)/Σ(15	Σ(49)/Σ(15)				Σ(53)/Σ(15)	Σ(00)/Σ(15)	Σ(54)/Σ(15)	
0.0000				0.0000	0.0000	0.0000				0.0000	0.0000	0.0000	

56	57	58	
Soil 5			
(18)*(55)/(23)			-(2)*(14)/(23)
(18)*sec²Φ'/ni(θ)	**A*d(1/niθ)/dϕ**		-Δxi*tanΦ'/ni(θ)
C=	D=	C+D=	
		0.0000	0.0000
		dF0/dϕ5	dF0/du5
		Σ(58)/Σ(15)	Σ(00)/Σ(15)
		0.0000	0.0000

Spreadsheet: Janbu – Prob – SmallIncrement

(COV(u) = based on soil layers)

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD

DETERMINISTIC

Probability calculation is valid upto 5 different soil layers

											CALCULATION-STAGE 1		
1	2	3	4	5	6		7	8	9	10	11	12	13
Slice	Slice Width Δxi (m)	θi (deg)	h1 (m)	h2 (m)	Pore Pressure ui (kN/m2)	Soil Type	c' (kN/m2)	ϕ' (deg)	qi (kN/m2)	γ (kN/m3)	{(4)+(5)}/2 hav (m)	(2)*(10)*(11) wi (kN-per m width)	(9)*(2) Qi (kN-per m width)
1	2.800	-12.020	0.000	2.000	8.83	1	28.50	20.00	0.00	18.84	1.0000	52.7520	
2	2.600	-12.020	2.000	3.850	22.56	1	28.50	20.00	0.00	18.84	2.9250	143.2782	
3	3.200	16.780	3.850	4.870	31.39	2	0.00	10.00	0.00	18.84	4.3600	262.8557	
4	2.900	16.780	4.870	5.440	31.39	2	0.00	10.00	0.00	18.84	5.1550	281.6486	
5	2.900	16.780	5.440	6.020	34.34	2	0.00	10.00	0.00	18.84	5.7300	313.0643	
6	2.900	16.780	6.020	6.600	37.28	2	0.00	10.00	0.00	18.84	6.3100	344.7532	
7	2.900	16.780	6.600	7.170	40.22	2	0.00	10.00	0.00	18.84	6.8850	376.1689	
8	2.900	16.780	7.170	7.750	40.22	2	0.00	10.00	0.00	18.84	7.4600	407.5846	
9	2.000	16.780	7.750	7.840	40.22	2	0.00	10.00	0.00	18.84	7.7950	293.7156	
10	1.900	16.780	7.840	7.270	40.22	2	0.00	10.00	0.00	18.84	7.5550	270.4388	
11	2.750	16.780	7.270	6.440	37.28	2	0.00	10.00	22.28	18.84	6.8550	355.1576	61.2700
12	2.610	16.780	6.440	5.640	34.34	2	0.00	10.00	26.84	18.84	6.0400	297.0013	70.0524
13	2.040	16.780	5.640	4.550	31.39	2	0.00	10.00	31.71	18.84	5.0950	195.8192	64.6884
14	2.60	60.26	4.55	0.000	8.83	1	28.50	20.00	36.86	18.84	2.2750	111.4386	95.8360
15													
16													

f0	1.05

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD

DETERMINISTIC

	CALCULATION											
14	15	16	17	18	19	20	21	22	23	24	25	26
			Ui=				Trial 1	Trial 1	Trial 2	Trial 2	Trial 3	Trial 3
tan ϕ	(wi+Qi) tan θi	c'Δxi	ui*Δxi	(wi+Qi -uiΔxi)	(18)*tanϕ'	(16)+(19)	ni(θ)	(20)/(21)	ni(θ)	(20)/(23)	ni(θ)	(20)/(25)
0.3640	-11.2320	79.8000	24.7240	28.0280	10.2014	90.0014	0.8240	109.2198	0.8473	106.2246	0.8504	105.8339
0.3640	-30.5070	74.1000	58.6560	84.6222	30.8000	104.9000	0.8240	127.2998	0.8473	123.8087	0.8504	123.3534
0.1763	79.2607		100.4480	162.4077	28.6369	28.6369	1.0038	28.5279	0.9885	28.9687	0.9865	29.0291
0.1763	84.9275		91.0310	190.6176	33.6110	33.6110	1.0038	33.4831	0.9885	34.0005	0.9865	34.0713
0.1763	94.4004		99.5860	213.4783	37.6420	37.6420	1.0038	37.4987	0.9885	38.0782	0.9865	38.1575
0.1763	103.9558		108.1120	236.6412	41.7262	41.7262	1.0038	41.5674	0.9885	42.2097	0.9865	42.2977
0.1763	113.4288		116.6380	259.5309	45.7623	45.7623	1.0038	45.5881	0.9885	46.2926	0.9865	46.3890
0.1763	122.9018		116.6380	290.9466	51.3017	51.3017	1.0038	51.1065	0.9885	51.8962	0.9865	52.0043
0.1763	88.5661		80.4400	213.2756	37.6062	37.6062	1.0038	37.4631	0.9885	38.0420	0.9865	38.1213
0.1763	81.5473		76.4180	194.0208	34.2111	34.2111	1.0038	34.0809	0.9885	34.6075	0.9865	34.6796
0.1763	125.5683		102.5200	313.9076	55.3504	55.3504	1.0038	55.1397	0.9885	55.9917	0.9865	56.1084
0.1763	110.6803		89.6274	277.4263	48.9177	48.9177	1.0038	48.7316	0.9885	49.4846	0.9865	49.5877
0.1763	78.5527		64.0356	196.4720	34.6433	34.6433	1.0038	34.5115	0.9885	35.0447	0.9865	35.1178
0.3640	362.8023	74.1000	22.9580	184.3166	67.0858	141.1858	0.5265	268.1770	0.4773	295.7823	0.4707	299.9377
							1.0000		1.0000		1.0000	
							1.0000		1.0000		1.0000	
	1404.8529					785.4959		952.3949		980.4320		984.6888
					FOS(ini)	0.5591	FOS(1)	0.6779	FOS(2)	0.6979	FOS(3)	0.7009

27	28	29	30
Trial 4	**Trial 4**	**Trial 5**	**Trial 5**
ni(θ)	**(20)/(27)**	**ni(θ)**	**(20)/(29)**
0.8509	105.7768	0.8509	105.7683
0.8509	123.2868	0.8509	123.2770
0.9862	29.0379	0.9861	29.0393
0.9862	34.0818	0.9861	34.0833
0.9862	38.1692	0.9861	38.1709
0.9862	42.3106	0.9861	42.3126
0.9862	46.4032	0.9861	46.4053
0.9862	52.0203	0.9861	52.0226
0.9862	38.1330	0.9861	38.1347
0.9862	34.6903	0.9861	34.6918
0.9862	56.1256	0.9861	56.1282
0.9862	49.6029	0.9861	49.6051
0.9862	35.1285	0.9861	35.1301
0.4697	300.5578	0.4696	300.6501
1.0000		1.0000	
1.0000		1.0000	
	985.3247		985.4194
FOS(4)	0.7014	FOS(5)	0.7014
		F0S(F0)	0.7014
		FOS	0.7330

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD

PROBABILISTIC(First Order Second Moment - small increment)

	c					φ								u				
						(DEG)				(RAD)								
Soil Ty	Mean	COV	Del C	s	V	Mean	COV	Del Fi	s	Mean	del fi rad	s	V	Mean	COV	Del C	s	V
1	28.5	0.2	5.7	5.7	32.49	20	0.3	6	6	0.349066	0.10472	0.10472	0.010966	13.29	0.3	3.99	3.99	15.9
2	0			0	0	10	0.2	2	2	0.174533	0.034907	0.034907	0.001218	36.05	0.2	7.21	7.21	51.98
3				0	0				0	0	0	0	0				0	0
4				0	0				0	0	0	0	0				0	0
5				0	0				0	0	0	0	0				0	0

OUTPUT

F0	$F0_{MLV}$	0.7014				
	FC1+	0.7584	Fφ1+	0.7242	Fu1+	0.6870
	FC1--	0.6451	Fφ1--	0.6824	Fu1--	0.7159
	FC2+	0.7014	Fφ2+	0.7736	Fu2+	0.6701
	FC2--	0.7014	Fφ2--	0.6288	Fu2--	0.7327
	Fc3+	0.7014	Fφ3+	0.7014	Fu3+	0.7014
	Fc3--	0.7014	Fφ3--	0.7014	Fu3--	0.7014
	Fc4+	0.7014	Fφ4+	0.7014	Fu4+	0.7014
	Fc4--	0.7014	Fφ4--	0.7014	Fu4--	0.7014
	Fc5+	0.7014	Fφ5+	0.7014	Fu5+	0.7014
	Fc5--	0.7014	Fφ5--	0.7014	Fu5--	0.7014

CENTRAL DIFFERENCES

F0	Δ Fc1	0.1133	Δ Fφ1	0.0418	Δ Fu1	####
	Δ Fc2	0.0000	Δ Fφ2	0.1448	Δ Fu2	####
	Δ Fc3	0.0000	Δ Fφ3	0.0000	Δ Fu3	0.0000
	Δ Fc4	0.0000	Δ Fφ4	0.0000	Δ Fu4	0.0000
	Δ Fc5	0.0000	Δ Fφ5	0.0000	Δ Fu5	0.0000

	Fc1/2Δ c1	0.00994	Δ Fφ1/2Δ Ff1	0.19976	Δ Fu1/2Δ u1	-0.004
	Fc2/2Δ c2	0	Δ Fφ2/2Δ Ff2	2.07352	Δ Fu2/2Δ u2	-0.004

FORWARD DIFFERENCES

F0	Δ Fc1	0.0570	Δ Fφ1	0.0228	Δ Fu1	-0.0144
	Δ Fc2	0.0000	Δ Fφ2	0.0722	Δ Fu2	-0.0313
	Δ Fc3	0.0000	Δ Fφ3	0.0000	Δ Fu3	0.0000
	Δ Fc4	0.0000	Δ Fφ4	0.0000	Δ Fu4	0.0000
	Δ Fc5	0.0000	Δ Fφ5	0.0000	Δ Fu5	0.0000

Δ Fc1/Δ c1	0.01	Δ Fφ1/2Δ Ff1	0.2178108	Δ Fu1/Δ u1	-0.0036118
Δ Fc2/Δ c2	0	Δ Fφ2/2Δ Ff2	2.06801333	Δ Fu2/Δu2	-0.0043403

A						
	Fc3/2Δ c3	0	Δ Fϕ3/2Δ Ff3	0	Δ Fu3/2Δ u3	0
	Fc4/2Δ c4	0	Δ Fϕ4/2Δ Ff4	0	Δ Fu4/2Δ u4	0
	Fc5/2Δ c5	0	Δ Fϕ5/2Δ Ff5	0	Δ Fu5/2Δ u5	0

A*sigma						
c	0.05664	ϕ	0.02092	u	-0.014
2	0	2	0.07238	2	-0.031
3	0	3	0	3	0
4	0	4	0	4	0
5	0	5	0	5	0

F0		
V(FOS)	0.01007	
σ(FOS)	0.10035	TAYLOR SERIES
FOS(MLV	0.70	
COV(F)	0.14307	

F		
f0	1.05	
V(FOS)	0.011	$=f_0^2 \cdot V(F_0)$
σ(FOS)	0.10487	
FOS(MLV	0.7330	
COV(F)	0.14307	

(NORMAL DISTRIBUTION)		
RELIABILITY INDEX	-2.546	
RELIABILITY	0.0054	0.54 %
PROB. FAIL	0.9946	99.46 %

(LOGNORMAL DISTRIBUTION)		
$1+[COV(F)]^2$	1.0205	
RELIABILITY INDEX	-2.254	
RELIABI	0.0121	1.21 %
PROB. F	0.9879	98.79 %

Δ Fc3/Δ c3	0	Δ Fϕ3/2Δ Ff3	0	Δ Fu3/Δ u3	0
Δ Fc4/Δ c4	0	Δ Fϕ4/2Δ Ff4	0	Δ Fu4/Δ u4	0
Δ Fc5/Δ c5	0	Δ Fϕ5/2Δ Ff5	0	Δ Fu5/Δ u5	0

c	0.057	ϕ	0.02280909	u	-0.0144003
2	0	2	0.07218728	2	-0.0312936
3	0	3	0	3	0
4	0	4	0	4	0
5	0	5	0	5	0

F0		
V(FOS)	0.0102	
σ(FOS)	0.1008	TAYLOR SERIES
FOS(M	0.70	
COV(F	0.1437	

F		
f0	1.05	
V(FOS)	0.0111	$=f_0^2 \cdot V(F_0)$
σ(FOS)	0.1053	
FOS(M	0.7330	
COV(F	0.1437	

(NORMAL DISTRIBUTION)		
RELIABILITY INDEX	-2.53	
RELIABILITY	0.006	0.56 %
PROB. FAIL	0.994	99.44 %

(LOGNORMAL DISTRIBUTION)		
$1+[COV(F)]^2$	1.021	
RELIABILITY INDEX	-2.24	
RELIA	0.012	1.24 %
PROB.	0.988	98.76 %

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD

Fc1+

											CALCULATION-STAGE 1	
1	2	3	4	5	6		7	8	9	10	11	12
Slice	**Slice Width**				**Pore Pressure**	**Soil Type**					**{(4)+(5)}/2**	**(2)*(10)*(11)**
	Δxi	**θi**	**h1**	**h2**	**ui**		**c'**	**ϕ'**	qi	**γ**	**hav**	**wi**
	(m)	**(deg)**	**(m)**	**(m)**	**(kN/m2)**		**(kN/m2)**	**(deg)**	(kN/m2)	**(kN/m3)**	**(m)**	**(kN-per m width)**
1	2.800	-12.020		2.000	8.830	1	34.20	20.000		18.840	1.000	52.752
2	2.600	-12.020	2.000	3.850	22.560	1	34.20	20.000		18.840	2.925	143.278
3	3.200	16.780	3.850	4.870	31.390	2		10.000		18.840	4.360	262.856
4	2.900	16.780	4.870	5.440	31.390	2		10.000		18.840	5.155	281.649
5	2.900	16.780	5.440	6.020	34.340	2		10.000		18.840	5.730	313.064
6	2.900	16.780	6.020	6.600	37.280	2		10.000		18.840	6.310	344.753
7	2.900	16.780	6.600	7.170	40.220	2		10.000		18.840	6.885	376.169
8	2.900	16.780	7.170	7.750	40.220	2		10.000		18.840	7.460	407.585
9	2.000	16.780	7.750	7.840	40.220	2		10.000		18.840	7.795	293.716
10	1.900	16.780	7.840	7.270	40.220	2		10.000		18.840	7.555	270.439
11	2.750	16.780	7.270	6.440	37.280	2		10.000	22.280	18.840	6.855	355.158
12	2.610	16.780	6.440	5.640	34.340	2		10.000	26.840	18.840	6.040	297.001
13	2.040	16.780	5.640	4.550	31.390	2		10.000	31.710	18.840	5.095	195.819
14	2.600	60.260	4.550		8.830	1	34.20	20.000	36.860	18.840	2.275	111.439
15												
16												

f0	1.045

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD

Fc1+

		CALCULATION										
13	14	15	16	17	18	19	20	21	22	23	24	25
(9)*(2) Qi (kN-per m width)	tan ϕ	(wi+Qi) tan θi	c'Δxi	Ui= ui*Δxi	(wi+Qi -uiΔxi)	(18)*tanϕ'	(16)+(19)	Trial 1 ni(θ)	Trial 1 (20)/(21)	Trial 2 ni(θ)	Trial 2 (20)/(23)	Trial 3 ni(θ)
	0.364	-11.23	95.76	24.72	28.03	10.20	105.96	0.83	127.46	0.86	123.91	0.86
	0.364	-30.51	88.92	58.66	84.62	30.80	119.72	0.83	144.01	0.86	139.99	0.86
	0.176	79.26		100.45	162.41	28.64	28.64	1.00	28.66	0.98	29.12	0.98
	0.176	84.93		91.03	190.62	33.61	33.61	1.00	33.64	0.98	34.18	0.98
	0.176	94.40		99.59	213.48	37.64	37.64	1.00	37.68	0.98	38.28	0.98
	0.176	103.96		108.11	236.64	41.73	41.73	1.00	41.77	0.98	42.43	0.98
	0.176	113.43		116.64	259.53	45.76	45.76	1.00	45.81	0.98	46.54	0.98
	0.176	122.90		116.64	290.95	51.30	51.30	1.00	51.35	0.98	52.17	0.98
	0.176	88.57		80.44	213.28	37.61	37.61	1.00	37.64	0.98	38.24	0.98
	0.176	81.55		76.42	194.02	34.21	34.21	1.00	34.24	0.98	34.79	0.98
61.270	0.176	125.57		102.52	313.91	55.35	55.35	1.00	55.40	0.98	56.29	0.98
70.052	0.176	110.68		89.63	277.43	48.92	48.92	1.00	48.96	0.98	49.75	0.98
64.688	0.176	78.55		64.04	196.47	34.64	34.64	1.00	34.68	0.98	35.23	0.98
95.836	0.364	362.80	88.92	22.96	184.32	67.09	156.01	0.51	305.25	0.46	338.68	0.45
								1.00		1.00		1.00
								1.00		1.00		1.00
		1404.85					831.10		1026.56		1059.60	
						FOS(ini)	0.59	FOS(1)	0.73	FOS(2)	0.75	FOS(3)

26	27	28	29	30
Trial 3	**Trial 4**	**Trial 4**	**Trial 5**	**Trial 5**
(20)/(25)	**ni(θ)**	**(20)/(27)**	**ni(θ)**	**(20)/(29)**
123.45	0.86	123.38	0.86	123.37
139.48	0.86	139.40	0.86	139.39
29.18	0.98	29.19	0.98	29.19
34.25	0.98	34.26	0.98	34.26
38.36	0.98	38.37	0.98	38.37
42.52	0.98	42.54	0.98	42.54
46.64	0.98	46.65	0.98	46.65
52.28	0.98	52.30	0.98	52.30
38.32	0.98	38.34	0.98	38.34
34.86	0.98	34.87	0.98	34.88
56.41	0.98	56.42	0.98	56.43
49.85	0.98	49.87	0.98	49.87
35.30	0.98	35.32	0.98	35.32
343.68	0.45	344.41	0.45	344.52
	1.00		1.00	
	1.00		1.00	
1064.59		1065.33		1065.44
0.76	FOS(4)	0.76	FOS(5)	0.76
			F0S(F0)	0.76
			FOS	0.79

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD

Fc1-

											CALCULATION-STAGE 1	
1	2	3	4	5	6		7	8	9	10	11	12
Slice	**Slice Width**				**Pore Pressure**	**Soil Type**					**{(4)+(5)}/2**	**(2)*(10)*(11)**
	Δxi	**θi**	**h1**	**h2**	**ui**		**c'**	**ϕ'**	qi	**γ**	**hav**	**wi**
	(m)	**(deg)**	**(m)**	**(m)**	**(kN/m2)**		**(kN/m2)**	**(deg)**	(kN/m2)	**(kN/m3)**	**(m)**	**kN-per m width**
1	2.800	-12.020		2.000	8.830	1	22.80	20.000		18.840	1.000	52.752
2	2.600	-12.020	2.000	3.850	22.560	1	22.80	20.000		18.840	2.925	143.278
3	3.200	16.780	3.850	4.870	31.390	2		10.000		18.840	4.360	262.856
4	2.900	16.780	4.870	5.440	31.390	2		10.000		18.840	5.155	281.649
5	2.900	16.780	5.440	6.020	34.340	2		10.000		18.840	5.730	313.064
6	2.900	16.780	6.020	6.600	37.280	2		10.000		18.840	6.310	344.753
7	2.900	16.780	6.600	7.170	40.220	2		10.000		18.840	6.885	376.169
8	2.900	16.780	7.170	7.750	40.220	2		10.000		18.840	7.460	407.585
9	2.000	16.780	7.750	7.840	40.220	2		10.000		18.840	7.795	293.716
10	1.900	16.780	7.840	7.270	40.220	2		10.000		18.840	7.555	270.439
11	2.750	16.780	7.270	6.440	37.280	2		10.000	22.280	18.840	6.855	355.158
12	2.610	16.780	6.440	5.640	34.340	2		10.000	26.840	18.840	6.040	297.001
13	2.040	16.780	5.640	4.550	31.390	2		10.000	31.710	18.840	5.095	195.819
14	2.600	60.260	4.550		8.830	1	22.80	20.000	36.860	18.840	2.275	111.439
15												
16												

f0	1.045

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD

Fc1-

		CALCULATION										
13	14	15	16	17	18	19	20	21	22	23	24	25
								Trial 1	Trial 1	Trial 2	Trial 2	Trial 3
(9)*(2) Qi (kN-per m width)	tan ϕ	(wi+Qi) tan θi	c'Δxi	Ui= ui*Δxi	(wi+Qi -uiΔxi)	(18)*tanϕ'	(16)+(19)	ni(θ)	(20)/(21)	ni(θ)	(20)/(23)	ni(θ)
	0.364	-11.23	63.84	24.72	28.03	10.20	74.04	0.82	90.75	0.84	88.34	0.84
	0.364	-30.51	59.28	58.66	84.62	30.80	90.08	0.82	110.41	0.84	107.48	0.84
	0.176	79.26		100.45	162.41	28.64	28.64	1.01	28.38	0.99	28.79	0.99
	0.176	84.93		91.03	190.62	33.61	33.61	1.01	33.30	0.99	33.79	0.99
	0.176	94.40		99.59	213.48	37.64	37.64	1.01	37.30	0.99	37.85	0.99
	0.176	103.96		108.11	236.64	41.73	41.73	1.01	41.35	0.99	41.95	0.99
	0.176	113.43		116.64	259.53	45.76	45.76	1.01	45.35	0.99	46.01	0.99
	0.176	122.90		116.64	290.95	51.30	51.30	1.01	50.83	0.99	51.58	0.99
	0.176	88.57		80.44	213.28	37.61	37.61	1.01	37.26	0.99	37.81	0.99
	0.176	81.55		76.42	194.02	34.21	34.21	1.01	33.90	0.99	34.40	0.99
61.270	0.176	125.57		102.52	313.91	55.35	55.35	1.01	54.85	0.99	55.65	0.99
70.052	0.176	110.68		89.63	277.43	48.92	48.92	1.01	48.47	0.99	49.19	0.99
64.688	0.176	78.55		64.04	196.47	34.64	34.64	1.01	34.33	0.99	34.83	0.99
95.836	0.364	362.80	59.28	22.96	184.32	67.09	126.37	0.54	232.40	0.50	254.42	0.49
								1.00		1.00		1.00
								1.00		1.00		1.00
		1404.85					739.90		878.88		902.11	
						FOS(ini)	0.53	FOS(1)	0.63	FOS(2)	0.64	FOS(3)

26	27	28	29	30
Trial 3	**Trial 4**	**Trial 4**	**Trial 5**	**Trial 5**
(20)/(25)	**ni(θ)**	**(20)/(27)**	**ni(θ)**	**(20)/(29)**
88.02	0.84	87.97	0.84	87.97
107.09	0.84	107.03	0.84	107.02
28.85	0.99	28.86	0.99	28.86
33.86	0.99	33.87	0.99	33.87
37.92	0.99	37.94	0.99	37.94
42.04	0.99	42.05	0.99	42.05
46.11	0.99	46.12	0.99	46.12
51.69	0.99	51.70	0.99	51.70
37.89	0.99	37.90	0.99	37.90
34.47	0.99	34.48	0.99	34.48
55.77	0.99	55.78	0.99	55.78
49.28	0.99	49.30	0.99	49.30
34.90	0.99	34.91	0.99	34.92
257.77	0.49	258.28	0.49	258.35
	1.00		1.00	
	1.00		1.00	
905.66		906.20		906.28
0.64	FOS(4)	0.65	FOS(5)	0.65
			F0S(F0)	0.65
			FOS	0.67

Annex 6

SAMPLE SET OF SPREADSHEETS – MODEL BASED ON BISHOP'S METHOD FOR SLOPES STABILIZED BY SOIL NAILING

{Data correspond to Example 5 (FileName: ACAD1a)}

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD (to account for soil nails)

INPUT/OUTPUT

Slice	Slope Geometry					Nail Data				
	Slice Width Δx_i (m)	θ_i (deg)	r (m)	h1 (m)	h2 (m)	No. of Nails n	Diameter d (m)	L_e (m)	f_b	fy N/mm^2
1	1.010	49.80	26.44	0.000	1.258					
2	1.500	45.75	26.44	1.258	1.728	2.67	0.025	9.8	1	460
3	1.500	41.27	26.44	1.728	2.557	1.33	0.025	8.87	1	460
4	1.500	37.08	26.44	2.557	2.941	2.67	0.025	8.2	1	460
5	1.500	33.10	26.44	2.941	3.170	1.33	0.025	7.6	1	460
6	1.500	29.30	26.44	3.170	3.262	1.33	0.025	7.39	1	460
7	1.500	25.64	26.44	3.262	3.300	1.33	0.025	7.31	1	460
8	1.500	22.16	26.44	3.300	3.092	1.33	0.025	7.54	1	460
9	1.500	18.62	26.44	3.092	2.847	1.33	0.025	7.74	1	460
10	1.500	15.22	26.44	2.847	2.505	1.33	0.025	7.4	1	460
11	1.50	11.87	26.44	2.51	2.071					
12	1.50	8.57	26.44	2.07	1.547	1.33	0.025	8.59	1	460
13	1.50	5.30	26.44	1.55	0.936					
14	1.94	1.56	26.44	0.94	0.000					
15					0.000					
16					0.000					
					0.000					

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD (to account for soil nails)

INPUT/OUTPUT

Depth from Top (m)	Inclination α (deg)	Pore Pressure ui (kN/m2)	Soil Type	c' (kN/m2)	φ' (deg)	qi (kN/m2)	γ (kN/m3)
		0.00	1	3.00	19.60		20.00
1.49335	12	0.00	1	3.00	19.60		20.00
2.1424	12	0.00	1	3.00	19.60		20.00
2.7488	12	0.00	1	3.00	19.60		20.00
3.05545	12	0.00	1	3.00	19.60		20.00
3.21605	12	0.00	1	3.00	19.60		20.00
3.28115	12	0.00	1	3.00	19.60		20.00
3.19575	12	0.00	1	3.00	19.60		20.00
2.96925	12	0.00	1	3.00	19.60		20.00
2.6761	12	0.00	1	3.00	19.60		20.00
		0.00	1	3.00	19.60		20.00
1.8088	12	0.00	1	3.00	19.60		20.00
		0.00	1	3.00	19.60		20.00
		0.00	1	3.00	19.60		20.00
					FOS		1.68

Note:
If there is a surcharge involved for a structure with a nail arrangement the value of Q applicable should be manually inserted in the NailResistance worksheet.

CALCULATION OF PROBABILITY OF FAILURE OF A SELECTED FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD

PROBABILISTIC(First Order Second Moment)

Direct Differentiation

DATA INPUT

Probabilistic Parameters	COV		Mean		c'(kPa)			Φ'(rad)		
	c'	Φ'	c'(kPa)	Φ'(deg)	Mean	σ	V	Mean	σ	V
Soil 1	0.2	0.3	3	19.6	3.00	0.6000	0.3600	0.34	0.1026	0.0105
Soil 2					0.00	0.0000	0.0000	0.00	0.0000	0.0000
Soil 3					0.00	0.0000	0.0000	0.00	0.0000	0.0000
Soil 4					0.00	0.0000	0.0000	0.00	0.0000	0.0000
Soil 5					0.00	0.0000	0.0000	0.00	0.0000	0.0000

	Variance
u (kPa)	0

Xr	(∂F/∂Xr)	(∂F/∂Xr)^2	(∂F/∂Xr)^2*V(Xr)
c1	0.09	0.008	0.003
c2	0.00	0	0
c3	0.00	0	0
c4	0.00	0	0
c5	0.00	0	0
ϕ1	4.50	20.21	0.213
ϕ2	0.00	0	0
ϕ3	0.00	0	0
ϕ4	0.00	0	0
ϕ5	0.00	0	0
u	-0.03	1E-03	0
			0.216

F				
	V(FOS)		0.216	TAYLOR SEIRIES
	σ(FOS)		0.464	
	FOS(MLV)		1.6804	
	COV(F)		0.276	

(NORMAL DISTRIBUTION)		
RELIABILITY INDEX	1.466	
RELIABILITY	0.929	92.86 %
PROB. FAIL	0.071	7.14 %

(LOGNORMAL DISTRIBUTION)		
1+[COV(F)]^2	1.076	
RELIABILITY INDEX	1.778	
RELIABILITY	0.962	96.23 %
PROB. FAIL	0.038	3.77 %

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD (to account for soil nails)

CALCULATIONS

	INPUTS													CALCULATIO
1	2	3	4	5	6	7	8	9		10	11	12	13	14
Slice	Slice Width Δxi (m)	θi (deg)	r (m)	h1 (m)	h2 (m)	Force in Nail T_N (kN)	Inclination α (deg)	Pore Pressure ui (kN/m2)	Soil Type	c' (kN/m2)	φ' (deg)	qi (kN/m2)	γ (kN/m3)	{(5)+(6)}/2 hav (m)
1	1.0095	49.8000	26.4400		1.2584				1	3.0000	19.6000		20.0000	0.6292
2	1.5000	45.7500	26.4400	1.2584	1.7283	24.3554	12.0000		1	3.0000	19.6000		20.0000	1.4934
3	1.5000	41.2700	26.4400	1.7283	2.5565	14.5452	12.0000		1	3.0000	19.6000		20.0000	2.1424
4	1.5000	37.0800	26.4400	2.5565	2.9411	33.1747	12.0000		1	3.0000	19.6000		20.0000	2.7488
5	1.5000	33.1000	26.4400	2.9411	3.1698	16.7590	12.0000		1	3.0000	19.6000		20.0000	3.0555
6	1.5000	29.3000	26.4400	3.1698	3.2623	17.0307	12.0000		1	3.0000	19.6000		20.0000	3.2161
7	1.5000	25.6400	26.4400	3.2623	3.3000	17.1410	12.0000		1	3.0000	19.6000		20.0000	3.2812
8	1.5000	22.1600	26.4400	3.3000	3.0915	17.2817	12.0000		1	3.0000	19.6000		20.0000	3.1958
9	1.5000	18.6200	26.4400	3.0915	2.8470	16.6546	12.0000		1	3.0000	19.6000		20.0000	2.9693
10	1.5000	15.2200	26.4400	2.8470	2.5052	14.5799	12.0000		1	3.0000	19.6000		20.0000	2.6761
11	1.5000	11.8700	26.4400	2.5052	2.0707				1	3.0000	19.6000		20.0000	2.2880
12	1.5000	8.5700	26.4400	2.0707	1.5469	12.3119	12.0000		1	3.0000	19.6000		20.0000	1.8088
13	1.5000	5.3000	26.4400	1.5469	0.9359				1	3.0000	19.6000		20.0000	1.2414
14	1.9439	1.5600	26.4400	0.9359					1	3.0000	19.6000		20.0000	0.4680
15														
16														

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD (to account for soil nails)

CALCULATIONS

N-STAGE 1			CALCULATION										
15	16	17	18	19	20	21	22	23	24	25	26	27	28
(2)*(14)*(13) wi (kN-per m width)	(2)*(12) Qi (kN-per m width)	tan fi	(wi+Qi) sin θi	$T_N \cos(\alpha+\theta_i)$	(18)-(19)	c'Δxi	Ui= ui*Δxi	$T_N \sin\alpha$	(wi+Qi -uiΔxi +$T_N \sin\alpha$)	(24)*tanϕ'	(21)+(25)	Trial 1 Mi(θ)	Trial 1 (26)/(27)
12.7035		0.3561	9.7029		9.7029	3.0285			12.7035	4.5235	7.5520	0.8122	9.2984
44.8005		0.3561	32.0907	12.9964	19.0943	4.5000		5.0638	49.8643	17.7559	22.2559	0.8542	26.0560
64.2720		0.3561	42.3943	8.6987	33.6956	4.5000		3.0241	67.2961	23.9631	28.4631	0.8956	31.7811
82.4640		0.3561	49.7200	21.7296	27.9904	4.5000		6.8974	89.3614	31.8202	36.3202	0.9294	39.0788
91.6635		0.3561	50.0576	11.8297	38.2279	4.5000		3.4844	95.1479	33.8806	38.3806	0.9569	40.1081
96.4815		0.3561	47.2164	12.7946	34.4218	4.5000		3.5409	100.0224	35.6164	40.1164	0.9789	40.9812
98.4345		0.3561	42.5941	13.5733	29.0208	4.5000		3.5638	101.9983	36.3200	40.8200	0.9960	40.9843
95.8725		0.3561	36.1626	14.3001	21.8625	4.5000		3.5931	99.4656	35.4181	39.9181	1.0085	39.5827
89.0775		0.3561	28.4416	14.3324	14.1092	4.5000		3.4627	92.5402	32.9521	37.4521	1.0174	36.8132
80.2830		0.3561	21.0764	12.9653	8.1111	4.5000		3.0313	83.3143	29.6669	34.1669	1.0222	33.4238
68.6385		0.3561	14.1184		14.1184	4.5000			68.6385	24.4411	28.9411	1.0235	28.2761
54.2640		0.3561	8.0863	11.5269	-3.4406	4.5000		2.5598	56.8238	20.2340	24.7340	1.0214	24.2167
37.2420		0.3561	3.4401		3.4401	4.5000			37.2420	13.2613	17.7613	1.0159	17.4835
18.1930		0.3561	0.4953		0.4953	5.8317			18.1930	6.4782	12.3099	1.0056	12.2417
												1.0000	
												1.0000	
												1.0000	
					250.8495						409.1915		420.3256

FOS(ini)	1.6312	FOS(1)	1.6756

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD (to account for soil nails)

CALCULATIONS

						Probabilistic							
29	30	31	32	33	34	35	36	37	38	39	40	41	42
Trial 2	**Trial 2**	**Trial 3**	**Trial 3**	**Trial 4**	**Trial 4**	**Pore Pressure**	**Soil 1**			**Soil 2**			
Mi(θ)	**(26)/(29)**	**Mi(θ)**	**(26)/(31)**	**Mi(θ)**	**(26)/(33)**	**-(2)*(19)/(33) -Δxi*tanΦ'/Mi(θ)**	**(2)/(33) Δxi/Mi(θ)**	**$sec^2Φ'$**	**(24)*$sec^2Φ'$/Mi(θ)**	**Δxi/Mi(θ)**	**$sec^2Φ'$**	**4)*$sec^2Φ'$/Mi(**	**Δxi/Mi(θ)**
0.8078	9.3492	0.8074	9.3540	0.8073	9.3545	-0.445261677	1.25044006	1.1267958	17.73073786	0	0	0	0
0.8500	26.1830	0.8496	26.1951	0.8496	26.1962	-0.62869122	1.76557006	1.1267958	66.13455789	0	0	0	0
0.8918	31.9170	0.8914	31.9299	0.8914	31.9311	-0.59920639	1.68276704	1.1267958	85.06835196	0	0	0	0
0.9259	39.2259	0.9256	39.2398	0.9256	39.2412	-0.577082319	1.62063543	1.1267958	108.7900817	0	0	0	0
0.9538	40.2409	0.9535	40.2535	0.9534	40.2547	-0.560206575	1.57324284	1.1267958	112.4472652	0	0	0	0
0.9761	41.1000	0.9758	41.1112	0.9758	41.1123	-0.54738605	1.53723862	1.1267958	115.502791	0	0	0	0
0.9935	41.0876	0.9933	41.0973	0.9932	41.0983	-0.537767456	1.51022647	1.1267958	115.7148369	0	0	0	0
1.0063	39.6685	1.0061	39.6766	1.0061	39.6774	-0.530905281	1.49095524	1.1267958	111.4015665	0	0	0	0
1.0155	36.8801	1.0153	36.8864	1.0153	36.8870	-0.52606733	1.4773687	1.1267958	102.7006657	0	0	0	0
1.0207	33.4735	1.0206	33.4782	1.0206	33.4787	-0.523366851	1.46978487	1.1267958	91.98721645	0	0	0	0
1.0223	28.3090	1.0222	28.3121	1.0222	28.3124	-0.522523072	1.46741526	1.1267958	75.66147054	0	0	0	0
1.0205	24.2371	1.0204	24.2391	1.0204	24.2392	-0.523440835	1.46999264	1.1267958	62.74790646	0	0	0	0
1.0154	17.4927	1.0153	17.4936	1.0153	17.4936	-0.52607741	1.47739701	1.1267958	41.33178598	0	0	0	0
1.0054	12.2436	1.0054	12.2438	1.0054	12.2438	-0.688474971	1.93346234	1.1267958	20.38967886	0	0	0	0
1.0000		1.0000		1.0000	0.0000	0	0	0	0	0	0	0	0
1.0000		1.0000		1.0000	0.0000	0	0	0	0	0	0	0	0
1.0000		1.0000		1.0000	0.0000	0	0	0	0	0	0	0	0
	421.4082		421.5107		421.5204	-7.74	21.73		1127.61	0.00		0.00	0.00
FOS(2)	1.6799	FOS(3)	1.6803	FOS(4)	1.6804	dF/du Σ(35)/Σ(20)	dF/dc Σ(36)/Σ(20)		dF/dΦ' Σ(38)/Σ(20)	dF/dc Σ(39)/Σ(20)		dF/dΦ' Σ(41)/Σ(20)	dF/dc Σ(42)/Σ(20)
				FOS	1.6804	-0.03	0.09		4.50	0.00		0.00	0.00

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

BISHOP'S SIMPLIFIED METHOD (to account for soil nails)

CALCULATIONS

43	44	45	46	47	48	49	50
Soil 3		Soil 4			Soil 5		
$sec^2\Phi'$	4)*$sec^2\Phi'$/Mi(	$\Delta xi/Mi(\theta)$	$sec^2\Phi'$	4)*$sec^2\Phi'$/Mi(	$\Delta xi/Mi(\theta)$	$sec^2\Phi'$	(24)*$sec^2\Phi'$/Mi(θ)
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
	0.00	0.00		0.00	0.00		0.00
	dF/dΦ' Σ(44)/Σ(20)	dF/dc Σ(45)/Σ(20)		dF/dΦ' Σ(47)/Σ(20)	dF/dc Σ(48)/Σ(20)		dF/dΦ' Σ(50)/Σ(20)
	0.00	0.00		0.00	0.00		0.00

Annex 7

SAMPLE SET OF SPREADSHEETS – MODEL BASED ON JANBU'S SIMPLIFIED METHOD FOR SLOPES STABILIZED BY SOIL NAILING

{Data applicable for Example 6 (FileName: ACAD4)}

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD (to account for soil nails)

INPUT/OUTPUT

Slice	Slope Geometry				Nail Data					
	Slice Width Δxi (m)	θi (deg)	h1 (m)	h2 (m)	No. of Nails n	Diameter d (m)	L_e (m)	f_b	fy N/mm^2	Depth from Top (m)
1	2.60	60.26	0.00	4.550						
2	2.040	16.780	4.550	5.640						
3	2.610	16.780	5.640	6.440						
4	2.750	16.780	6.440	7.270						
5	1.900	16.780	7.270	7.840						
6	2.000	16.780	7.840	7.750						
7	2.900	16.780	7.750	7.170	6	0.025	2.17	1	460	7.46
8	2.900	16.780	7.170	6.600	4	0.025	3.16	1	460	6.885
9	2.900	16.780	6.600	6.020	4	0.025	3.95	1	460	6.31
10	2.900	16.780	6.020	5.440	4	0.025	4.78	1	460	5.73
11	2.900	16.780	5.440	4.870	4	0.025	5.53	1	460	5.155
12	3.200	16.780	4.870	3.850	2	0.025	6.13	1	460	4.36
13	2.600	-12.020	3.850	2.000						
14	2.800	-12.020	2.000	0.000						
15										
16										

f0	1.045

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD (to account for soil nails)

INPUT/OUTPUT

Inclination α (deg)	Pore Pressure ui (kN/m2)	Soil Type	c' (kN/m2)	ϕ' (deg)	qi (kN-per m2)	γ (kN/m3)
	8.83	1	28.50	20.00	36.86	18.84
	31.39	2	0.00	10.00	31.71	18.84
	34.34	2	0.00	10.00	26.84	18.84
	37.28	2	0.00	10.00	22.28	18.84
	40.22	2	0.00	10.00	0.00	18.84
	40.22	2	0.00	10.00	0.00	18.84
12	40.22	2	0.00	10.00	0.00	18.84
12	40.22	2	0.00	10.00	0.00	18.84
12	37.28	2	0.00	10.00	0.00	18.84
12	34.34	2	0.00	10.00	0.00	18.84
12	31.39	2	0.00	10.00	0.00	18.84
12	31.39	2	0.00	10.00	0.00	18.84
	22.56	1	28.50	20.00	0.00	18.84
	8.83	1	28.50	20.00		18.84
			FOS(4)	1.09	FOS(5)	1.09
					FOS	1.14

Note:
If there is a surcharge involved for a structure with a nail arrangement the value of Q applicable should be manually inserted in the NailResistance worksheet.

CALCULATION OF PROBABILITY OF FAILURE OF A SELECTED FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD

PROBABILISTIC(First Order Second Moment)

Direct Differentiation

DATA INPUT

Probabilistic Parameters	COV		Mean		c'(kPa)			Φ'(rad)		
	c'	Φ	c'(kPa)	Φ'(deg)	Mean	σ	V	Mean	σ	V
Soil 1	0.2	0.3	28.5	20	28.50	5.7000	32.4900	0.35	0.1047	0.0110
Soil 2	0	0.2	0	10	0.00	0.0000	0.0000	0.17	0.0349	0.0012
Soil 3	0	0	0	0	0.00	0.0000	0.0000	0.00	0.0000	0.0000
Soil 4	0	0	0	0	0.00	0.0000	0.0000	0.00	0.0000	0.0000
Soil 5	0	0	0	0	0.00	0.0000	0.0000	0.00	0.0000	0.0000

	Variance
u (kPa)	42.38

Xr	$(\partial F/\partial X_r)$	$(\partial F/\partial X_r)^2$	$(\partial F/\partial X_r)^2 * V(X_r)$
c1	0.013	2E-04	0.005
c2	0.0307	9E-04	0
c3	0	0	0
c4	0	0	0
c5	0	0	0
ϕ1	0.6915	0.478	0.005
ϕ2	2.8913	8.36	0.01
ϕ3	0	0	0
ϕ4	0	0	0
ϕ5	0	0	0
u	-0.0101	1E-04	0.004
			0.025

F0	V(FOS)			0.0253	TAYLOR SEIRIES
	σ(FOS)			0.1590	
	FOS(MLV)			1.0867	
	COV(F)			0.1463	

	f0			1.0450	
F	V(FOS)			0.0276	$=f_0^2*V(F_0)$
	σ(FOS)			0.1661	
	FOS(MLV)			1.1356	
	COV(F)			0.1463	

(NORMAL DISTRIBUTION)

RELIABILITY INDEX	0.816	
RELIABILITY	0.793	79.29 %
PROB. FAIL	0.207	20.71 %

(LOGNORMAL DISTRIBUTION)

$1+[COV(F)]^2$	1.021	
RELIABILITY INDEX	0.801	
RELIABILITY	0.789	78.85 %
PROB. FAIL	0.211	21.15 %

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD (to account for soil nails)

CALCULATIONS

	INPUTS												CALCULATION-STAGE 1	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Slice	Slice Width				Force in Nail	Inclination	Pore Pressure						{(4)+(5)}/2	(2)*(14)*(13)
	Δxi	θi	h1	h2	T_N	α	ui	Soil Type	c'	ϕ'	qi	γ	hav	wi
	(m)	(deg)	(m)	(m)	(kN)	(deg)	(kN/m2)		(kN/m2)	(deg)	(kN-per m2)	(kN/m3)	(m)	(kN-per m width)
1	2.6000	60.2600		4.5500			8.8300	1	28.5000	20.0000	36.8600	18.8400	2.2750	111.4386
2	2.0400	16.7800	4.5500	5.6400			31.3900	2		10.0000	31.7100	18.8400	5.0950	195.8192
3	2.6100	16.7800	5.6400	6.4400			34.3400	2		10.0000	26.8400	18.8400	6.0400	297.0013
4	2.7500	16.7800	6.4400	7.2700			37.2800	2		10.0000	22.2800	18.8400	6.8550	355.1576
5	1.9000	16.7800	7.2700	7.8400			40.2200	2		10.0000		18.8400	7.5550	270.4388
6	2.0000	16.7800	7.8400	7.7500			40.2200	2		10.0000		18.8400	7.7950	293.7156
7	2.9000	16.7800	7.7500	7.1700	72.5084	12.0000	40.2200	2		10.0000		18.8400	7.4600	407.5846
8	2.9000	16.7800	7.1700	6.6000	67.1473	12.0000	40.2200	2		10.0000		18.8400	6.8850	376.1689
9	2.9000	16.7800	6.6000	6.0200	79.8780	12.0000	37.2800	2		10.0000		18.8400	6.3100	344.7532
10	2.9000	16.7800	6.0200	5.4400	91.7114	12.0000	34.3400	2		10.0000		18.8400	5.7300	313.0643
11	2.9000	16.7800	5.4400	4.8700	100.4227	12.0000	31.3900	2		10.0000		18.8400	5.1550	281.6486
12	3.2000	16.7800	4.8700	3.8500	51.3077	12.0000	31.3900	2		10.0000		18.8400	4.3600	262.8557
13	2.6000	-12.0200	3.8500	2.0000			22.5600	1	28.5000	20.0000		18.8400	2.9250	143.2782
14	2.8000	-12.0200	2.0000				8.8300	1	28.5000	20.0000		18.8400	1.0000	52.7520
15														
16														

f0	1.0450

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD (to account for soil nails)

CALCULATIONS

		CALCULATION											
16	17	18	19	20	21	22	23	24	25	26	27	28	29
											Trial 1	Trial 1	Trial 2
Qi (kN-per m width)	tan fi	(wi+Qi) tan θi	$T_N \cos(\alpha+\theta_i)/\cos\theta$	(18)-(19)	c'Δxi	Ui= ui*Δxi	$T_N \sin\alpha$	(wi+Qi -uiΔxi +$T_N \sin\alpha$)	(24)*tanϕ'	(21)+(25)	ni(θ)	(26)/(27)	ni(θ)
95.8360	0.3640	362.8023		362.8023	74.1000	22.9580		184.3166	67.0858	141.1858	0.4377	322.5379	0.3961
64.6884	0.1763	78.5527		78.5527		64.0356		196.4720	34.6433	34.6433	0.9762	35.4866	0.9633
70.0524	0.1763	110.6803		110.6803		89.6274		277.4263	48.9177	48.9177	0.9762	50.1085	0.9633
61.2700	0.1763	125.5683		125.5683		102.5200		313.9076	55.3504	55.3504	0.9762	56.6978	0.9633
	0.1763	81.5473		81.5473		76.4180		194.0208	34.2111	34.2111	0.9762	35.0439	0.9633
	0.1763	88.5661		88.5661		80.4400		213.2756	37.6062	37.6062	0.9762	38.5217	0.9633
	0.1763	122.9018	66.3782	56.5237		116.6380	15.0753	306.0219	53.9599	53.9599	0.9762	55.2735	0.9633
	0.1763	113.4288	61.4703	51.9585		116.6380	13.9607	273.4916	48.2239	48.2239	0.9762	49.3979	0.9633
	0.1763	103.9558	73.1247	30.8311		108.1120	16.6076	253.2487	44.6546	44.6546	0.9762	45.7416	0.9633
	0.1763	94.4004	83.9576	10.4429		99.5860	19.0679	232.5461	41.0042	41.0042	0.9762	42.0023	0.9633
	0.1763	84.9275	91.9324	-7.0049		91.0310	20.8790	211.4966	37.2926	37.2926	0.9762	38.2004	0.9633
	0.1763	79.2607	46.9698	32.2909		100.4480	10.6675	173.0751	30.5178	30.5178	0.9762	31.2607	0.9633
	0.3640	-30.5070		-30.5070	74.1000	58.6560		84.6222	30.8000	104.9000	0.8660	121.1317	0.8857
	0.3640	-11.2320		-11.2320	79.8000	24.7240		28.0280	10.2014	90.0014	0.8660	103.9278	0.8857
											1.0000		1.0000
											1.0000		1.0000
											1.0000		1.0000
				981.0200						802.4688		#####	

FOS(ini)	0.8180	FOS(1)	1.0452	FOS(2)

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD (to account for soil nails)

CALCULATIONS

							CALULATIONS - STAGE 3						
30	31	32	33	34	35	36	37	38	39	40	41	42	43
Trial 2	**Trial 3**	**Trial 3**	**Trial 4**	**Trial 4**	**Trial 5**	**Trial 5**	**Pore Pressure**	**Soil 1**			**Soil 2**		
(26)/(29)	ni(θ)	(26)/(31)	ni(θ)	(26)/(33)	ni(θ)	(26)/(35)	-(2)*(17)/(35) -Δxi*tanΦ'/ni(θ)	(2)/(35) Δxi/ni(θ)	$sec^2Φ'$	(24)*(39)/(35) (24)*$sec^2Φ'$/ni(θ)	(2)/(35) Δxi/ni(θ)	$sec^2Φ'$	(24)*(42)/(35) (24)*$sec^2Φ'$/ni(θ)
356.4607	0.3911	361.0160	0.3904	361.6139	0.3903	361.6922	-2.4243	6.6607	1.1325	534.7380			
35.9637	0.9617	36.0218	0.9615	36.0294	0.9615	36.0303	-0.3741				2.1217	1.0311	210.6913
50.7822	0.9617	50.8642	0.9615	50.8749	0.9615	50.8763	-0.4786				2.7145	1.0311	297.5045
57.4600	0.9617	57.5528	0.9615	57.5649	0.9615	57.5664	-0.5043				2.8601	1.0311	336.6261
35.5150	0.9617	35.5724	0.9615	35.5798	0.9615	35.5808	-0.3484				1.9761	1.0311	208.0627
39.0396	0.9617	39.1026	0.9615	39.1108	0.9615	39.1119	-0.3668				2.0801	1.0311	228.7110
56.0166	0.9617	56.1071	0.9615	56.1188	0.9615	56.1203	-0.5318				3.0161	1.0311	328.1697
50.0620	0.9617	50.1428	0.9615	50.1533	0.9615	50.1547	-0.5318				3.0161	1.0311	293.2850
46.3566	0.9617	46.4315	0.9615	46.4412	0.9615	46.4424	-0.5318				3.0161	1.0311	271.5772
42.5670	0.9617	42.6358	0.9615	42.6447	0.9615	42.6459	-0.5318				3.0161	1.0311	249.3763
38.7139	0.9617	38.7765	0.9615	38.7846	0.9615	38.7857	-0.5318				3.0161	1.0311	226.8033
31.6810	0.9617	31.7322	0.9615	31.7388	0.9615	31.7397	-0.5868				3.3281	1.0311	185.6012
118.4375	0.8881	118.1224	0.8884	118.0817	0.8884	118.0764	-1.0652	2.9266	1.1325	107.8699			
101.6162	0.8881	101.3458	0.8884	101.3109	0.8884	101.3064	-1.1471	3.1517	1.1325	35.7280			
	1.0000		1.0000		1.0000								
	1.0000		1.0000		1.0000								
	1.0000		1.0000		1.0000								
1060.6721		1065.4239		1066.0477		1066.1293	-9.9548	12.7390		678.3359	30.1611		2836.4083
1.0812	FOS(3)	1.0860	FOS(4)	1.0867	FOS(5)	1.0868	dF0/du Σ(37)/Σ(20)	dF0/dc1 Σ(38)/Σ(20)		dF0/dϕ1 Σ(40)/Σ(20)	dF0/dc2 Σ(41)/Σ(20)		dF0/dϕ2 Σ(43)/Σ(20)
					F0	1.0867							
					FOS	1.1356	-0.0101	0.0130		0.6915	0.0307		2.8913

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD (to account for soil nails)

CALCULATIONS

44	45	46	47	48	49	50	51	52
Soil 3			Soil 4			Soil 5		
(2)/(35) $\Delta xi/ni(\theta)$	$sec^2\Phi'$	(24)*(45)/(35 4)*$sec^2\Phi'$/ni(	(2)/(35) $\Delta xi/ni(\theta)$	$sec^2\Phi'$	(24)*(48)/(35 4)*$sec^2\Phi'$/ni(	(2)/(35) $\Delta xi/ni(\theta)$	$sec^2\Phi'$	(24)*(51)/(35) (24)*$sec^2\Phi'$/ni(θ)
dF0/dc3 $\Sigma(44)/\Sigma(20)$		dF0/dϕ3 $\Sigma(46)/\Sigma(20)$	dF0/dc4 $\Sigma(47)/\Sigma(20)$		dF0/dϕ4 $\Sigma(49)/\Sigma(20)$	dF0/dc5 $\Sigma(50)/\Sigma(20)$		dF0/dϕ5 $\Sigma(52)/\Sigma(20)$
0.0000		0.0000	0.0000		0.0000	0.0000		0.0000

CALCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

CA

JANBU'S SIMPLIFIED METHOD (to account for soil nails)

CALCULATION OF NAIL FORCE

	Nail Data									Manual			
	No.of Nails n	Diameter d (m)	Lc (m)	fb	fy N/mm^2	Depth from Top z (m)	Inclination α (deg)	c' (kN/m2)	φ (deg)	Qi (kN-per m width)	γ (kN/m3)	ko	σv = (q+γz) kN/m^2
1								28.50	20.00		18.84	0.6580	
2									10.00		18.84	0.8264	
3									10.00		18.84	0.8264	
4									10.00		18.84	0.8264	
5									10.00		18.84	0.8264	
6									10.00		18.84	0.8264	
7	6	0.025	2.17	1	460	7.46	12	28.50	20.00		18.84	0.6580	140.55
8	4	0.025	3.16	1	460	6.885	12	28.50	20.00		18.84	0.6580	129.71
9	4	0.025	3.95	1	460	6.31	12	28.50	20.00		18.84	0.6580	118.88
10	4	0.025	4.78	1	460	5.73	12	28.50	20.00		18.84	0.6580	107.95
11	4	0.025	5.53	1	460	5.155	12	28.50	20.00		18.84	0.6580	97.12
12	2	0.025	6.13	1	460	4.36	12	28.50	20.00		18.84	0.6580	82.14
13								28.50	20.00		18.84	0.6580	
14								28.50	20.00		18.84	0.6580	
15												1.0000	
16												1.0000	
												1.0000	
								Manual Insertion	Manual Insertion	Manual Insertion			

LCULATION OF FACTOR OF SAFETY OF A TRIAL FAILURE SURFACE

JANBU'S SIMPLIFIED METHOD (to account for soil nails)

CALCULATION OF NAIL FORCE

σH kN/m^2	σ = 0.5 *(σv+σH) kN/m^2	area m^2	Nail Capacity Pullout kN	Strength kN	Capacity kN
92.48	116.51	0.0004909	72.508	1354.812	72.508
85.35	107.53	0.0004909	67.147	903.208	67.147
78.22	98.55	0.0004909	79.878	903.208	79.878
71.03	89.49	0.0004909	91.711	903.208	91.711
63.90	80.51	0.0004909	100.423	903.208	100.423
54.05	68.10	0.0004909	51.308	451.604	51.308

Annex 8

ADDITIONAL DETAILS OF THE STABILIZED WATAWALA LANDSLIDE

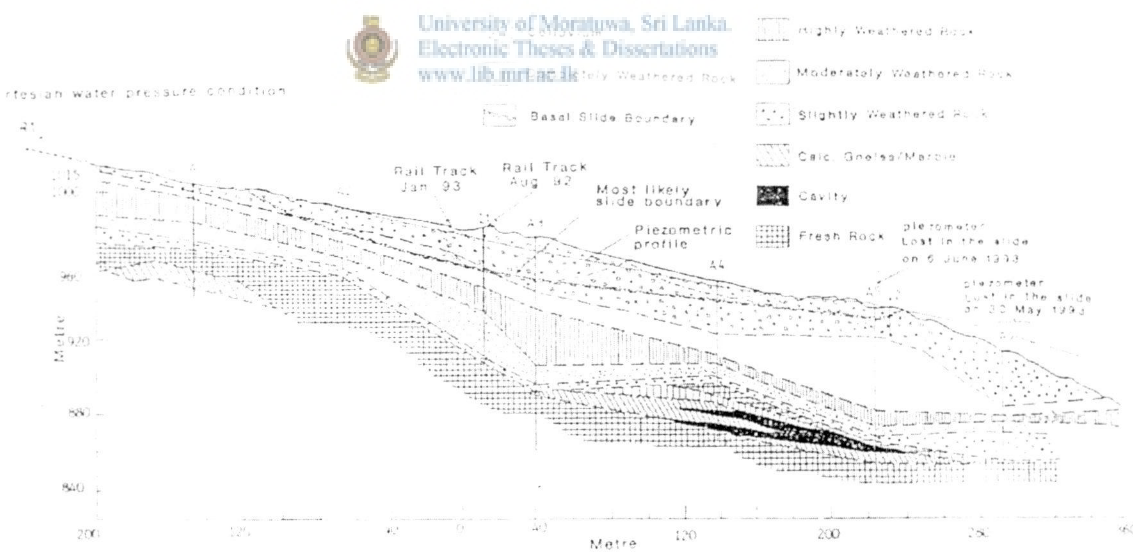

Figure A8.1: Subsurface Profile of the Watawala Slope (Rajaratnam and Bhandari, 1994)

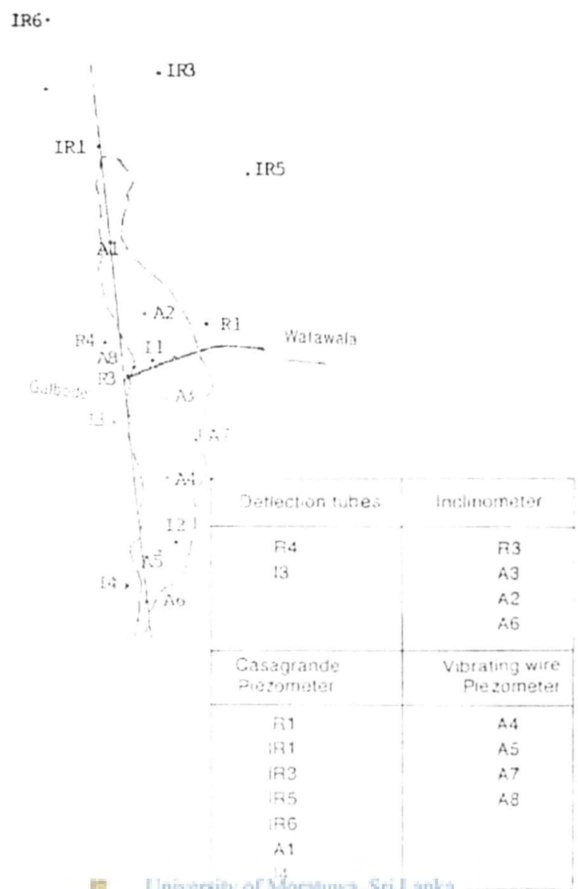

Figure A8.2: Location of Instruments at Watawala Landslide

(Rajaratnam and Bhandari, 1994)

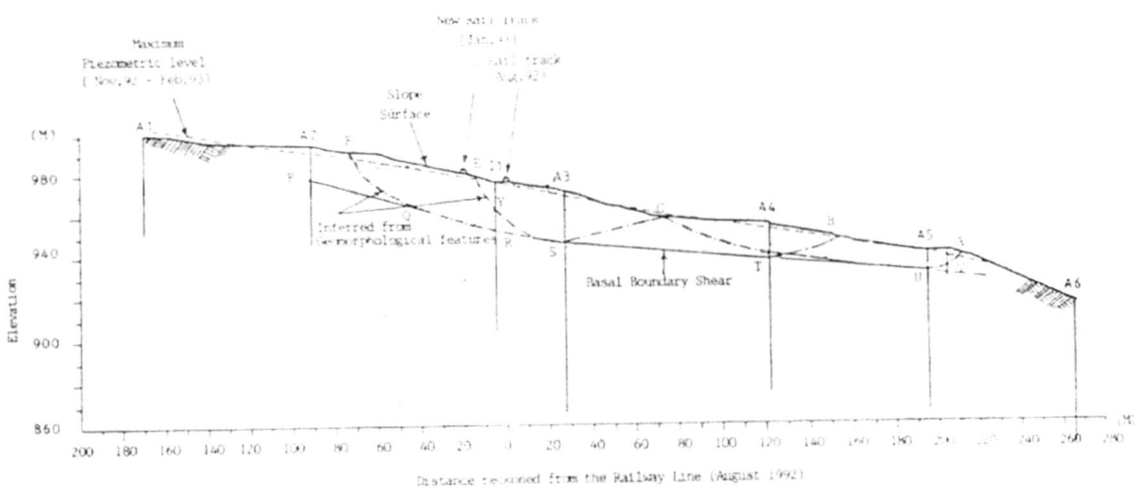

Figure A8.3: Identified Failure Surfaces at Watawala Landslide

(Rajaratnam and Bhandari, 1994)

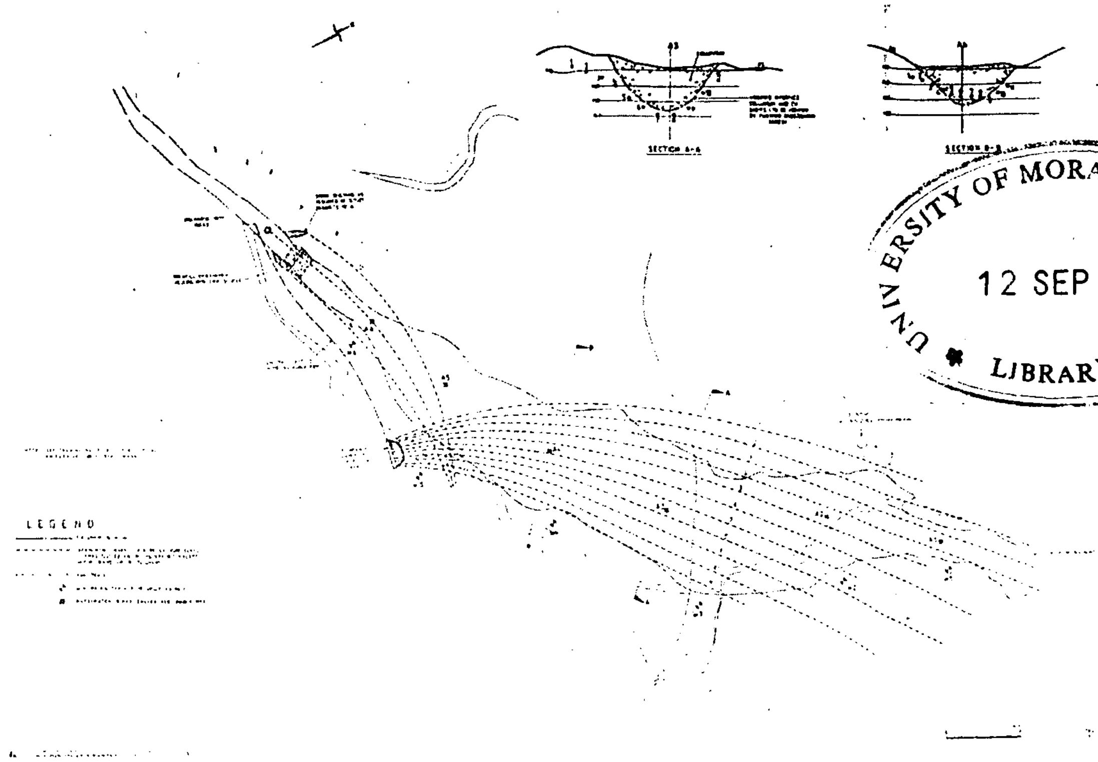

Figure A8.4: Plan View of the Directional Drains

(Rehabilitated Watawala Landslide)

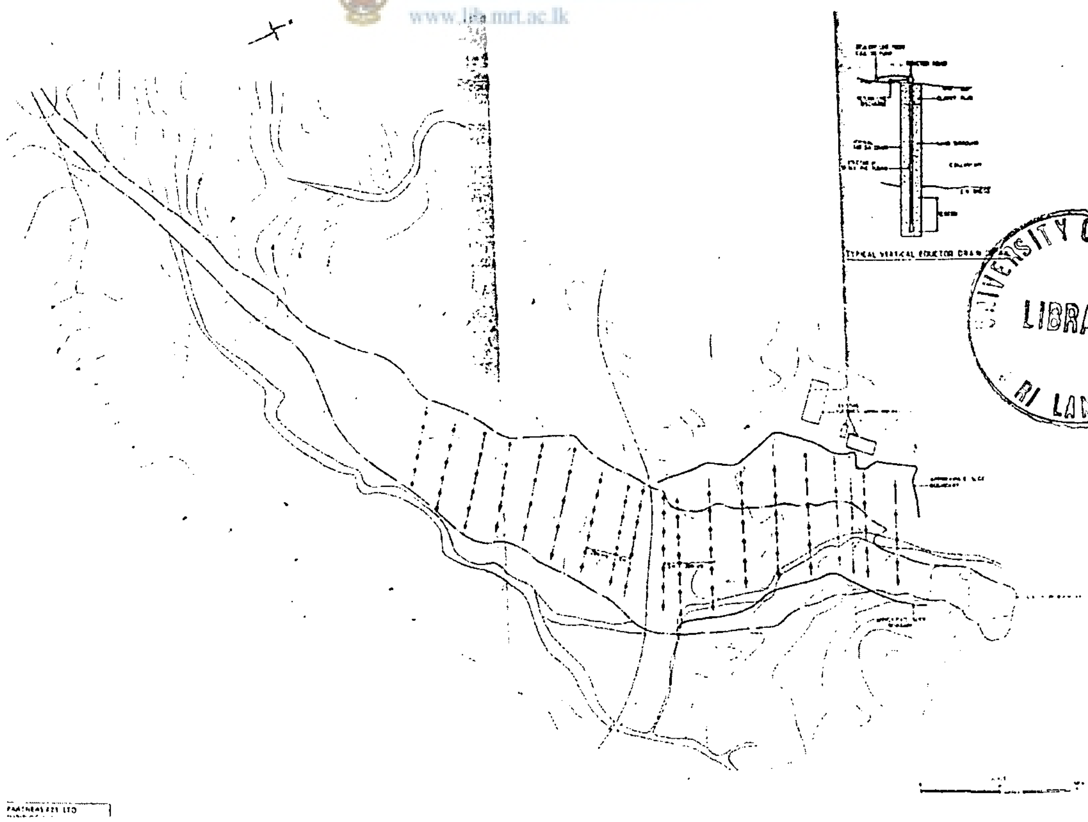

Figure A8.5: Plan View of the Installations of Eductor Drains

(Rehabilitated Watawala Landslide)