QUANTIFYING THE ROLE OF VEGETATION IN SLOPE STABILITY

A Project Report

Submitted by

K.VENKATA SAMBASIVARAO

In Partial fulfilment of the requirements

for the award of the Degree of

MASTER OF TECHNOLOGY

In

GEOTECHNICAL ENGINEERING

DEPARTMENT OF CIVIL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

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DEPARMENT OF CIVIL ENGINEERING

NATIONAL INSTITUTE OFTECHNOLOGY, ROURKELA

ORISSA, INDIA -769008

CERTIFICATE

*This is to affirm that the thesis entitled, **"Quantifying the role of vegetation in slope stability"** submitted by **K.Venkata sambasivarao** in partial fulfilment of the requirements for the award of **Master of Technology** Degree in **Civil Engineering** with specialization in "Geotechnical Engineering" at **National Institute of Technology**, **Rourkela**, is an authentic work carried out by him under my supervision and guidance.*

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

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Date:

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I am greatly indebted to my parents for their encouragement and endless support that helped me at every step of life. Their blessings and wishes have enabled me to complete my work successfully.

K.Venkata sambasivarao

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ABSTRACT

Soil erosion and landslides are the two great concerns to the land managers in the world. The presence of root system in the soil plays good role in increasing the stability of the slope .The hydrological and geo mechanical effects due to the vegetation increase the stability of the slope. The hydrological effect due to the vegetation is related to the soil suction regime and the geo mechanical effect is related to the reinforcement provided by the root network in soil. In this project, the mechanical effect of vegetation on the slope stability is calculated. The finite element package PLAXIS 3D version 2013 is used for stability analysis of the slope. This study also highlights the use of reliability analysis in slope stability. Reliability analysis is performed on the slope which is covered with vegetation. The limit state function is developed by using the linear response surface model. The two level full factorial design is used for the design of experiments (DoE). The reliability index (β) is calculated by using the first order reliability method. The standard USACE chart is used to calculate the probability of failure (P_f) of the slope.

Chapter 1

Introduction

1.1 Introduction

Soil Erosion and loss of soil mass from the land (landslides) are the two great concerns to the Land managers in the world. The root system in the soil plays a good role in increasing the stability of the slopes which may be artificial or natural slopes. The following are the two main effects responsible for the increase in stability of slopes which are covered with vegetation. Those are hydrological and mechanical effects. The geo-mechanical effect is related to the reinforcement that is provided by the root system and the soil hydrological effect is related to the soil suction (capillary) regime which is effected by the root water uptake. The mentioned two effects are very much interrelated. The root distribution in the soil is effected by the climatic regions and the soil-hydrological properties, particularly in the regions where the plant-growth occurs in water-limited conditions and the mechanical strength parameters of the root-soil network is effected by the strength of the single root, strength of the soil, root distribution in the soil and the strength at the interface of the soil and the root. In this project, the methodology is developed for quantifying the effect of vegetation on the slope stability and also the reliability analysis is performed for the slope which is covered with the vegetation.

Why Reliability?

In geotechnical engineering the uncertainties are unavoidable. The properties of soil at a given location diffuse within significant range. The properties of soil which are obtained from the laboratory testing or field vary depending on the borehole methods, borehole location and the number of boreholes etc.. Laboratory testing method, sampling methods(disturbed or undisturbed) ,instrumental error and human error are also considered as uncertainty related to the performance of the structure. Furthermore in some cases however the probability of failure (P_f) of the structure is high but as per deterministic analysis the structure shows the high safety factor value. In general, uncertainties associated with the root zone of the vegetation are incremental cohesion in the soil due to vegetation, modulus of elasticity and tensile strength of the root. These uncertainties in the parameters significantly affect the safety factor of the slope.

Reliability:

Generally, Reliability of the system shows the relation between the loads, the system must and should carry and its ability to carry the loads. The term reliability index is used to express the reliability of the system. The standard graph USACE is used to calculate the probability of failure of the system. Reliability and the risk both are complementary terms. Risk indicating the unsatisfactory performance of the system where as reliability indicating the satisfactory performance of the system.

1.2 Organization of the thesis

Chapter 1 describes the brief introduction of the project. The literature corresponding to the vegetation effect on slope stability, reliability analysis, finite element analysis (PLAXIS 3D) is described in the Chapter 2. The design methodology for the quantifying the effect of vetiver roots on the slope stability is also described in this Chapter.

Chapter 3 describes the Equivalent cohesion approach which is used for determining the effect of vegetation on slope stability. As per this approach, the incremental cohesion values are assigned to the root zone. The entire modeling of slope is done by using the PLAXIS 3D software. The use of Reliability analysis also described in this chapter. The variables considered for the reliability analysis are cohesion, incremental cohesion and angle of internal friction. By using the First Order Reliability Method (FORM) Reliability index and the probability of failure of the developed model is calculated.

In Chapter 4, the effect of vegetation on slope stability is calculated by using the Root as pile approach. As per this approach, entire root zone is considered as pile and the root properties such as Young's modulus (E) and Root tensile strength values are assigned to this pile. The Reliability analysis also performed on the developed model (by using root as pile approach).The variables considered for the analysis are Young's modulus of root, cohesion, angle of internal friction and R_{inter}. The probability of failure *(P_f)* for the developed model is calculated by using the First order reliability method.

In Chapter 5, the effect of inclined pile on slope stability is analyzed by using Finite element method. The percentage increase in the factor of safety under steady seepage condition due to the vegetation is also described in this chapter.

Chapter 6 describes the conclusion made from the above all studies. The general layout and different approaches used in this thesis for quantifying the effect of vetiver root on slope stability in each (Chapter 3 to chapter 5) is shown in the flow diagram (Fig 1.1).

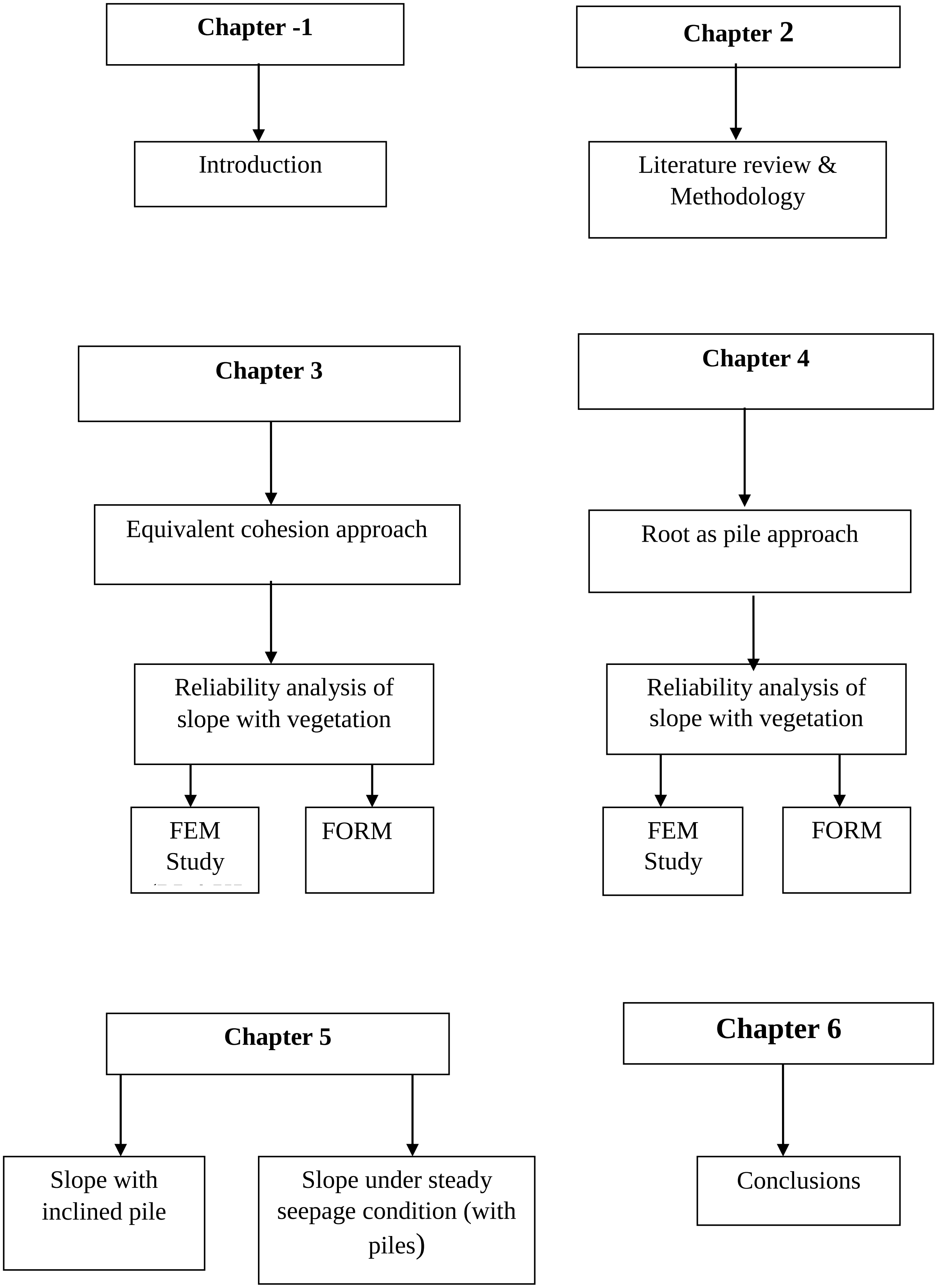


Fig 1.1 Flow diagram showing the organization of the thesis

Chapter 2

Literature Review and Methodology

2.1.1 Literature review on slope stability analysis with vegetation

Soil erosion and Landslides are the two natural phenomena which lead to cause the economical and human loss. Many of the researchers developed different methods to quantify the effect of the vegetation on the slope stability.

Zhou et.al (1998) studied on the effect of lateral roots of ***pine forest*** on shallow soil .This study reveals that the lateral roots of the ***pine forest*** produce excellent tractive resistance in the upper region of the soil i.e. 60cm below the surface of the soil. From this study it is also observed that the tensile strength of the upper soil is increased by minimum of 5.7 kPa.

Comino et.al (2001) conducted the laboratory experiments in order to know the root reinforcement effect on the shear strength of the soil. From this study, it is observed that shear strength of soil is increased very effectively at 10 cm depth from the surface of the soil due to the presence of the root network.

Pollen et.al (2004) studied on the hydrological effects of the riparian root system on stream bank stability. From this study it is observed that the hydrological reinforcement to the soil is due to the increased in matric suction which is not constant throughout the year. The increased in shear strength is due to the increased in the apparent cohesion in the root zone. It is observed that due to the hydrological effects of riparian roots the apparent cohesion in the vegetated columns varied from 0.95-3.2 kPa at 30 cm and 0.54-5.2 kPa at 70 cm.

Pollen et.al (2005) studied on ‘The geo- mechanical effects of riparian roots on stream bank stability’. Fiber bundle approach is used in this study to model the tensile strength of riparian vegetation. From this study, it is observed that the tensile strength of the root is decreased non-linearly with the increase in diameter of the root species tested and force required for breaking the root linearly increases with diameter of the root.

P.Lac et.al (2006) developed the finite element model to analyze the effect of 3-dimensional spatial distribution of trees on the hill slope. By using geometric patterns (cylindrical, cone and sphere), different types of root zones are modelled according to their root system structure. The finite element software ABAQUS is used to analyze the effect of forest structure on the hill slopes.

Schwarza et.al (2009**)** used WU model and FBM for determining the role of the grass species on the slope stability. Results of the experiments shows that lateral roots influence the stability of the slope up to certain area and the stabilizing effect magnitude depends on the distribution of the root in the soil, soil mechanical properties and inclination of the root.

Naghdi Ramin et.al (2012**)** studied the biotechnical characteristics of root system of the ***Alder***. The biotechnical characteristics considered for this study are root area ratio and the tensile strength of the root. The results of this investigation shows that the root area ratio decreases with depth and its maximum value is observed at depth of 10 cm below the top of the soil surface and they also reported that the mean tensile strength of root is equal to the 16.29 MPa and this value decreases with increase in the diameter of the root.

2.1.2 Literature review on Reliability analysis:

. In geotechnical engineering, the Reliability analysis is developed over the years and some of the developed studies are presented as follows .Fardis et.al (1981) considers the uncertainties caused by stress non-uniformity and the effect of sample preparation in shear test. Based on the statistical analysis of liquefaction of sand, probabilistic model is developed. For the progressive failure of the slopes, Chowdhury et.al (1982) developed the probabilistic model. For the calculation of P_L (probability of the liquefaction index) based on the standard penetration test value Hwang et.al (1991) considers the uncertainties in both seismic parameters and the site parameters. The parameter P_L indicates the severity of the liquefaction. Low et.al (1997) explained the calculation procedure for the reliability index (Hasofer-Lind second moment) using the Excel sheet. By using co-related normal random variable data, Low (2005) analyzed the Retaining wall problem against the sliding and overturning effect. Basha and Babu (2008) used the target Reliability approach for the analysis of the sheet pile wall problem. Babu et.al (2010) performed the Reliability analysis on earthen dam by using FDM. Subramanian (2011) performed the Reliability analysis on the foundation, slope and retaining wall by using Finite element software (PLAXIS). Nagendhra (2014) also performed the Reliability analysis on the foundation reinforced with geocell, stone column and dam embankment using FEM.

2.2 Objective and Scope:

The main objective of this study is numerical analysis of the slope with vegetation and the scope of this study includes the deterministic and reliability analysis of the slope with and without vegetation by using the finite element package PLAXIS 3D

2.3. METHODOLOGY

2.3.1 Present Methodology for quantifying the effect of vetiver root on the stability of the slope:

Many different solutions techniques are developed over the years to determine the effect of vegetation on the stability of the slope. In this project, the effect of the vetiver root on the slope stability is quantified by using the following two approaches.

1. Equivalent cohesion approach
2. Root as pile approach

2.3.1.1 Equivalent cohesion criteria:

As per this criteria the entire root zone is considered as single block and to this block the increased shear strength parameters are assigned. Many of the investigation results show that the increase in shear strength in the root zone area is mainly due to the increase in the cohesion value of the soil in the root zone. Mathematically, the increase in the cohesion in the root zone is expressed as follows.

$$C_r = \ t_r(\cos\theta\tan\emptyset + \sin\theta)$$

Where

C_r = increase in cohesion value in the root zone

t_r = average tensile strength of the considered roots per unit area of the soil.

Φ = angle of internal friction of the soil.

The incremental cohesion in the root zone mainly depends on the root and soil properties. Generally for the Vetiver roots the additional cohesion in the root zone varies from 15- 20 Kilo

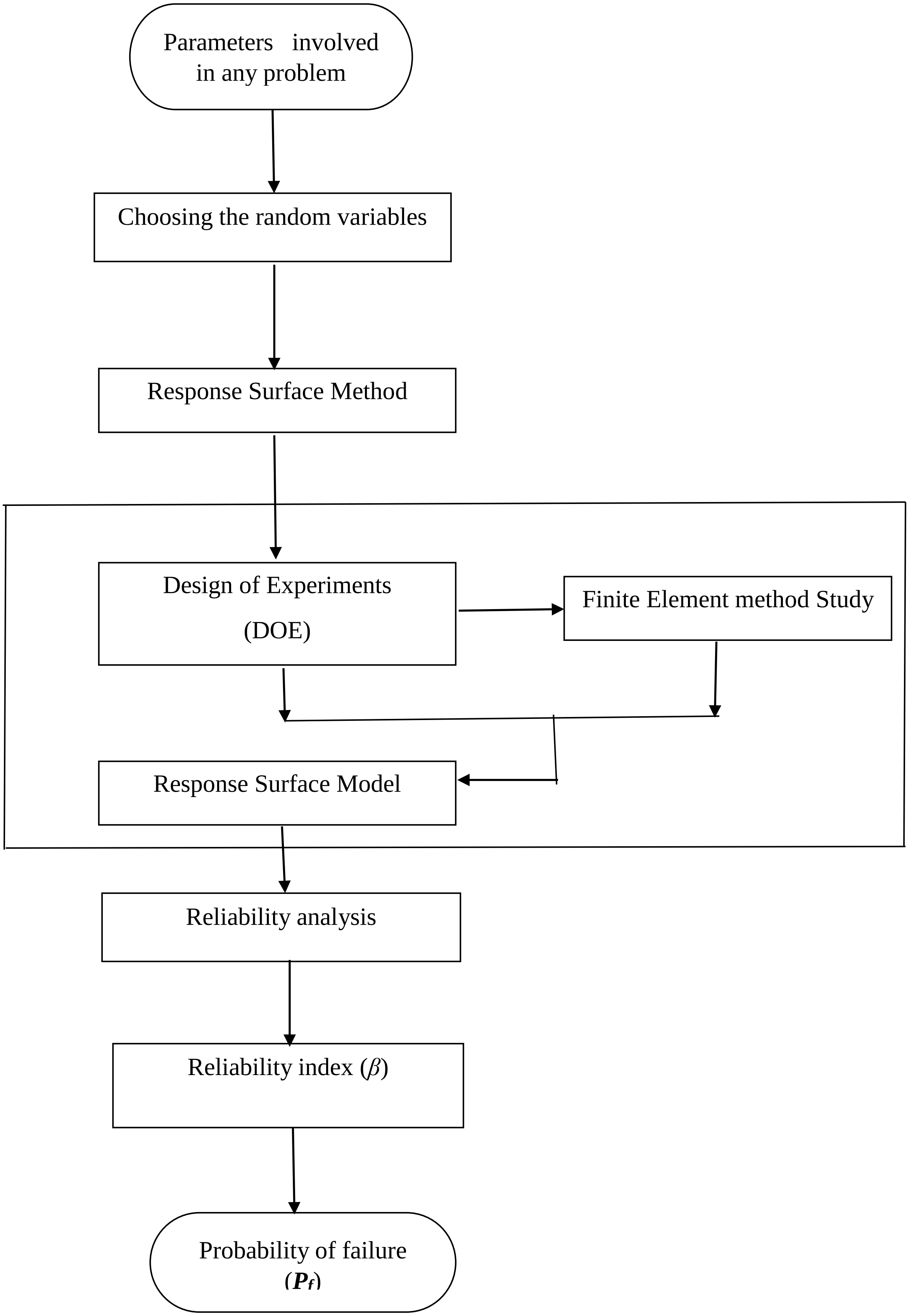
Pascal. Finally, the whole slope is assumed to be consisting of two parts; surrounding soil whose soil properties are not disturbed by the vegetation columns and the root reinforced soil Zone.

2.3.1.2 Root as pile criteria:

In this approach, the entire root zone is considered as a single pile and to this pile the root properties such as modulus of elasticity and tensile strength of the roots are assigned. Generally the modulus of elasticity of Vetiver root is about 2.6 Giga Pascal and the tensile strength of this root is varying from 45-145 Mega Pascal (average 75 MPa). The diameter of the Vetiver is generally varying from the 0.2-2mm.

2.3.2 Methodology for the Reliability analysis:

The different parameters involved in a problem are studied. The random variables from the parameters are selected in such way that the selected parameters effects the output value. Then the experimental design (DOE) is developed by using the full factorial design. For each set of the input variables the output parameter is calculated. The PLAXIS 3D software is used for the calculation of the output parameter. By using the selected input and corresponding output data the linear surface model is developed. The First order Reliability method (FORM) is followed in order to calculate the Reliability index (β). The Reliability index value (β) is optimized by using MS-Excel solver tool. From the Reliability index value, the probability of failure (P_f) of the developed model is calculated by using Excel sheet. Fig 2.1 shows the procedure followed for the calculation of the Reliability index.



2.1 Flow chart for the reliability analysis

2.3.2 PLAXIS

PLAXIS is a finite element software which is used to model and analyze the complex problems that are commonly encountered in Geotechnical Engineering. As per Burd (1999), this finite element package was initially launched by the Pieter Vermeer in 1974 for solving the Cone penetration problem. The name PLAXIS is derived from the Plasticity and Axis symmetry. This software also allows the modelling of soil –structure interaction problems which are very difficult analyze mathematically. By using this software total displacement, displacement in different direction, pore water pressure, total and effective stresses can be calculated. In this project PLAXIS 3D is used for quantifying the effect of the Vetiver grass on stability of slope.

Constitutive models used in the PLAXIS

PLAXIS 3D software allows the modelling of behavior of different types of soil by using different available models. Some of the important models are discussed below:

1. Mohr – Coulomb model
2. Linear Elastic model.
3. Hardening soil model
4. Soft soil model

Mohr-Coulomb model:

This one is an example for the linear elastic and perfectly plastic model. This model is a first order model. This model assigns the average stiffness to the entire soil .Due to this effect, time taken for calculation is undergo relatively fast when compared to the other models. Mohr –Coulomb model engages with the following parameters; Young's modulus (E), Poisson's ratio (ν), Angle of internal friction (Φ), Cohesion (c) and Dilatancy angle (Ψ).

Linear elastic model:

This model obeys the Hook's law i.e. within proportionality stresses in the soil are directly proportional to the strain in the soil. Generally this type of model is used for the stiff structures in the soil. This model engages with the two parameter; Poisson's ratio (ν) and Modulus of Elasticity (E).

Hardening soil model:

This type of model showing the behavior of elasto-plastic type of hyperbolic. Hardening soil model is an example for the Second order model. This model is generally used to model the behavior of gravel and sands as well as for the soft soils such as silts and clays.

Soft soil model:

Soft soil model is generally used to simulate the soft soil behavior such as peat and NCC.

Mesh generation

In 3D finite element mesh, the soil elements are 10- nodded tetrahedron elements. Figure 2.2 shows the ten nodded tetrahedron element.

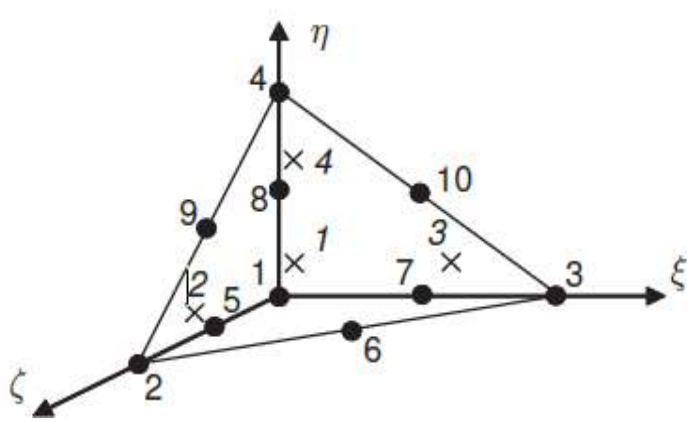


Fig 2.2 : 10-node tetrahedron element

To simulate the structural behavior special types of elements are used in this software. For soil-structure interaction problems, 12- noded interface elements are used. To simulate the geogrid and plate 6- noded tetrahedron elements are used. This software allows the choosing of different sizes of the mesh such as very coarse,coarse,medium,fine and very fine.The calculation time increases with the decrease of the size of the mesh but the greater accuracy can be achieved with the very fine mesh when compared to the other types of mesh.Local refinement makes the mesh to be more finer and it is generally used in places where large deformation and higher stress concentration are expected.

Model simulation

In the present work PLAXIS 3D version 2013 is used to simulate the effect of the vetiver grass on the stability of slope.

Strength reduction technique

In slope stability analysis , the initial stresses are generated by using the gravity loading method. The initial stresses are developed due to the self-weight of the soil/strucure and generated pore water pressure.The K_0 procedure is used for the models if their ground surface is horizontal in position. The earth pressure coefficient at rest can be calculated by using the Jaky's formula .

$$K_0 = 1 - \sin \emptyset'$$

Where ø' = Effective angle of internal friction of soil.

In PLAXIS 3D, the safety factor of the slope is calculated by using the phi-c reduction method. The parameters cohesion (c) and the angle of internal friction (ø) of the soil are reduced until the slope becomes unstable. The parameters Poisson's ratio (ν) and the Modulus of Elasticity (E) has no influence on the safety factor (M_{sf}).

$$safety\ factor = \frac{Resisting\ force}{Driving\ force}$$

2.3.3 Response Surface Method

Box and Wilson developed the Respose surface Method in 1951. RSM is collection of mathematical and statistical techniques which are helpful for the empirical model building. The main objective of this methdology is to optimize the output variable(response) which is influenced by the diffrerent input variables(independent variables). This method consists of Response surface analysis and the Design of Experiments(DoE) . In DoE , the data which mainly influences the output response are selected. The number of tests are conducted in such way that , the changes are made in the independent variables (input data) in order to know the causes for the changes in the response (output variable). The main objective of the Response surface analysis is to interpolate the available data to predict the correlation between the independent variables (input data) and response(output variable). If the given data follows the flat/linear surface, then the first order model is sufficient for the analysis.The following equation shows that the response y in experiment with the two parametrs x_1 and x_2

$$y = \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_{12} x_1 x_2 + \epsilon$$

In the above equation ϵ indicates error due to the uncontrolled factors in the experiment and the terms $\alpha_1 x_1$ and $\alpha_2 x_2$ are showing major effect on the output response. Figure 2.3 shows the linear response surface with the two controlled input parametrs $x_1$and x_2.

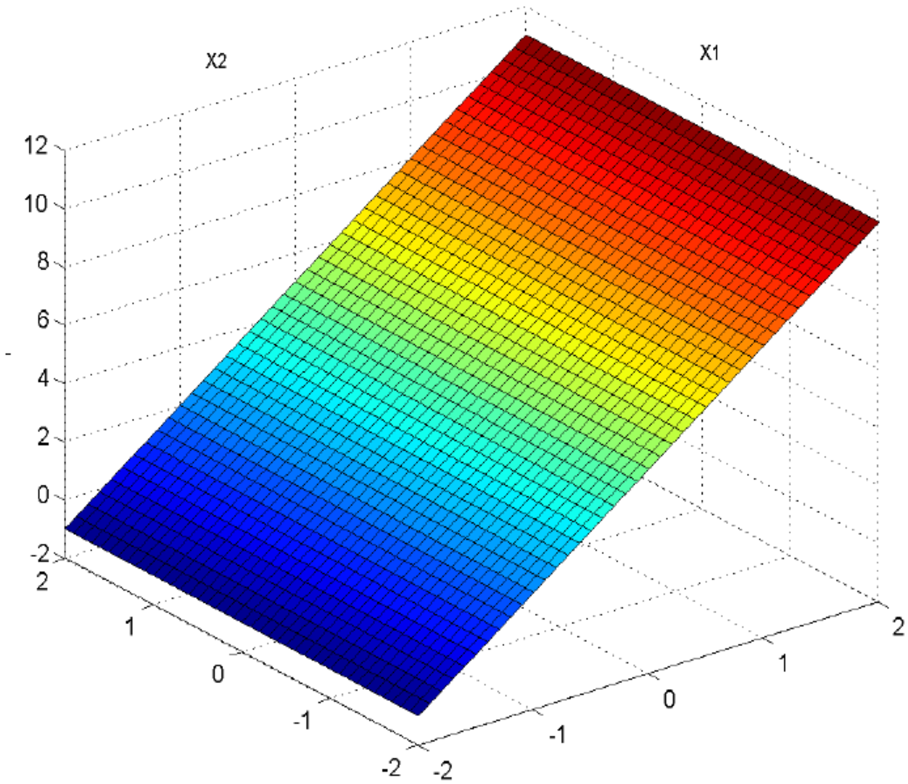


Fig 2.3 Linear Respnse surface

If the input data follows the curvature , higher order model are generally used. Figure 2.4 shows the Non- Linear Resonse surface. The following equation indicating generalized polynomial model with number of input varibles.

$$y = \alpha_0 + \sum_{j=1}^{k} \alpha_j x_j + \sum_{j=1}^{k} \alpha_{jj} x_j^2 + \sum_{i<j} \sum_{=2}^{k} \alpha_{ij} x_i x_j + \varepsilon$$

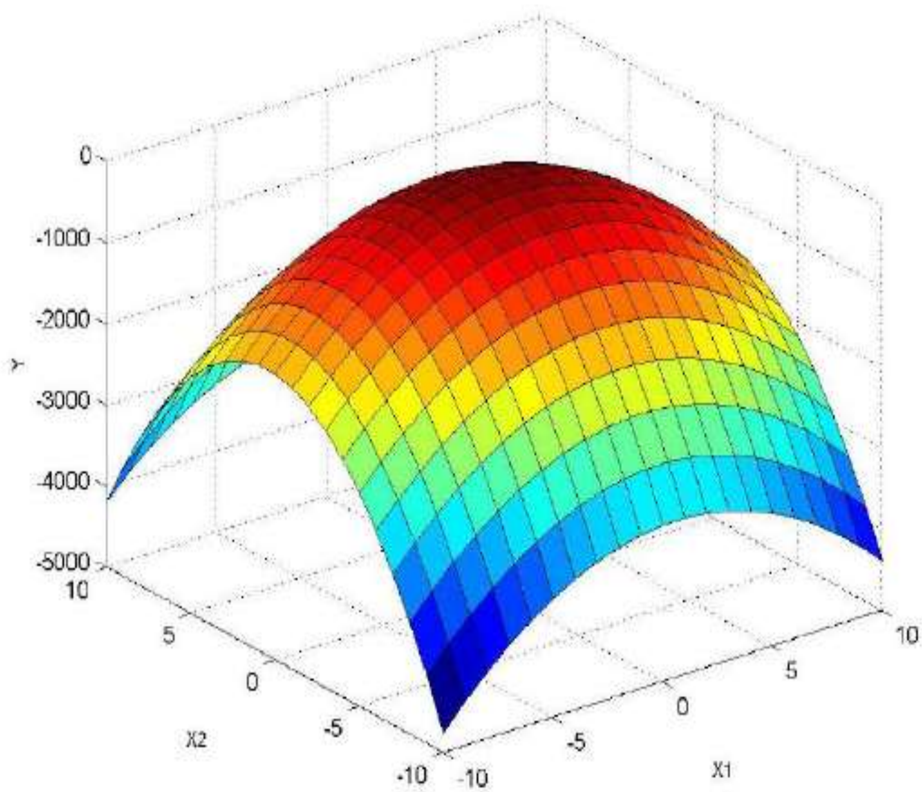


Fig 2.4 Non – Linear Response surface

Design of Experiment (DoE) **:**

Factorial Design- It is a type of experimental tactic in which different design (input) variables are varied together. The important type of factorial design is two-level factor in which each factor having only two levels. For example 2^k indicates , k number of factors having the only two values. The number of experiments to be performed in order to know the design varibles. This two-level factorial design also used to fit the Linear surface model.

Two – level full factorial design :

The two level factor is an example for the simplest factorial design. The MATLAB code used for the Design of Experiment is as follows.

dFF2 = ff2n(n)

The result of dFF2 gives the matrix with R –number of rows and C- number of coloumns. Each row in matrix indicates the single treatement in an experiment and the each coloumn indicates the single design varible with two values which are in binary system are 0 and 1. For example if the number of parametrs involved in a problem is four , then by using Matlab code an experiment is designed as follows.

```
>> dFF2 = ff2n(4)

     0     0     0     0
     0     0     0     1
     0     0     1     0
     0     0     1     1
     0     0     0     0
     0     0     0     1
     0     0     1     0
     0     0     1     1
     1     0     0     0
     1     0     0     1
     1     0     1     0
     1     0     1     1
     1     0     0     0
     1     0     0     1
     1     0     1     0
     1     0     1     1
```

In this experimental design sixteen data sets are generated by using the MATLAB code. The values 0 and 1 are calculated by using $\mu + 1.65\sigma$ and $\mu - 1.65\sigma$ where σ indicates the standard deviation and μ indicates the mean value of the design variable. The Z value 1.65 is related to the 90 % probability analysis. By using the sixteen data set point Linear surface model or Non-Linear surface model are developed by using the MS-Excel sheet.

2.3.4 Reliability analysis :

Reliability : Reliability of the geo-technical structure is defined as the probability that the structure will not attain the specified limit (permissible value) during the specified time.

Methods of Reliability :

1.FORM - First Order Reliability Method

2. SORM – Second Order Reliability Method

3. MCS – Monte Carlo Sampling

4. NI – Nimerical Integration

5. IVS – Increased Variance Sampling .

In this project, First Order Reliability Method is used for calculation of the probability of the failure (P_f) of the system.

Terminology :

Mean (μ) : Mean is defined as the average value for the given data set. It is also termed as the first central moment.

Variance (σ^2) : Variance detemines the spread in the data about the expected (mean) value of the sample. It is also termed as the second central moment.

Coefficent of Variation (CoV): It is defined as the ratio of standard devation to the mean . Generally , CoV indicates the dispersion of data . Higher Cov indicates higher dispersion about the mean value of the sample.

Covarience : It measures the linear relationship between any two selected random variables. Covarience of the given two random variables x and y is calculated as follows.

$$Cov\,(x, y) = E[\,(x - \mu_x)(y - \mu_y)$$

$$= E[\,xy - \mu_x\mu_y]$$

$$= E(xy) - E(x)E(y)$$

Correlation coefficent : If the parametrs involved in the given problem is more than one variable then , in that case the uncertainites in any one of the variable may be associated with uncertainites in another varible. The relation coefficent between the two varibles is calculated by using the correlation coefficent (p_{xy}) . It is defined as the ratio of covarience of the given two random variables x and y to the product of standard devations of x and y.

$$Correlation\ coefficent\,(p_{xy}) = \frac{Cov\,(x\,,y)}{\sigma_x\sigma_y}$$

The p_{xy} values are ranges from -1 to +1 and higher the p_{xy} value indicates the higher the correlation between the variables.

Continuous random variable : The random variable X is said to be an continuous random variable if it takes the all the values in between the given interval. The probability distribution curve for this kind of random variable follows the density curve. This kind of random variable may follow the log normal distribution or normal distribution.

properties for the Normal distribution curve :

1. The Parameters in the probability density function varies from $-\infty$ to $+\infty$.
2. Normal distribution is exactly symmetrical about the Expectation (mean)
3. The values mode ,mean and meridian all these three having the same value.

The probability density function for the Normal distribution is as follows:

$$f_x(x) = \frac{1}{\sigma_{x\sqrt{2\pi}}} \exp\left[-\frac{1}{2}\left(\frac{x-\mu_x}{\sigma_x}\right)^2\right] \quad -\infty \le x + \infty \ .$$

Reliability of the structure is generally taken as the probability of success which is equal to the *1-* P_f .Where P_f is the probability of failure of the structure. For example, any structure undergoes failure when the loads (Q) on it exceeds the resistance (R).For this structure, the probability of failure is calculated as follows.

$$p_f = P[R \le Q] = P[(R - Q) \le 0]$$

Figure 2.5 shows the overlapped area which is indicating the probability of failure for the considered random variables R and Q.

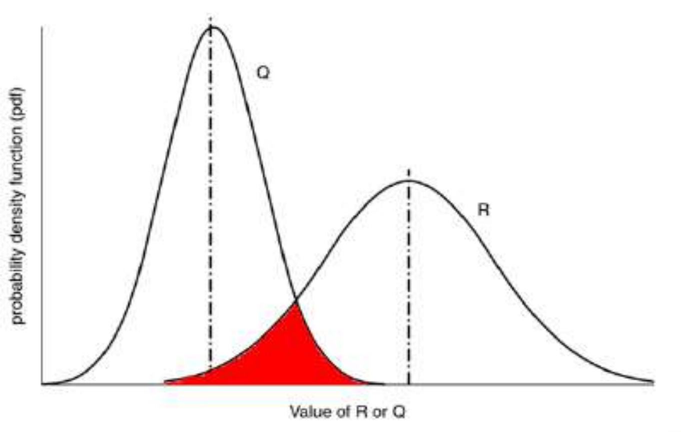


Fig 2.5 : overlapped area for the random variables Q and R

Figure 2.5 shows the probability density functions of load and resistance. If $F_Q(q)$ is the PDF of the load and the $F_R(r)$ is the CDF(cumulative disrtibution function) of the resistance ,then the overlapped area in the Figure 2.5 indicates the probability of failure (P_f) which is mathmatically described as follows.

$$p_f = \int_{-\infty}^{+\infty} F_R(q) F_Q(q) dq$$

Therefore Reliability of the structure is expressed as follows .

$$R_o = 1 - P_f$$

$$= 1 - \int_{-\infty}^{+\infty} F_R(q) F_Q(q) dq$$

In the above case, only two random variables are there which are Load and Resistance.If these two random variables are the functions of other random variables then in that case it is required to derive the Limit state finction which can be expressed as follows.

Margin of saftey , $Z = R - Q$

$$= g(R\ , Q)$$

$$= g(X_1, X_2, X_3, X_4 \ldots \ldots X_n)$$

If the developed Limit state equation (margin of safety) is equal to zero , then in that case it represents the failure equation.Figure 2.6 shows the distibution of Z . If the Z value is less than or equal to zero, then it is said to be failure case. If the Z value is greater than one, then the structure is safe.In the Figure 2.6 hatched area shows the probability of failure for the considered model.

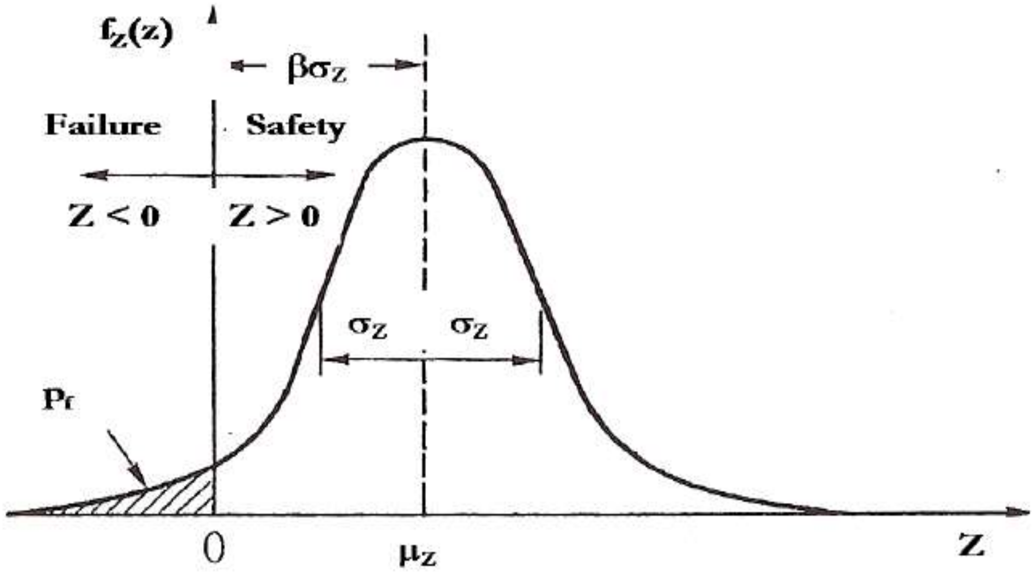


Fig 2.6 : probability distibution for the margin of saftey (Z = R –Q)

Th probability of failure is expressed in terms of the Reliability index which measures the distance between the Z=0 (critical value) to the Mean of the margin safety and it is expressed as follows.

$$Reliability\ index(\beta) = \frac{\mu_Z}{\sigma_Z}$$

Where μ_z = Mean of the random variable Z

& σ_z = Standard deviation of the variable Z

The probability of failure (P_f) in terms of Reliability index is expressed as follows

$$Probability\ of\ failure\ (P_f) = \emptyset(-\beta)$$

From this , Reliability is expressed as follows

$$Reliability\ (R_0) = 1 - P_f$$

First Order Reliability Methods (FORM):

In this method, only first order terms are used for the calculation of the mean and standard deviation of the performance function in the Taylor's series expansion. This method ignores the square, cube and higher powers of the (x_i - μ_i). This FORM method is commonly termed as the First Order Second Moment method (FOSM) because the variance is form of second moment. The methodology that is to be followed for the calculation of probability of failure in the First Order Second Moment (FOSM) method is described in detail in the book John.T.Christian and G.B Beacher (2003) but for the purpose of completeness it is described shortly as follows.

First Order Second Moment (FOSM):

Let the Load acting on the system is taken as Q and the Resistance of the system is considered as R.

Margin of Safety (Z) = R-Q

The failure surface equation for this system is written as follows

Z = R-Q = 0

Then the probability failure of system is, $P_f = P[(R - Q) \leq 0]$.

If the Load (Q) and the Resistance (R) are independent variables, then the Reliability index is calculated by using the following equation.

$$\beta = \frac{(\mu_R - \mu_Q)}{\sqrt{(\sigma_R^2 - \sigma_Q^2)}}$$

If the performance function (Z) is expressed as the linear function of input variables, then

$$Z = a_0 + a_1 X_1 + a_2 X_2 \dots \dots \dots . + a_n X_n$$

Then, mean of the performance function is equal to

$$\mu_Z = A_0 + \sum_{i=1}^{n} a_i \mu_i$$

and the Variance of the function Z is expressed as follows (if the random variables are uncorrelated)

$$\sigma_Z^2 = \sum_{i=1}^{n} a_i^2 \sigma_i^2$$

If the Limit state function (Z) is in nonlinear form of the variables, then the MVFOSM (Mean Value First Order Moment Method) is used to calculate the mean and variance of the performance function.

$$\mu_Z = g(\mu_1, \mu_2, \mu_3 \dots, \mu_n)$$

$$\sigma_Z^2 = \sum_{i=1}^{n} \sum_{j=1}^{n} \left(\frac{\partial g}{\partial x}\right)$$

MVFOSM method has one disadvantage when compared to other methods, it gives the objectionable errors which is mainly due to the linearized limit state function at the mean value.

Hasofer – Lind Reliability Method:

This method is advanced First Order Second Moment method (FOSM). This method is also termed as the geometric Reliability. In this method, in order to calculate the Reliability index (β), the input variables are converted to the normalized variables. For the calculation of the Reliability index (β), this method uses the reduced input variables as the coordinate axes. If the performance function is of nonlinear form, then the Reliability index (β) can be calculated based on the assumptions of linear failure criteria. Figure 2.7 shows the plot with the reduced input variables as the coordinate axis. From this figure, the Reliability index can be calculated for the nonlinear performance function.

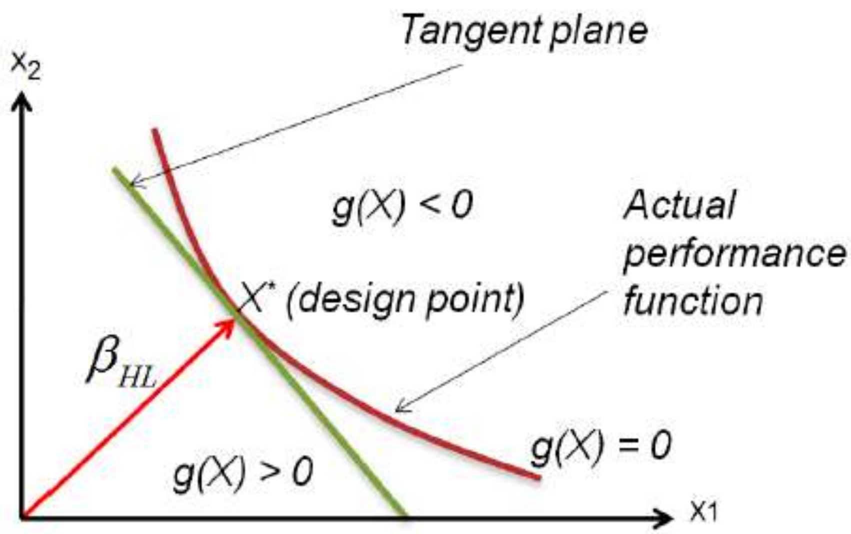


Fig 2.7: Hasofer –Lind Reliability index (β_{HL})

Hasofer – Lind Reliability index is measure of distance between the design point on the failure surface to the origin of the reduced coordinate system. The performance function in transformed coordinate system is expressed as follows

$$g(x_1, x_2, x_3 \ldots \ldots .. x_n) = 0$$

Where $x_1, x_2, x_3 \ldots \ldots .. x_n$ are standard normal variables.

The X* on the function g(x) indicates the design point .If more than two input variables are there in the given problem ,then the Reliability index can be calculated by using the following formula.

$$\beta_{HL} = \underset{g(x*)=0}{min} \sqrt{(X^t)X}$$

Where X is the matrix of standard normal variables.

Then, probability of failure, $P_f = \varphi(-\beta_{HL})$

Figure 2.8 shows the USACE chart, which shows the relation between the probability of failure (P_f) and Reliability index (β).

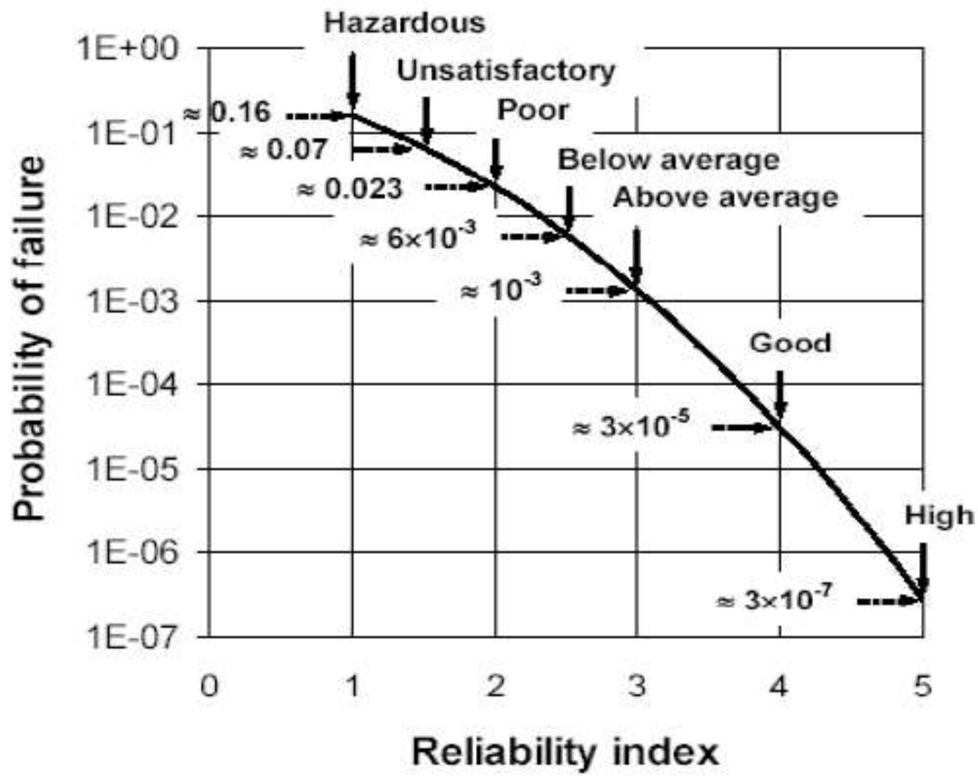


Fig 2.8: Chart between the Reliability index (β) and the probability of failure (P_f) (USACE 1997)

Chapter 3

Equivalent Cohesion approach

Many researchers developed different methods to quantify the effect of vegetation on the slope stability. In this present work, the effect of vegetation on the stability of slope is calculated by using the equivalent cohesion and root as pile approaches. The finite element package PLAXIS 3D version 2013 is used to model the slope with vegetation.

3.1 Deterministic analysis of slope (without vegetation):

For this study a homogenous slope of 8 meters height, 8 meters width and 10 meters length is considered. Table 3.1 shows the parameters used in the analysis of slope.

Table3.1: Parameters used in the analysis of slope

	Description	**Unit**	**Value**
Soil (Mohr -Coulomb model)	Unit Weight	kN/m3	16
	Modulus of Elasticity	kPa	7500
	Effective Poisson's ratio	-	0.35
	Effective Cohesion	kPa	5
	Effective friction angle	(^{0})	30

Figure 3.1 shows the PLAXIS 3D modelling of the considered slope. Figure 3.2 shows the deformed mesh of the considered slope.

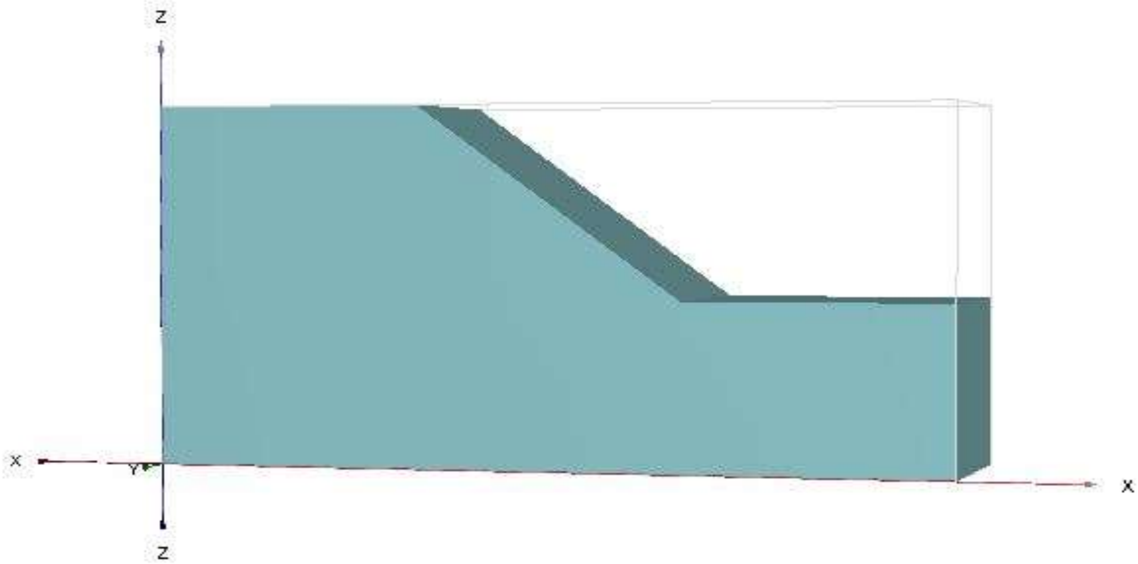


Fig 3.1: Geometric modelling of slope

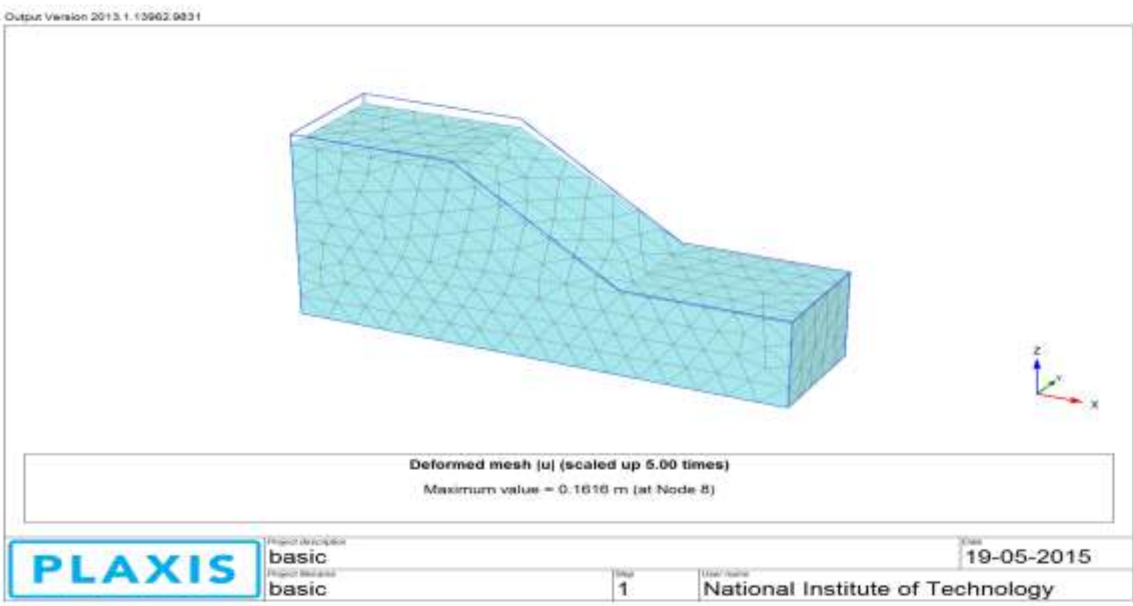


Fig 3.2: Deformed mesh

Figure 3.3 shows the incremental deviator strain which representing the critical failure surface of the considered slope. Figure 3.4 shows the graph between total displacement and incremental multipliers. From this graph safety factor of slope is measured as 1.36

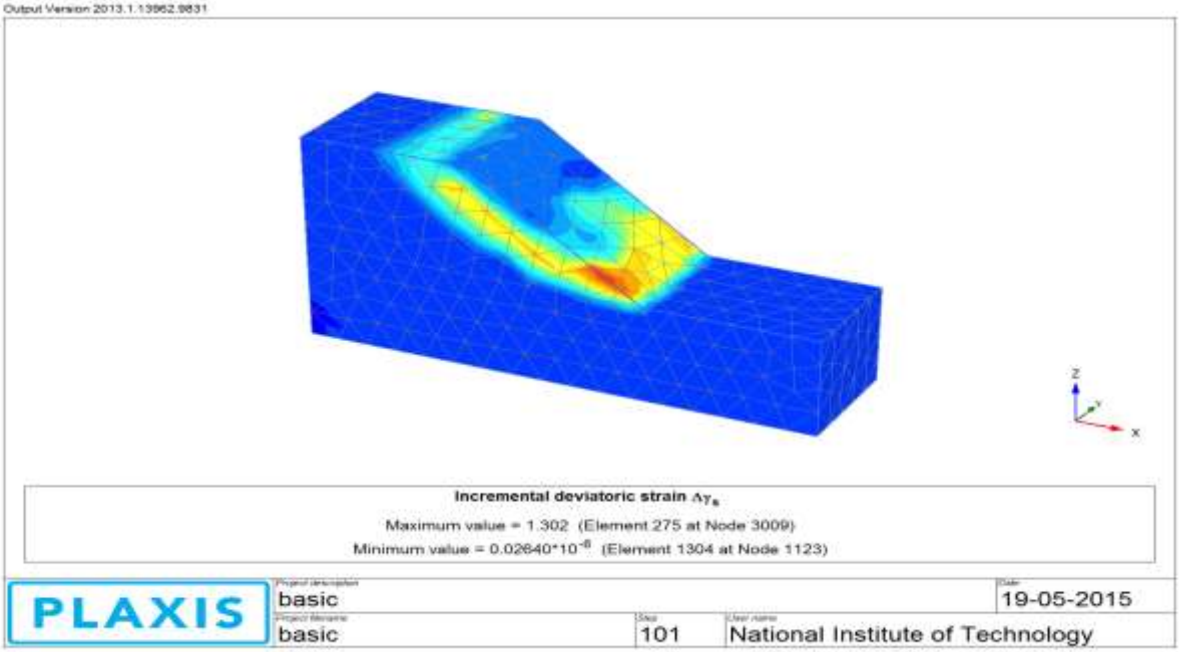


Fig 3.3: Failure surface of slope

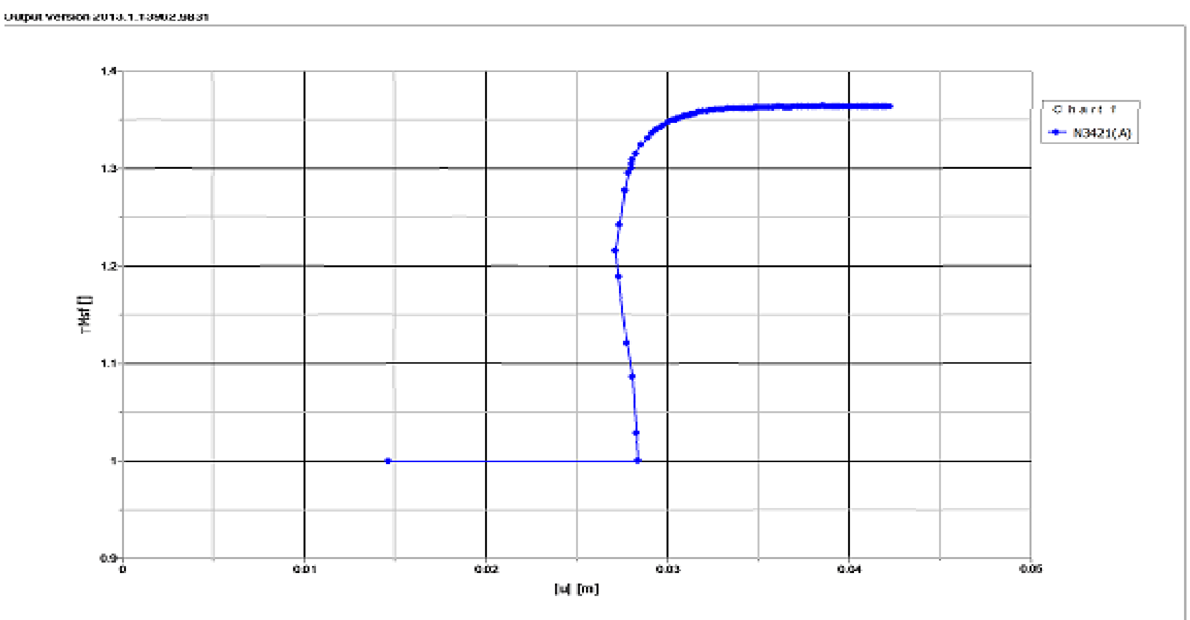


Fig 3.4: Total displacement (U) Vs Incremental multipliers (M_{sf})

3.1.1 Reliability analysis of slope:

The uncertainties involved in the soil properties are considered. In this problem Cohesion (C), Angle of friction (Φ) and Unit weight of the soil (γ) are considered as random variables. Table 3.2 shows the Mean and Coefficient of variation of the soil properties.

Table 3.2: Mean and CoV of the soil properties

Random Variables	**Mean (μ)**	**CoV**	**SD**
C (kN/m^2)	5	0.2	1
Φ (^{0})	30	0.13	3.9
γ (kN/m^3)	16	0.07	1.12

Full Factorial Design

By using MATLAB code, the design is done which consist of binary digits 0 and 1.

```
>>dFF2 = ff2n (3)
```

C	Φ	Γ
0	0	0
0	0	1
0	1	0
0	1	1
1	0	0

1	0	1
1	1	0
1	1	1

In this problem eight sample points are developed by using the two level full factorial design. The values 0 and 1 are calculated by using $\mu + 1.65\sigma$ and $\mu - 1.65\sigma$, where μ is mean and σ is the standard deviation of the variable.

$\sigma = 1.65 * CoV$

Table 3.3 shows the safety factor of slope corresponding to the eight sample points. By using this Table Regression analysis is performed in order to find the limit state function.

Table 3.3: Safety factor of slope corresponding to eight sample points in RSM by using PLAXIS 3D

	C (kN/m^2)	Φ (^{0})	γ (kN/m^3)	
$\mu+1.65\sigma$	6.65	36.435	17.848	
$\mu-1.65\sigma$	3.35	23.565	14.152	FOS
1	6.65	36.435	17.848	1.7
2	6.65	36.435	14.152	1.81
3	6.65	23.565	17.848	1.19
4	6.65	23.565	14.152	1.286
5	3.35	36.435	17.848	1.401

6	3.35	36.435	14.152	1.511
7	3.35	23.565	17.848	1.008
8	3.35	23.565	14.152	1.031

The regression analysis is performed by using the data in Table 3.6 to develop the response surface function.

$$Factor\ of\ saftey\ (FOS\ ) = 0.230657 + 0.078409 * C + 0.03704 * \emptyset - 0.02293 * \gamma$$

$$\left(R^2 = 0.9903\ , R^2_{adj} = 0.9831\right)$$

Case 1: If the parameters considered as uncorrelated normally distributed

The parameters are uncorrelated means, the degree of correlation between the variables is set as zero. The performance function g(x) is defined as follows

$$g(x) = FOS - 1$$

$$Reliability\ index\ (\beta_{HL}) = \min_{g(X)=0} \sqrt{(X^T X)}$$

Where X is the matrix of standard normal random variables(x_i).

$$x_i = \frac{X_i - \mu_i}{\sigma_i}$$

The minimum distance between the origin to the design point (Reliability index) is calculated by using the MS-Excel Solver Tool.

Reliability index (β_{HL}) = 2.203

Probability of failure $P_f = \varphi(-\beta_{HL})$

By using Excel, P_f =NORMSDIST (-β_{HL})

= NORMSDIST (-2.203)

= 0.013

Case 2a: The considered parameters C and Φ are correlated linearly.

correlation coefficient = -0.2

	C	Φ	γ
C	1	-0.2	0
Φ	-0.2	1	0
γ	0	0	1

$$minimum\ \beta_{HL} = \min_{g(x)=0} \sqrt{X^T C^{-1} X}$$

By using MS –Excel solver β = 2.41

Probability of failure (P_f) = NORMSDIST (-2.41)

= 0.0791

Case 2b:

If the correlation coefficient= -0.3

	C	Φ	γ
C	1	-0.3	0
Φ	-0.3	1	0
γ	0	0	1

$$minimum\ \beta_{HL} = \min_{g(x)=0} \sqrt{X^T C^{-1} X}$$

By using Excel solver β = 2.54

Probability of failure (P_f) = NORMSDIST (-2.54)

= 0.0547

As per USACE chart, the Reliability analysis results shows that the considered slope is under Unsatisfactory to Poor region. But as per deterministic approach, the safety factor of the slope is 1.36 (stable slope) .This study also highlights the prominence of the Reliability analysis in stability of the slopes.

3.2 Deterministic analysis of slope (with vegetation):

The effect of vegetation on the slope stability is calculated by using the following two approaches.

1. Equivalent cohesion approach
2. Root as pile approach

3.2.1 Equivalent cohesion approach:

As per this approach, the entire root zone is considered as single block and to this increased shear strength properties are assigned .The increased in shear strength is mainly due to the increase in the cohesion value of the soil in the root zone. The modelling of the slope with vegetation is done by using the PLAXIS 3D software. Table 3.4 shows the parameters used in the analysis of the Vegetated slope.

Table 3.4: Parameters used in the analysis slope by using Equivalent Cohesion approach

	Description	Unit	Value
Soil (Mohr - Coulomb model)	Unit weight (γ)	kN/m^3	16
	Modulus of Elasticity (E)	kPa	7500
	Poisson's ratio (ν)	-	0.35
	Effective Cohesion (C)	kPa	5
	Effective Friction angle (Φ)	(^{0})	30
	Incremental Cohesion ($C^{'}$)	kPa	15

Figure 3.5 shows the PLAXIS 3D modelling of slope with vetiver grass by using the Equivalent cohesion approach. The size of the square block considered in this problem is 0.8m .Figure 3.6 shows the deformed mesh of the slope.

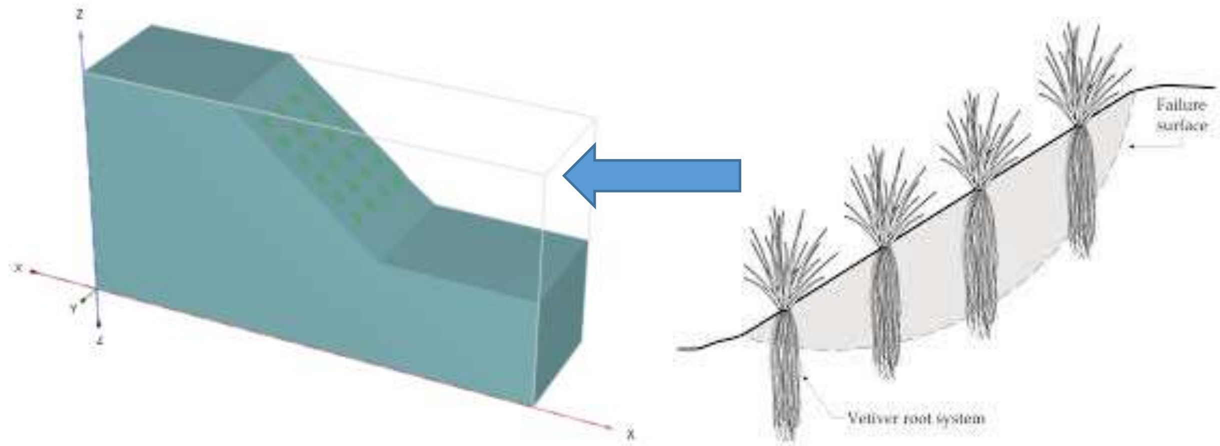


Fig 3.5: Geometric modelling of slope with vetiver grass

Figure 3.6 shows the deformed mesh of the slope. Figure 3.7 shows the critical failure surface of the slope. Figure 3.8 shows the graph between the total displacement and the incremental multipliers. From the graph it is observed that the safety factor of the slope is equal to 1.43

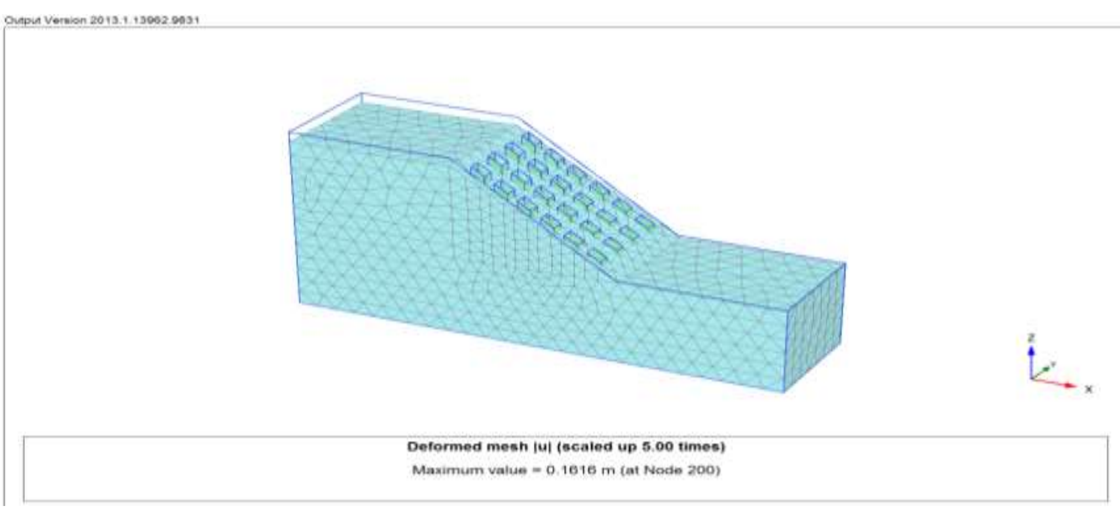


Fig 3.6: Deformed mesh of the slope

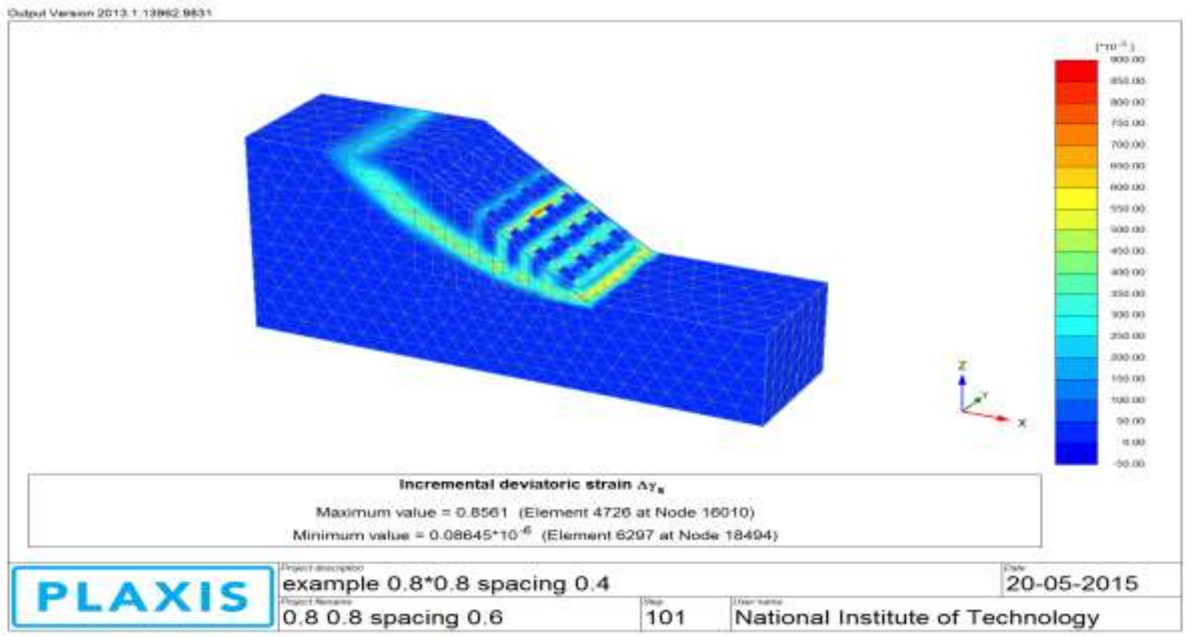


Fig 3.7: Critical failure surface of slope

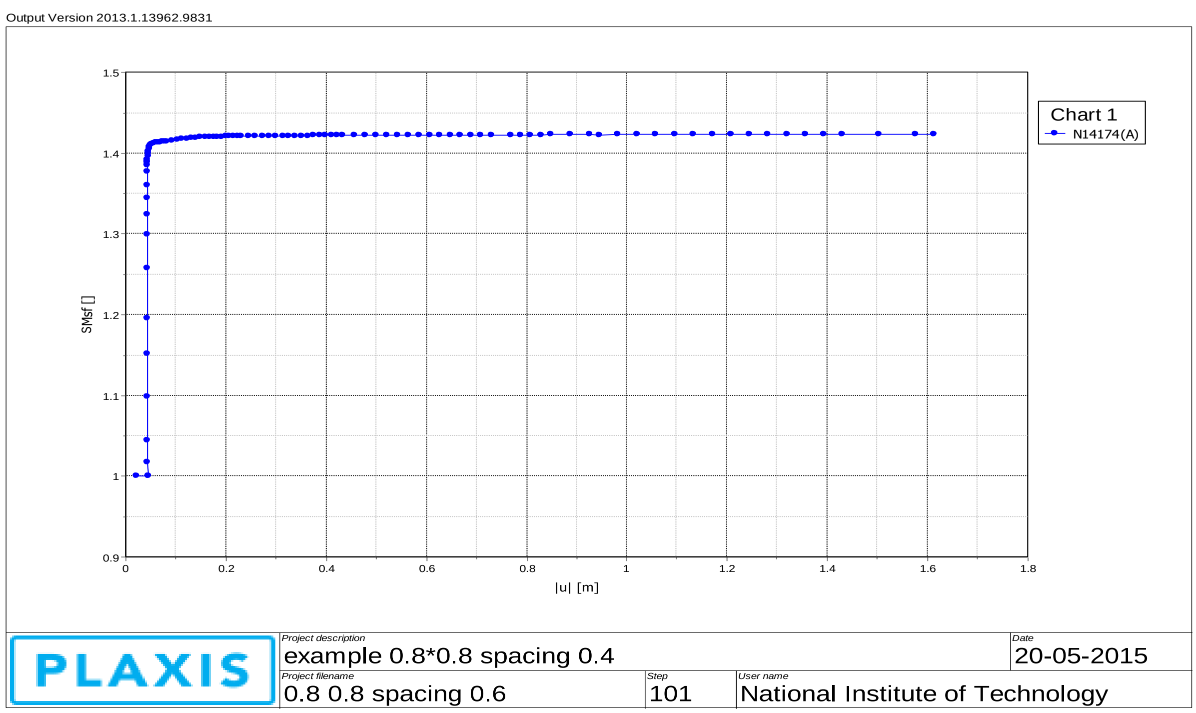


Fig 3.8: Total displacement (U) Vs Incremental multipliers (M_{sf})

Table 3.5 shows the percentage increase in the safety factor due to the vegetation for the different block sizes by using the Equivalent cohesion approach.

Table 3.5: Percentage increase in the safety factor due to the vegetation

Size of the block (mx m)	**spacing (m)**	**FOS**	**% increase**
0.6 x 0.6	0.6	1.396	2.6470588
	0.4	1.43	5.1470588
0.8x0.8	0.6	1.46	7.3529412
	0.8	1.43	5.2941176
1x1	0.6	1.523	11.985294
	0.8	1.482	8.9705882
	1	1.46	7.3529412

3.2.2 Reliability analysis of slope with vegetation:

The soil parameters Cohesion (C), Angle of internal friction (Φ), Unit weight of soil (γ) and increase in cohesion (C^1) are considered as the input random variables. Table 3.6 shows the mean and coefficient of variation of the considered random variable

Table 3.6: Mean and CoV of the random variables

	Mean	**CoV**	**SD**
C (kN/m^2)	5	0.2	1
Φ (^{0})	30	0.13	3.9
γ (kN/m^3)	16	0.07	1.12
C^1 (kN/m^2)	15	0.2	3

Design of Experiments (DoE):

By using MATLAB code the two level factorial design is developed.

```
>> dFF2 = ff2n (4)
```

C	C^1	φ	γ
0	0	0	0
0	0	0	1
0	0	1	0
0	0	1	1
0	1	0	0
0	1	0	1
0	1	1	0
0	1	1	1
1	0	0	0
1	0	0	1
1	0	1	0
1	0	1	1
1	1	0	0
1	1	0	1
1	1	1	0
1	1	1	1

The values 0 and 1 are calculated by using the $\mu + 1.65\sigma$ and $\mu - 1.65\sigma$. Table 3.7 shows the safety factor of the slope corresponding to sixteen sample points.

Table 3.7: Safety factor of slope with vegetation corresponding to sixteen sample points in RSM by using PLAXIS 3D

	C(kPa)	C^1 (kPa)	φ (^{0})	γ(kN/m^3)	FOS
μ+1.65σ	6.65	26.6	36.435	17.848	
μ-1.65σ	3.35	13.4	23.565	14.152	
1	6.65	26.6	36.435	17.848	1.779
2	6.65	26.6	36.435	14.152	1.923
3	6.65	26.6	23.565	17.848	1.324
4	6.65	26.6	23.565	14.152	1.421
5	6.65	13.4	36.435	17.848	1.582
6	6.65	13.4	36.435	14.152	1.784
7	6.65	13.4	23.565	17.848	1.181
8	6.65	13.4	23.565	14.152	1.293
9	3.35	26.6	36.435	17.848	1.562
10	3.35	26.6	36.435	14.152	1.649
11	3.35	26.6	23.565	17.848	1.11
12	3.35	26.6	23.565	14.152	1.22
13	3.35	13.4	36.435	17.848	1.449
14	3.35	13.4	36.435	14.152	1.542
15	3.35	13.4	23.565	17.848	1.06
16	3.35	13.4	23.565	14.152	1.19

The Regression analysis is performed by using the data in the above Table to develop the Limit state function.

$$Saftey\ factor\ (FOS) = 0.5328044 + 0.057005 * C + 0.00858902 * C' + 0.0337121 * \Phi$$
$$-0.0329748 * \gamma$$

$$\left(R^2 = 0.98337\ , R^2_{adj} = 0.977285\right)$$

Case 1: The parameters considered are uncorrelated normally distributed.

The performance function is defined as

$$f(x) = fos - 1$$

$$Reliability\ index\ (\beta_{HL}) = \min_{g(x)=0} \sqrt{X^T X}$$

By using MS –Excel solver β_{HL} = 3.1106

Probability of failure (P_f) = NORMSDIST (-3.1106)

= 0.000917

Case 2a: The parameters C and Φ are linearly correlated.

correlation coefficient = -0.2

	C	C^1	Φ	γ
C	1	0	-0.2	0
C^1	0	1	-0.2	0
Φ	-0.2	-0.2	1	0
γ	0	0	0	1

$$Reliability\ index\ \beta_{HL} = \min_{g(x)=0} \sqrt{X^T C^{-1} X}$$

By using MS –Excel solver minimum β_{HL} = 3.3421

Probability of failure (P_f) = NORMSDIST (-3.3421)

= 0.000416

Case 2b:

correlation coefficient = -0.3

	C	C^1	Φ	γ
C	1	0	-0.3	0
C^1	0	1	-0.3	0
Φ	-0.3	-0.3	1	0
Γ	0	0	0	1

$$Reliability\ index\ \beta_{HL} = \min_{g(x)=0} \sqrt{X^T C^{-1} X}$$

By using MS –Excel solver minimum β_{HL} = 3.5861

Probability of failure (P_f) = NORMSDIST (-3.5861)

= 0.000168

As per USACE chart, results of reliability analysis shows that the slope with vegetation is in above average to good region where as when there is no vegetation on the slope, the results of Reliability analysis shows that the considered slope is in Unsatisfactory to the Poor region. This study also highlights the prominence of the reliability analysis in stability of slope.

Chapter 4

Root as Pile approach

4.1 Deterministic analysis of slope with vegetation by using Root as Pile approach:

As per this approach, entire root zone is considered as single pile and to this pile root properties are assigned. The modulus of elasticity of vetiver root is about 2.6 GPa and its tensile strength of the root is varying in between 45 – 145 MPa (average 75MPa). The diameter of the vetiver root is generally varying form 0.2-2.2mm. Table 4.1 shows the parameters used in the analysis of slope.

Table 4.1: Parameters used in the analysis slope by using Root as Pile approach

	Description	**Unit**	**Value**
Soil (Mohr –Coulomb model)	Unit weight(γ)	kN/m^3	16
	Modulus of Elasticity (E)	MPa	7500
	Effective cohesion(C)	MPa	5
	Effective Friction angle(φ)	(^{0})	30
	Poisson's ratio(ν)	-	0.35
	R_{inter}	-	0.8
Pile	Modulus of Elasticity (E_{pile})	GPa	2.5

Figure 4.1 shows the geometric modelling of slope in PLAXIS 3D. The diameter of the pile considered in this problem is 0.8meter. Figure 4.2 shows incremental deviator strain of the slope which representing the critical failure surface of the slope.

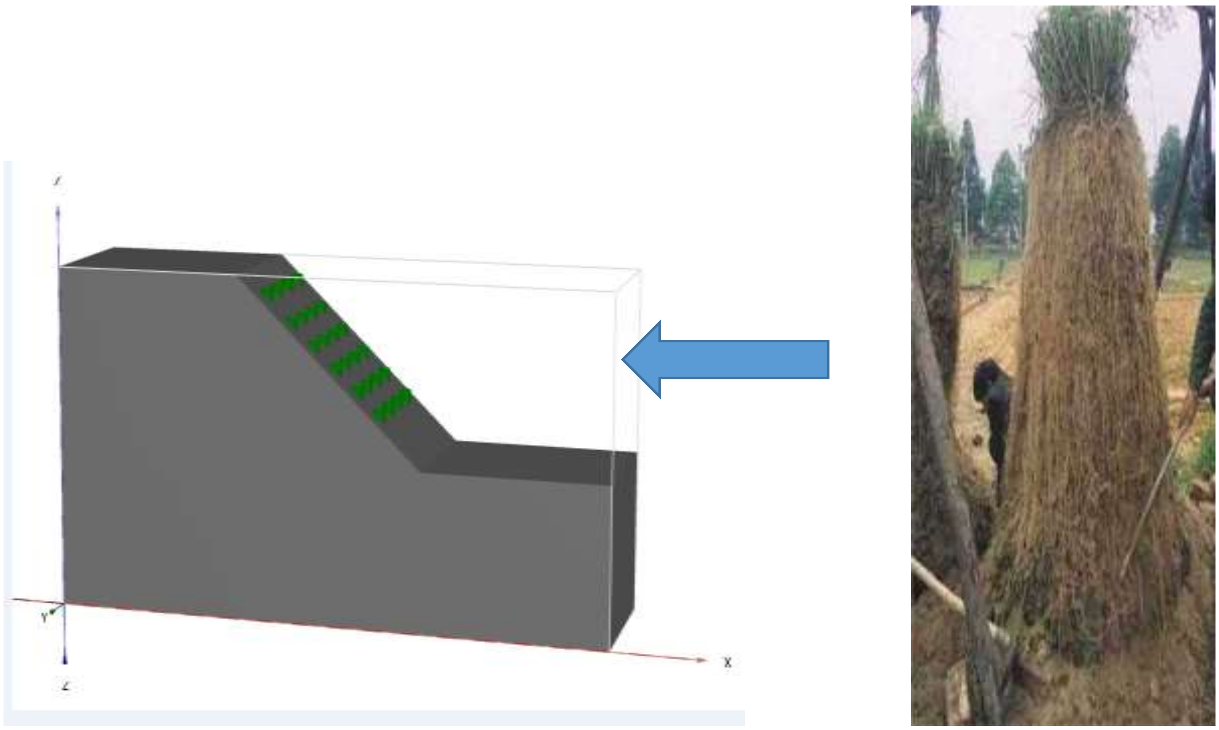


Figure 4.1: Geometric modelling of slope

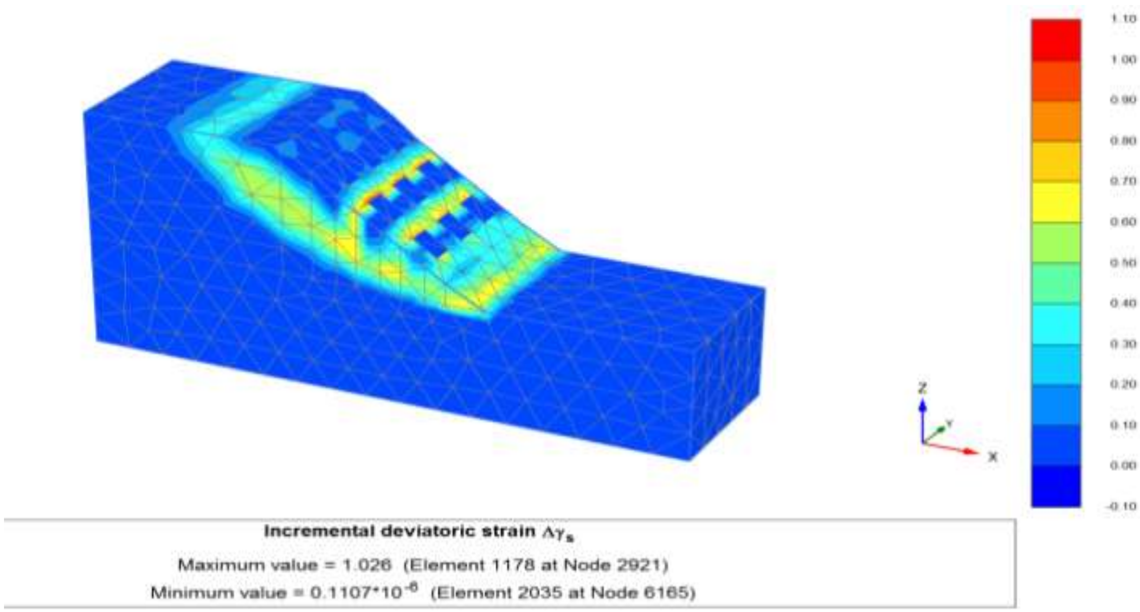
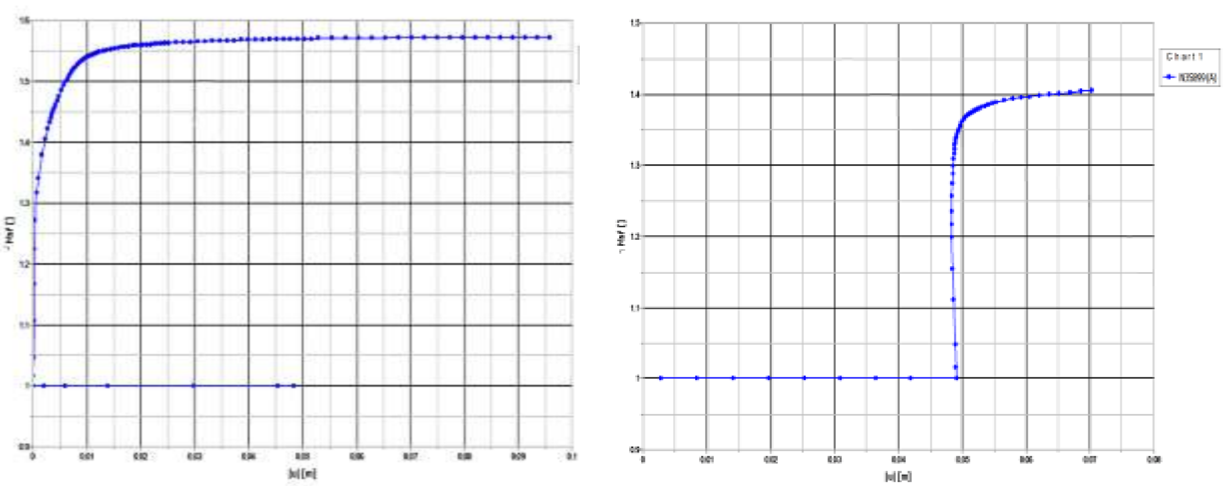


Figure 4.2 Critical failure surface of slope

Figure 4.3 (a) shows the graph between the total displacements and incremental multipliers. From this graph it is observed that the safety factor of the slope without interface is 1.56 and from the Figure 4.3 (b) safety factor of the slope is 1.412



a. Without interface b. with interface

Fig 4.3: Total displacement Vs Incremental multipliers

Table 4.2 shows the percentage increase in the safety factor due to vegetation for the different diameter of the piles.

Table 4.2: Percentage increase in the safety factor due to vegetation by using the Root as the pile approach

Diameter of the Pile (m)	Spacing (m)	FOS		% increase
0.6	0.6	Without interface	1.5	10.294118
		With interface	1.41	3.6764706
0.8	0.8	Without interface	1.5	10.294118
		With interface	1.412	3.721054
1	0.8	Without interface	1.54	13.235294
		With interface	1.478	8.6764706

4.2: Reliability analysis of slope with vegetation:

The parameters Cohesion (C), Angle of internal friction (Φ), Modulus of Elasticity of pile (E) and interface between the soil and root (R_{inter}) are considered as the random variables. Table4.3shows the mean and CoV of the random variables.

Table 4.3: Mean and CoV of the Random Variables

	Mean	COV	SD
C (kN/m^2)	5	0.2	1
Φ (^{0})	30	0.13	3.9
E pile (kN/m^2)	2500000	0.34	850000
Rinter	0.8	0.15	0.12

Design of Experiment (DoE)

By using MATLAB code two level full factorial design is developed.

```
>> dFF2 = ff2n (4)
```

C	Φ	E	R_{inter}
0	0	0	0
0	0	0	1
0	0	1	0
0	0	1	1
0	1	0	0
0	1	0	1

0	1	1	0
0	1	1	1
1	0	0	0
1	0	0	1
1	0	1	0
1	0	1	1
1	1	0	0
1	1	0	1
1	1	1	0
1	1	1	1

The values 0 and 1 are calculated by using $\mu + 1.65\sigma$ and $\mu - 1.65\sigma$. Table 4.4 shows the safety factor of slope corresponding to sixteen sample points.

Table 4.4: Safety factor of slope with piles corresponding to sixteen sample points in RSM by using PLAXIS 3D

	C(kN/m^2)	$\Phi(^0)$	E_{pile}(kN/m^2)	R_{inter}	FOS
$\mu+1.65\sigma$	6.65	36.435	3902500	0.998	
$\mu-1.65\sigma$	3.35	23.565	1097500	0.602	
1	6.65	36.435	3902500	0.998	1.902
2	6.65	36.435	3902500	0.602	1.84
3	6.65	36.435	1097500	0.998	1.905
4	6.65	36.435	1097500	0.602	1.87
5	6.65	23.565	3902500	0.998	1.318
6	6.65	23.565	3902500	0.602	1.317
7	6.65	23.565	1097500	0.998	1.321

8	6.65	23.565	1097500	0.602	1.308
9	3.35	36.435	3902500	0.998	1.62
10	3.35	36.435	3902500	0.602	1.6
11	3.35	36.435	1097500	0.998	1.6
12	3.35	36.435	1097500	0.602	1.617
13	3.35	23.565	3902500	0.998	1.091
14	3.35	23.565	3902500	0.602	1.074
15	3.35	23.565	1097500	0.998	1.093
16	3.35	23.565	1097500	0.602	1.072

The regression analysis is performed by using the data in the above table in order to develop the limit state function.

$$safety\ factor(fos) = 0.4254 - 0.019 * C + 0.03022 * \Phi + 0.0364 * E_{pile} - 1.468 * 10^{-8} * R_{inter}$$

$$(R^2 = 0.997605\ , R^2_{adj} = 0.9058)$$

Case 1: The considered parameters are uncorrelated normally distributed.

The performance function is defined as

$$f(x) = fos - 1$$

$$Reliability\ index\ (\beta_{HL}) = \min_{g(x)=0} \sqrt{X^T X}$$

By using MS –Excel solver β_{HL} = 3.234

Probability of failure (P_f) = NORMSDIST (-3.234) =0.000608

Case 2a: The parameters C and Φ are linearly correlated.

correlation coefficient =-0.2

	C	Φ	E	R_{inter}
C	1	-0.2	0	0
Φ	-0.2	1	0	0
E	0	0	1	0
R_{inter}	0	0	0	1

$$Reliability\ index\ \beta_{HL} = \min_{g(x)=0} \sqrt{X^T C^{-1} X}$$

By using MS –Excel solver minimum β_{HL} = 3.5161

Probability of failure *(P_f)* = NORMSDIST (-3.5161)

=0.000219

Case 2b:

correlation coefficient = -0.3

	C	Φ	E	R_{inter}
C	1	-0.3	0	0
Φ	-0.3	1	0	0
E	0	0	1	0
R_{inter}	0	0	0	1

$$Reliability\ index\ \beta_{HL} = \min_{g(x)=0} \sqrt{X^T C^{-1} X}$$

By using MS –Excel solver minimum β_{HL} = 3.5011

Probability of failure *(P_f)* = NORMSDIST (-3.5011)

= 0.000232

As per USACE chart, the results of the reliability analysis shows that the considered slope with vetiver grass is in above average to good region where as when there is no vegetation on it, the considered slope is in poor region.

Chapter 5

Special cases

5.1 If the piles are not in vertical position

If the considered root zone in the soil is not perfectly in vertical position, then it increases the stability of the slope. The percentage increase in safety factor due to the inclined root zone is calculated by using the Root as pile approach. Figure 5.1 shows the geometric modelling of slope with inclined piles in PLAXIS 3D. The diameter of the considered pile is 0.8 meter and it is making an inclination 30^0 with respect **z**-axis (Vertical axis)**.**

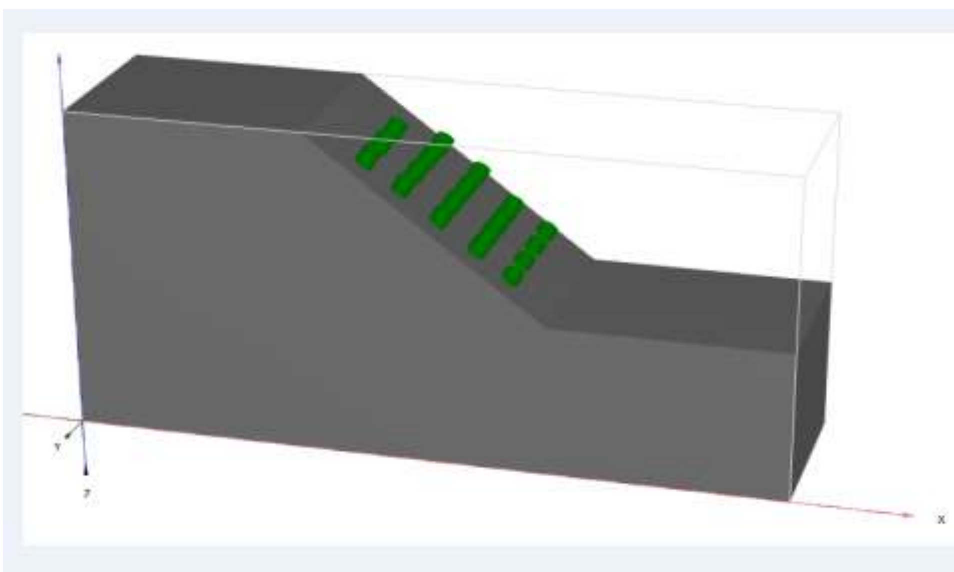


Fig 5.1: Geometric modelling of slope

Figure 5.2 shows the incremental deviator strain of the considered slope which representing the critical failure surface of the slope. Figure 5.3 shows the graph between the total displacement and incremental multipliers. Form the graph it is observed the safety factor of the slope without interface is 1.52 and with interface is 1.428.

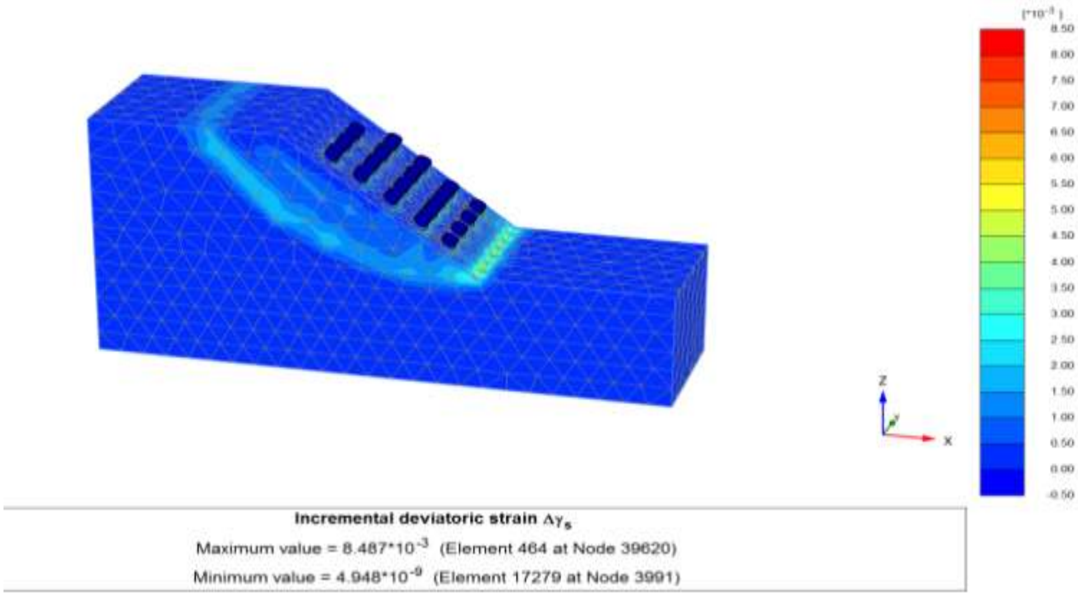


Fig 5.2: Critical failure surface of slope

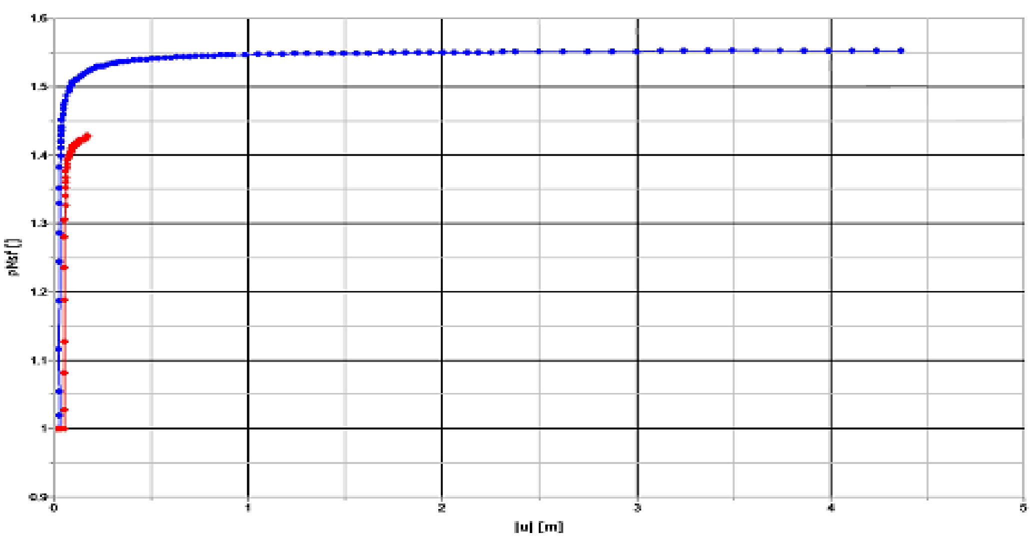


Fig 5.3: Total displacement (U) Vs Incremental multipliers (M_{sf})

The safety factor of the slope with inclined piles is calculated by using PLAXIS 3D and this value is equal to the 1.428 which is more 1.412 (when the piles are in vertical position). The inclination effect of root zone in this case increased the safety factory by 1.28 %.

5.2 Stability of slope under steady seepage condition:

Case 1: Without vegetation

In Earthen dam, the upstream slope is critical under sudden draw down condition whereas downstream slope is critical under steady seepage condition. In this case, stability of the slope with vegetation under steady seepage condition is calculated. Figure 5.5 shows the geometric modelling of slope with head of water 13 meters on the upstream side.

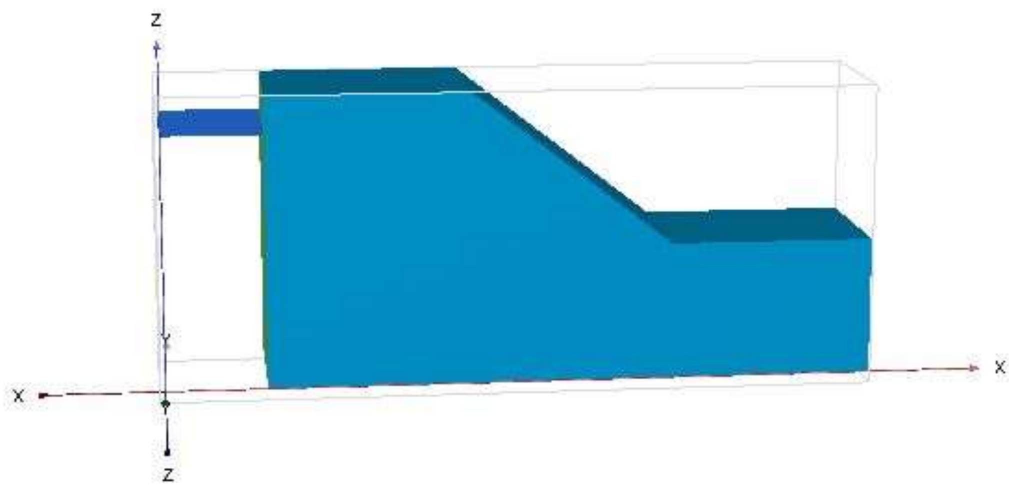


Fig 5.4: Geometric modelling of slope with head of water 13 meters on upstream side

Figure 5.5 shows the pore pressure distribution and the Figure 5.6 shows the incremental deviator strain of the slope which representing the critical failure surface of the slope.

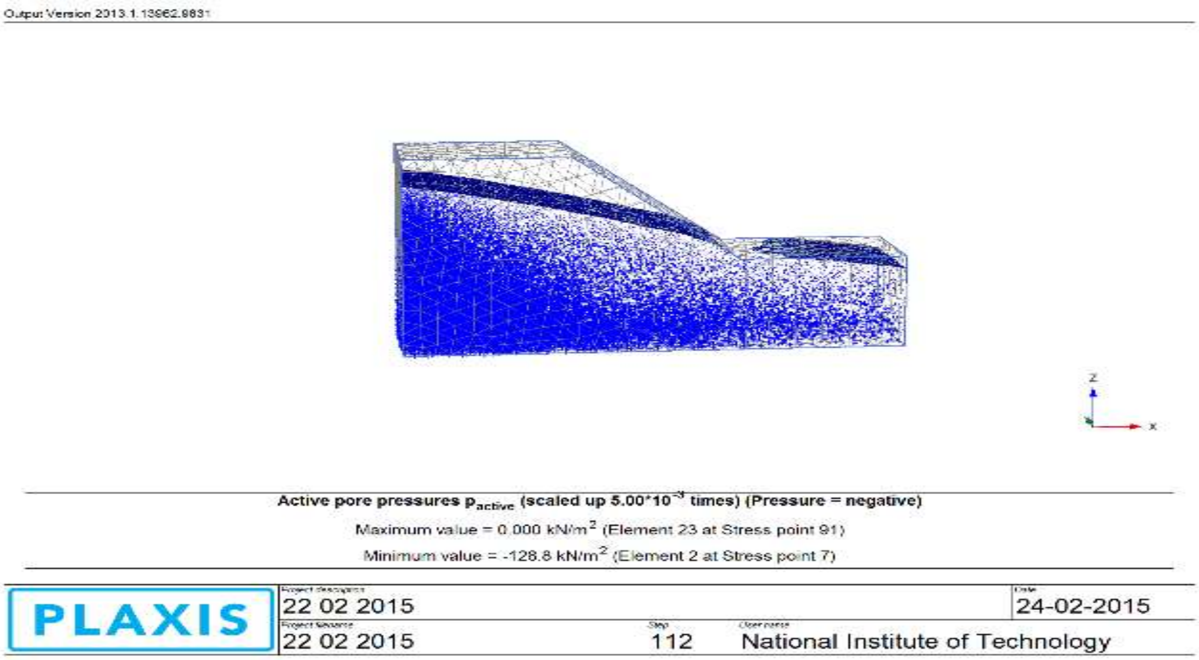


Fig 5.5: Active pore pressure distribution

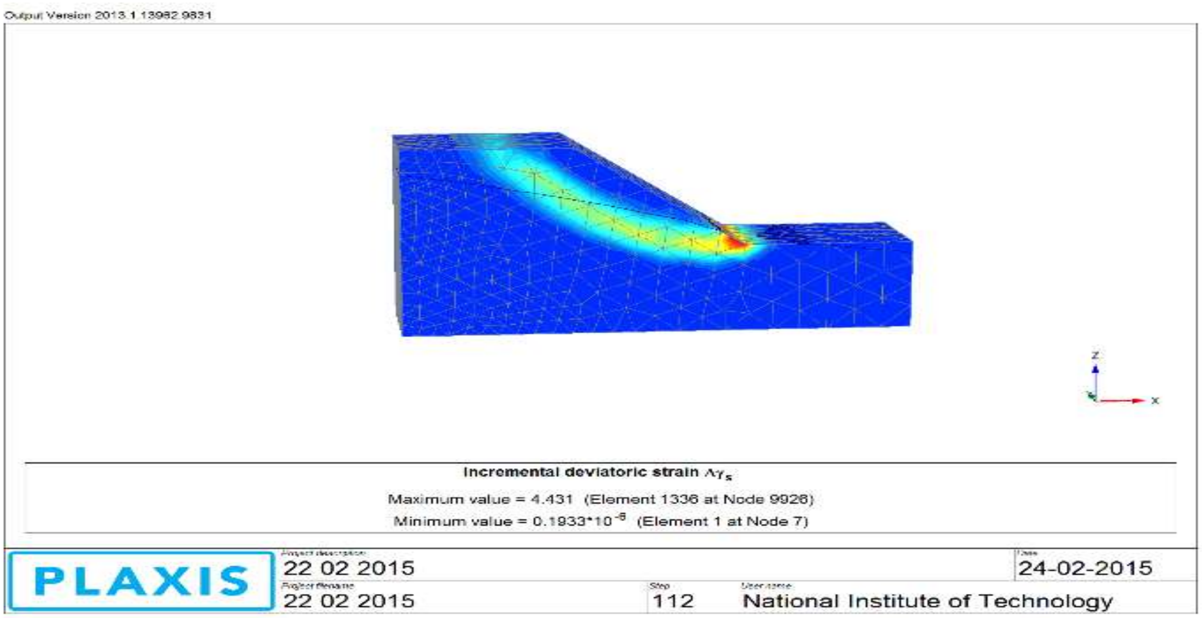


Fig 5.6: Critical failure surface of slope

Figure 5.9 shows the graph between the total displacement and incremental multipliers. From the graph it is observed that the safety factor of slope under steady seepage condition is 1.097.

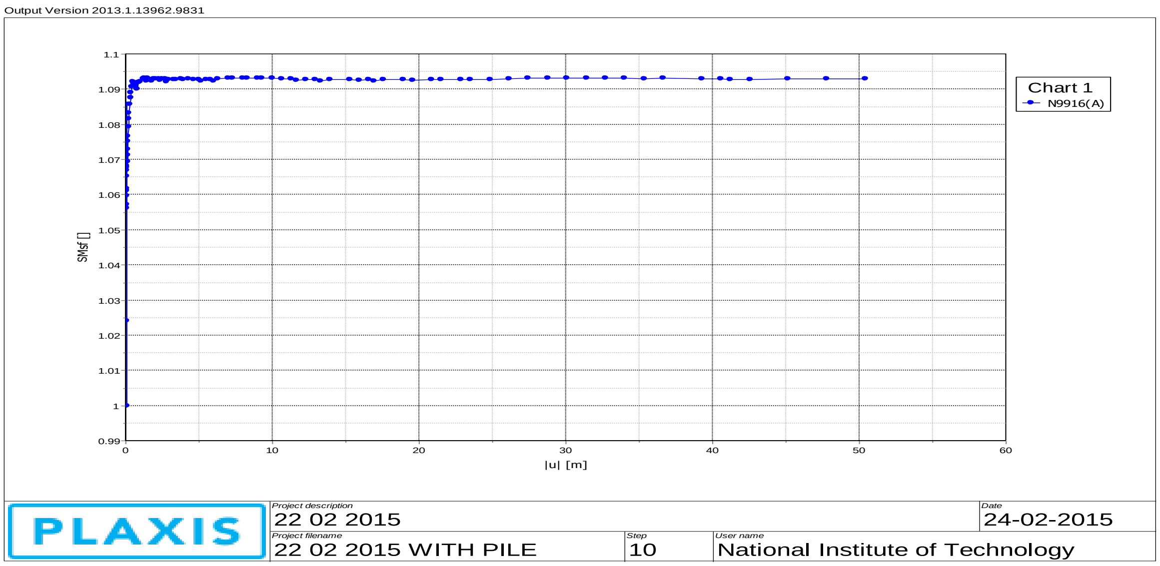


Fig 5.7: Total displacement (U) Vs incremental multipliers (M_{sf})

Case 2: With vegetation

Figure 5.10 shows the geometric modelling of the slope with Vegetation in PLAXIS 3D. The head of water on the upstream side of the slope is 13meters.

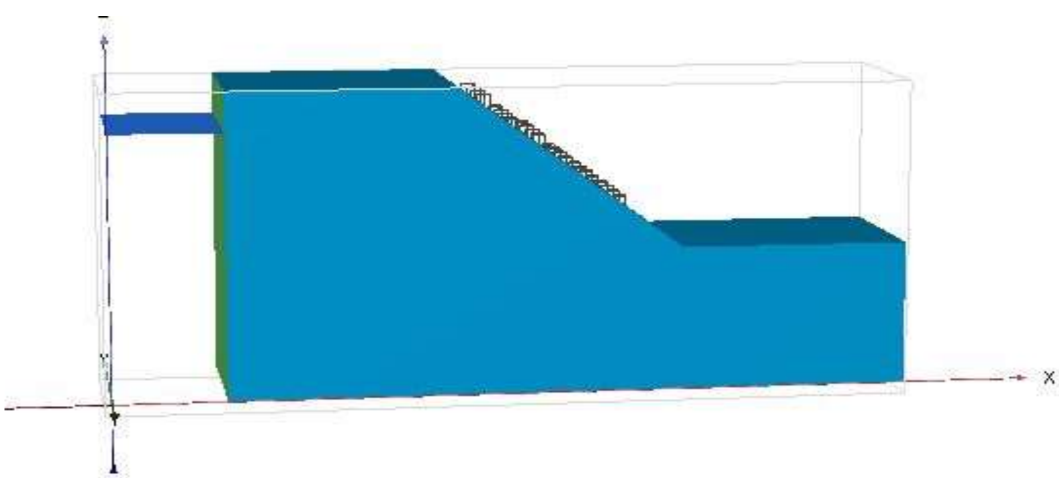


Fig 5.8: Geometric modelling of slope with Vertical piles (head of water on U/s =13 m)

Figure 5.11 shows the pore pressure distribution and the Figure 5.11 shows the graph between the Total displacement and incremental multipliers (M_{sf}).

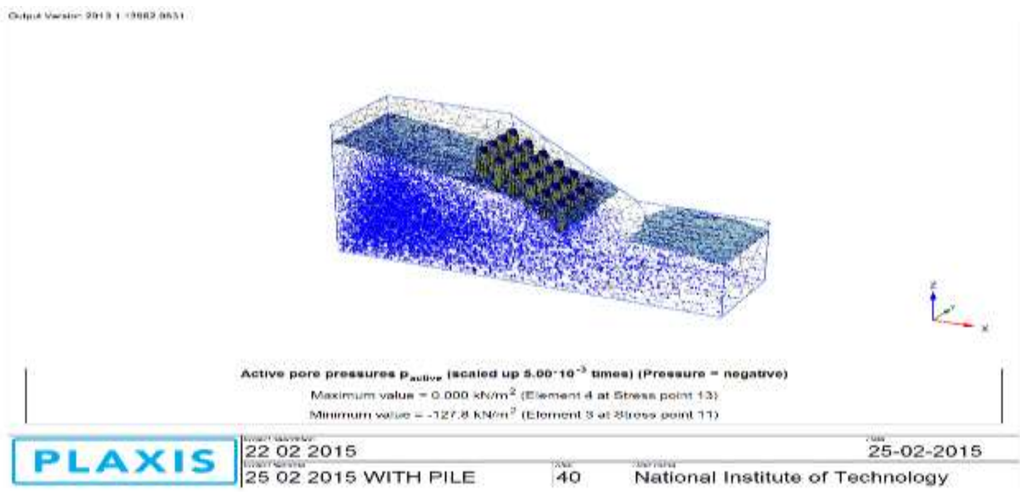


Fig 5.9: Active pore pressure distribution

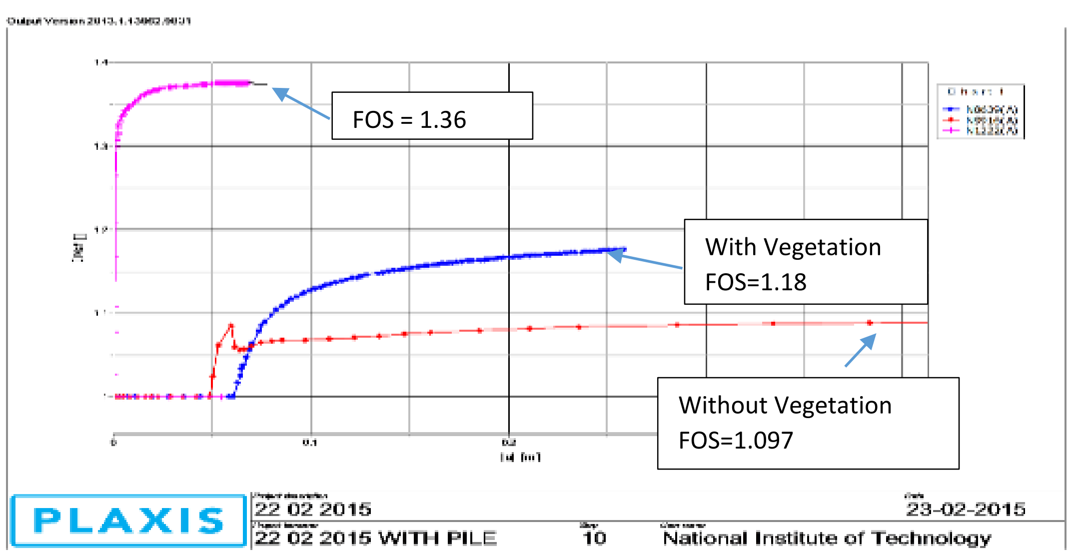


Fig 5.10: Total displacement (U) Vs Incremental multipliers (M_{sf})

From the graphs, it is observed that safety factor of slope with vegetation under steady seepage is 1.18 which is more than 1.097 (without vegetation). The percentage increase in the safety factor of slope under steady seepage due to vegetation is 8.256%.

Chapter 6

Conclusions

6. Conclusions:

In the present study, the mechanical effect of effect of vegetation on the slope stability is calculated. The reliability analysis is also performed on the slope with and without vegetation by using the first order reliability method (FORM).

From the present study the following conclusions are made:

1. Safety factor of the considered slope without vegetation as per deterministic analysis is found to be 1.36. Based on reliability analysis the probability of failure (P_f) of the slope for uncorrelated normally distributed parameters is 0.013 whereas for correlated normally distributed parameters (C and Φ) is 0.0547. This represents considered slope without vegetation is in unsatisfactory to poor zone as per USACE chart.
2. As per deterministic analysis, safety factor of the slope with vegetation by using the equivalent cohesion approach is found as 1.43. From the reliability analysis, the probability of failure (P_f) of the slope with vegetation is 0.000917 for uncorrelated and 0.000168 for correlated normally distributed parameters. This represents the considered slope with vegetation is in above average to good zone as per USACE chart.
3. Based on the deterministic analysis, the factor of safety of slope with vegetation by using root as pile approach is found as 1.412. Based on the reliability analysis, the probability of failure (P_f) of the slope with piles is 0.000608 for uncorrelated and 0.000232 for correlated

normally distributed parameters. This indicates the slope is in above average to good zone as per USACE chart.

4. From the results, it is observed that the Equivalent cohesion approach gives slightly higher value of safety factor compared to the Root as Pile approach.

5. The percentage increase in the safety factor due to inclination effect of piles ($\theta = 30^0$) is found as 1.28%.

6. The percentage increase in the safety factor due to vegetation under steady seepage condition is found as 8.256%

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