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"Seismic Stability Chart For Vegetated Homogeneous Dry Soil Slopes"

By

Pujan Giri

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DEPARTMENT OF CIVIL ENGINEERING

The undersigned certify that they have read and recommended to the Institute of Engineering for acceptance, a thesis entitled **"Seismic Stability Chart For Vegetated Homogeneous Dry Soil Slopes"** submitted by **Pujan Giri (070/MSG/811)** in partial fulfilment of the requirements for the degree of Master of Science in Geotechnical Engineering.

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ABSTRACT

Nepal is mountainous country perched in the subduction zone of Indian & Tibetan plate. Most of the landscape being covered with vegetation and being placed at the seismically prone area, a seismic stability chart that incorporates the effect of vegetation can aid in the preparedness against seismically induced landslide hazards.

Development of stability chart is a tedious, time consuming and computationally intensive task. So this thesis work presents a set of codes written in Visual Basic 6.0 that exploits the potential of command driven software SPECFEM3D_GEOTECH in batch processing.

Using batch processing, factor of safety of 8640 models have been computed. The models include 4 slope geometry 2H:1V, 1.5H:1V, 1H:1V & 0.5H:1V, having soil cohesion 1, 5, 10, 15, 20, 25 KN/m^2, and friction angle, 5, 10, 15, 20, 25, 30, 35, 40 degrees. Effect of vegetation has been modelled with a different layer of top soil; which has thickness equal to that of root depth and soil cohesion increased by a value equal to that of root cohesion. Root cohesion value 1, 5, 10, 15, 20 KN/m^2 and root depth 1, 2, 3 m have been adopted. And, the models are subjected to horizontal pseudo static seismic excitation of 0.1, 0.2, 0.3g along the direction of slope.

As the final outcome of this thesis work a set of nine charts have been developed in the format as prescribed by Michalowski (1998). These charts can be used to assess factor of safety of vegetated homogenous dry soil slopes. However, as these charts cannot distinguish whether the stability of slope is due to application of vegetation or the soil itself, three additional charts have been proposed to quickly assess the significance of vegetation in slope stability.

Further using SPSS, multi variable linear regression analysis has been performed to formulate an equation for FOS of vegetated dry homogenous soil slopes as given below;

$$FOS = 0.533 + 5.397\frac{c}{\gamma H} + 1.344\ \tan\emptyset - 0.301\ \tan\beta + 0.035\ R_d + 0.006\ c_r - 1.521\ K_x$$

The equation has regression coefficient R^2 0.916 and standard error 0.137.

Verification of the work has been carried out using commercial software Phase 2; which shows a strong correlation with the results from SPECFEM3D_GEOTECH.

ACKNOWLEDGEMENT

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070 MSG 811

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

c_r	Root Cohesion
c	Soil Cohesion
E	Young's Modulus of Elasticity
FEM	Finite Element Method
FOS	Factor of Safety
GLL	Gauss Lobato Legendre
HDD	Hard Disk Drive
LEM	Limit Equilibrium Method
RAM	Random Access Memory
SEM	Spectral Element Method
S26D2K0.3C5PH40CR10	S = Slope 26
	D = Root Depth 2
	K = pseudo static seismic coefficient 0.3
	C = Soil cohesion 5
	PHI= Friction angle 40
	CR= root cohesion 10
SRF	Strength Reduction Factor
USCS	Unified Soil Classification System
γ	Unit Weight
υ	Poisson's ratio
ψ	Dilation angle
φ	Angle of internal friction

CHAPTER ONE: INTRODUCTION

1.0 Background

Nepal is a mountainous country perched in the subduction zone of Eurasian and Tibetan Plate. Having hills mostly covered with forest and being situated in a seismically prone area, development of Seismic stability chart for vegetated soil slope can aid in the preparedness against seismic hazards.

Stability chart development is a computationally intensive job. It requires computation of FOS for all possible natural soil slope conditions. Stability chart developed so far are mostly based on LEM and a few are based on Stress Deformation Method. However charts incorporating the effect of vegetation on stability of slope under seismic is yet to be developed.

1.1 Objective

In general objective of this thesis work is to develop seismic stability chart for vegetated dry homogeneous soil slope. To achieve the main objective following specific objectives have been set:

a. Develop code to exploit the potential of command driven SPECFEM3D_GEOTECH for batch processing.
b. Perform parametric study on various model combinations

1.2 Scope

Once complete this thesis will present a set of code written in Visual Basic 6.0 that aid in batch processing using SPECFEM3D_GEOTECH. And, the Stability chart produced as a final outcome of this thesis will be applicable in preliminarily assessment of stability of vegetated homogeneous dry soil slope subjected to seismic excitation.

CHAPTER TWO: LITERATURE REVIEW

Stability Charts are the graphical tools that enable preliminary assessment of stability of slopes. Development of Stability Chart is a computationally intensive job, as it requires computation of all possible parametric variations that may occur in nature. Due to the analytical nature of calculation, Limit Equilibrium Method is much faster than Stress Deformation Method. Hence, most of the stability charts developed so far are based on LEM. However, with the advancement in the computation technique and tools stability charts based on Stress Deformation Method are gaining momentum.

2.0 Methods of Slope Stability Analysis

2.0.1 Limit Equilibrium Method (LEM)

LEM is an analytical method for determining the stability of slope. This method investigates whether a soil mass slides along a potential slip surface under the influence of gravity. Both soil mass; which slides and over which it slides, are considered rigid for this analysis and the shear stress along the slip surface is deemed to be equal to the shear strength of soil. However, in reality, neither the potential slip surface can be accurately predicted nor the shear stress all along the slip surface reaches critical at the same time.

There are many variations of this method such as: Swedish Circle ($\Phi = 0$) method, Logarithmic Spiral Method, Friction Circle Method, Ordinary Method of slices, Simplified Bishop Method, Janbu's Method, Spencer's Method, Morgenstern and Price's Method, Sarma's Method, etc

2.0.2 Stress Deformation Method

2.0.2.1 Finite Element Method (FEM)

Conventional methods of LEM are concerned either with calculation of critical height or the minimum factor of safety of the slope. With the development of personal computer, finite element method has been increasingly used in slope stability analysis. The advantage of a finite element approach over traditional limit equilibrium methods is that no assumption needs to be made in advance about the shape or location of the failure surface, slice side forces and their directions. The method can be applied with complex slope configurations and soil deposits in two or three dimensions to model all types of mechanisms. General soil material models that include Mohr-Coulomb and numerous others can be employed. The equilibrium stresses, strains, and the associated shear strengths in the soil mass can be computed very accurately. The critical failure mechanism developed can be general and need not be simple circular or logarithmic spiral arcs. The method can be extended to account for seepage induced failures, brittle soil behaviours, random field soil properties, and engineering interventions such as geo-textiles, soil nailing and retaining walls. This method can give information about the deformations at working stress levels and is able to monitor progressive failure including overall shear failure (Griffiths and Lane, 1999).

2.0.2.2 Spectral Element Method (SEM)

The governing equations contain high-order partial differential equations to represent the slope stability problem of infinitely long, large, and complex slopes. The FEM methods are not efficient to integrate high-order polynomial equations and demands a more sophisticated computing facility since it requires solving a whole mass matrix. A large number of meshes is required for the convergence of the results, and consideration of progressive failure also demands an increased number of iterations. In this context, a high-order FEM known as Spectral Element Method (SEM) has been developed to evaluate the stability of infinitely long and steep slopes.

SEM employs nodal quadrature, namely, Gauss-Legendre-Lobatto quadrature. In nodal quadrature, interpolation nodes coincide with integration points *(Figure 1).* The coincidence of integration and interpolation points has two main advantages: 1) interpolation is unnecessary to determine nodal quantities from quantities at quadrature points and vice versa, thus simplifying computation of the stiffness matrix, strain, stress, etc., and 2) interpolating functions become orthogonal on quadrature points, resulting in a diagonal mass matrix, thereby simplifying the time-consuming algorithm. SEM method adopts the geometric flexibility of finite element and implements high order polynomial equations, which lead to high numerical stability as well as reliable spectral accuracy in less computing time. (Gharti et. al, 2011)

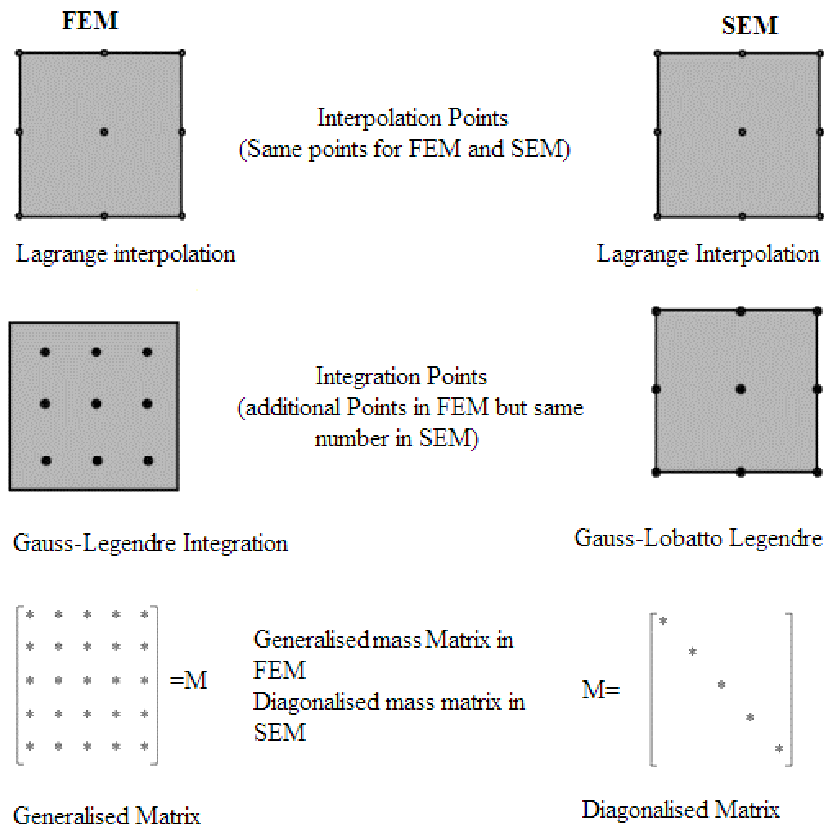


Figure 1 Comparison of SEM and FEM Formulation

2.1 Seismic Slope Stability Analysis

Seismic Slope stability can be carried out using a) Pseudo Static Analysis b) Stress Deformation Analysis and c) Newmark's Sliding Block method.

SPECFEM3D_GEOTECH employs pseudo static analysis hence only the method of analysis has been presented here.

2.1.1 Pseudo Static Analysis

The first known documentation of Pseudo static analysis in the technical literature was by Terzhagi (1950). In pseudo-static approach, the effects of an earthquake are represented by constant vertical (kv) and horizontal (kh) seismic acceleration coefficients and the factor of safety is evaluated by using limit equilibrium or finite element method. The constant horizontal or vertical accelerations produce horizontal inertial forces, Fh and vertical inertial forces Fv, acting through the centroid of the failure mass. The magnitude of the pseudo-static forces are

$$F_h = \frac{a_h W}{g} = k_h W \quad \text{and} \quad F_v = \frac{a_v W}{g} = k_v W$$

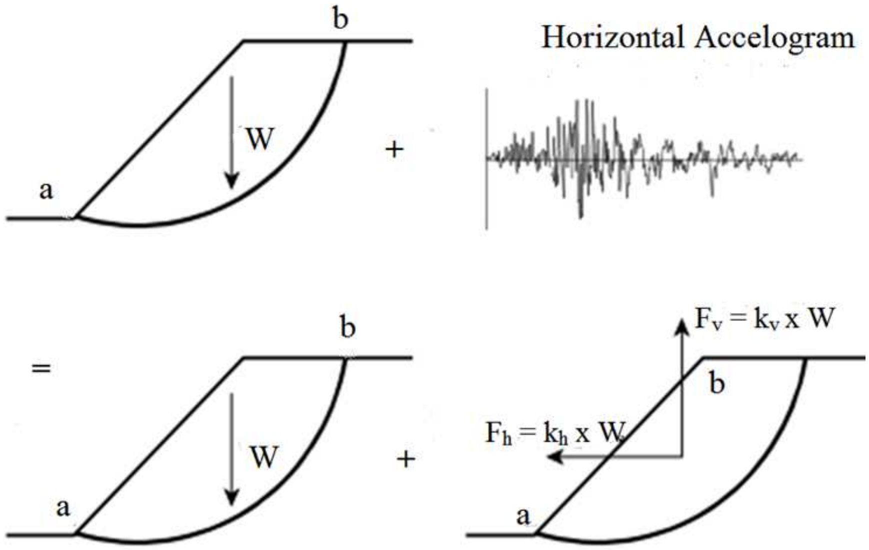


Figure 2 Pseudo Static seismic analysis

A common approach of using pseudo-static analysis is to iteratively conduct analysis using different values of k until FS=1. The resulting pseudo-static coefficient is called the yield coefficient, k_y. In the simplest sense, any ground acceleration exceeding k_y x g causes failure. The limitation of pseudo-static analysis is that, because it is a limit-equilibrium analysis, it tells the user nothing about what happens after equilibrium is exceeded. The analysis shows a slope to be either stable or unstable, but the consequences of instability, or even the likelihood of failure, cannot be judged.

2.1.2 Pseudo Static Seismic Coefficient

Selection of an appropriate seismic coefficient is the most important, and difficult, aspect of a pseudo static stability analysis. In theory, the seismic coefficient values should depend on some measure of the amplitude of the inertial force induced in the slope by the dynamic forces generated during an earthquake. Because soil slopes are not rigid and the peak acceleration generated during an earthquake last for only a very short period of time, seismic coefficients used in practice generally correspond to acceleration values well below the predicted peak accelerations (Kramer, 1966). However, the choice of coefficients used in the slope stability analysis is very subjective and lacks a clear rationale. *Table 1* below shows horizontal seismic coefficient values that have been recommended for design.

Table 1 Pseudo Static Seismic Coefficients

Authors	Application	Limiting disp. cm	Seismic coefficient	Safety Factor
Terzaghi (1950)	-	-	0.1 0.2 0.5	-
Seed (1979)	Earth dams	100	0.1 for M=6.5 and 0.15 for M=8.25	1.15
Marcuson (1981)	Earth dams	-	(0.33-0.50) x PGA	1.0
Hynes et al. (1984)	Earth dams	100	0.5 x PGA	1.0
Bray et al. (1984)	Solid waste landfills	15 to 30	0.75 x PGA	1.0
Euro code 8 (2005)	Design	-	k_h= 0.5αS k_v=±(0.33- 0.5) x k_h	-
USACE	Earth dams	-	0.10 0.15	1.0

2.2 Effect of Vegetation

Wu et. al has modelled the effect of root reinforcement in terms of the increase in cohesion of soil; which is given by the following relation.

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

Where,

C_r = root cohesion
t_r = tensile strength of root
ϕ = Friction angle
θ = angle of inclination of root wrt. to vertical.

Root cohesion varies within a range of 0 to 20 KN/m^2 and Root depth vary upto 3 meters.

2.3 Strength Reduction Factor

Failure of soil slope is due to the reduction in shear strength or increase in the shear stress. Strength of soil mass is given by the following equation.

$$\tau = \sigma \tan\phi' + c'$$

Where,
τ = shear strength
σ = Effective normal stress
ϕ' = Friction angle
c' = cohesion

Stress Deformation Method of slope stability assessment employ strength reduction approach to determine factor of safety. In this approach, strength of the soil is reduced by a factor, namely Strength Reduction Factor (SRF), until the slope fails. Failure is signified by sudden large deformation and the SRF at which the failure occurs is deemed as FOS.

Strength of soil is reduced using SRF as shown below.

$$\phi_f' = \tan^{-1}\left(\frac{\tan\phi'}{SRF}\right) \quad \text{and} \quad c_f' = \frac{c'}{SRF}$$

2.4 Stability Charts

Most of the charts available for seismic stability of slope are based on LEM. Michalowski (1998, 2010), Baker (2006) are the example of seismic stability chart developed using LEM for barren homogeneous soil slopes. Due to advancement of computation capabilities, Zhang et al (2010) has developed charts for 3D and 2D slopes using FEM however the effect of seismicity has not been considered on this chart. Moreover, effect of vegetation on slope stability under seismic excitation has not been incorporated in any of them.

2.4.1 Michalowski, 1998

Based on the chart of Michalowski, Khanal, 2015 made an attempt to develop seismic stability chart using SEM. He adopted 4 slope values (2H:1V, 1.5H:1V. 1H:1V, 0.5H:1V) using various pseudostatic seismic coefficients. He has verified his work against Phase2. The stability chart as prepared by Khanal, 2015 is as shown.

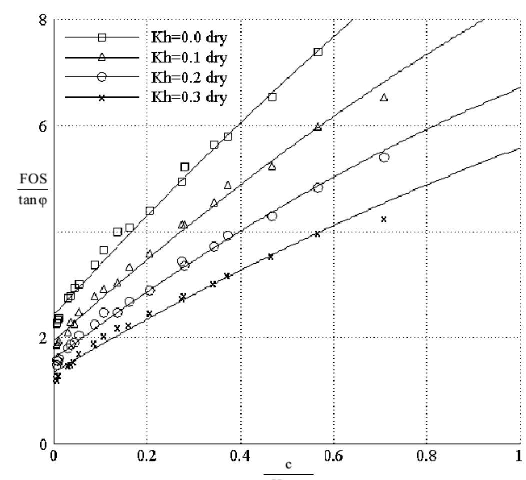


Figure 3 Pseudo static seismic stability chart prepared by Khanal, 2015 based on Michalowski 1998

However, the stability chart doesn't account for the effect of vegetations in the slope stability under seismic exitation.

2.4.2 Tiwari, et al., 2013

Tiwari, et al., 2013 used spectral element method to produce 3-D seismic slope stability charts. Stability charts were prepared for slopes of 26.26^0(2H:1V), 33.69^0(1.5H:1V), 45^0(1H:1V) and 63.4^0(1H:2V) involving general USCS material models and seismic coefficient of K_x=0.1 and K_x=0.2. Both dry and saturated slopes were used. The slopes were modelled as completely vegetated taking into consideration two root related factors (a) Root cohesion (C_r=0,10,20 kN/m^2) and (b) Root zone of 2.0 m.

A total of 540 model were used in the preparation of 28 stability charts. Pseudo static seismic stability chart as developed by Tiwari et al, 2013 is presented below.

However, selection of USCS soil parameters has limited the development of chart and the effect of root depth of only 2 meter has been considered into the development of the chart

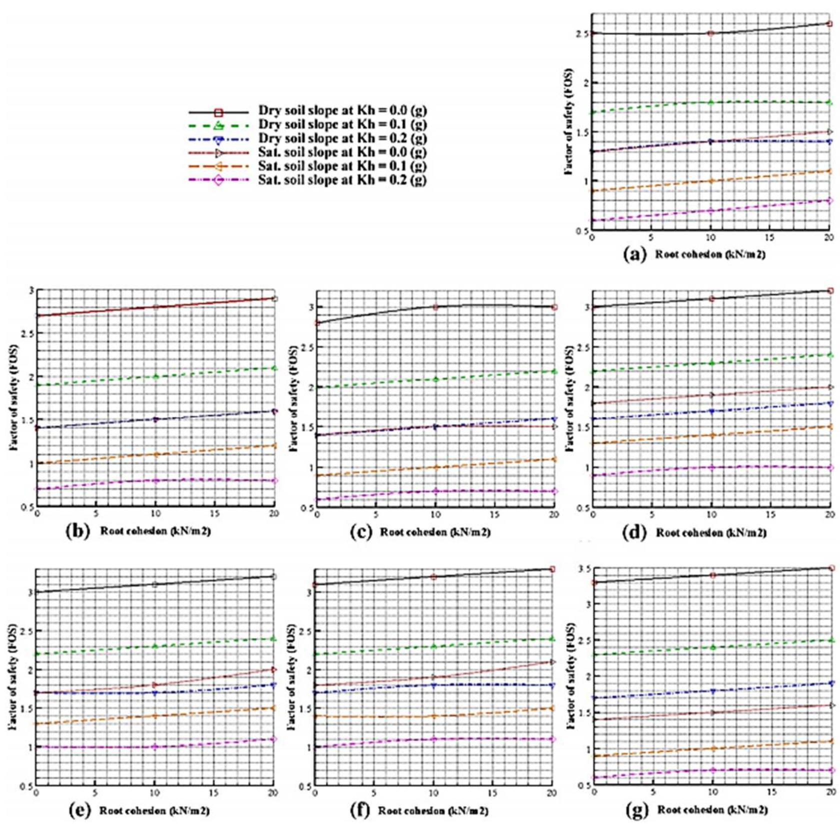


Figure 4: Stability charts of 33.69^0 after Tiwari et al, 2013

CHAPTER THREE: MATERIALS AND METHODS

3.0 Numerical Model

3.0.1 Model Geometry

Many researchers have successfully implemented stratified model to account for the effect of vegetation. Hence, vegetation has been modeled as a different layer of soil overlaying the base soil. Thickness of the top soil layer represents the root depth of the vegetation. 4 slopes (2H:1V, 1.5H:1V, 1H:1V, 0.5H:1V) each having 1, 2 & 3 meters of root depth have been modeled in Trelis as illustrated in Figure 5. Trelis journal used for model generation is included in the Annex 1.

3.0.2 Soil Properties

In nature, there is a wide variation in soil properties such as cohesion, friction angle and Unit weight. It's recommended that the laboratory tests be carried out to determine the soil properties incase of site specific modelling. However for the purpose of development of stability chart, it is desirable to incorporate all the variation in soil properties. Range within which value of various soil properties vary have been adopted from Unified Soil Classification System (USCS), and discretized as below in this thesis.

Cohesion 1, 5,10,15,20, 25 KN/m^{2,} friction angle 5, 10, 15, 20, 25, 30, 35, 40 degree and unit weight 20 KN/m^3 have been adopted in this thesis.

Root Cohesion 1, 5, 10, 15, 20 KN/m^2 have been adopted.

3.0.3 Constitutive Parameters

Stress Deformation Methods require constitutive parameters, such as Youngs Modulus of Elasticity, Poissions Ratio, Dilation Angle, be specified. Although these values actually vary with soil type and have profound effect on deformation, adopting E=10E5 KN/m^2 , υ=0.3 and Ψ=0 has little influence on FOS (Griffiths and Lane 1999)

For the elasto-plastic materials which have failure criterion as that of Mohr-Coulomb, Zhang et al. (2005) suggested that Φ-ν (phi-nu) inequality criterion should be satisfied. The inequality is given as: $\sin\phi \geq 1 - 2\nu$. If the criterion is not satisfied, it leads to over estimation of plastic zones and under estimation of FOS. So, the value of Poisson's ratio has been adjusted accordingly in this thesis report. Poisson's ratio has been adopted as 0.42 for soil having angle of internal friction up to 20° and 0.33 has been adopted for soil having higher values of internal friction.

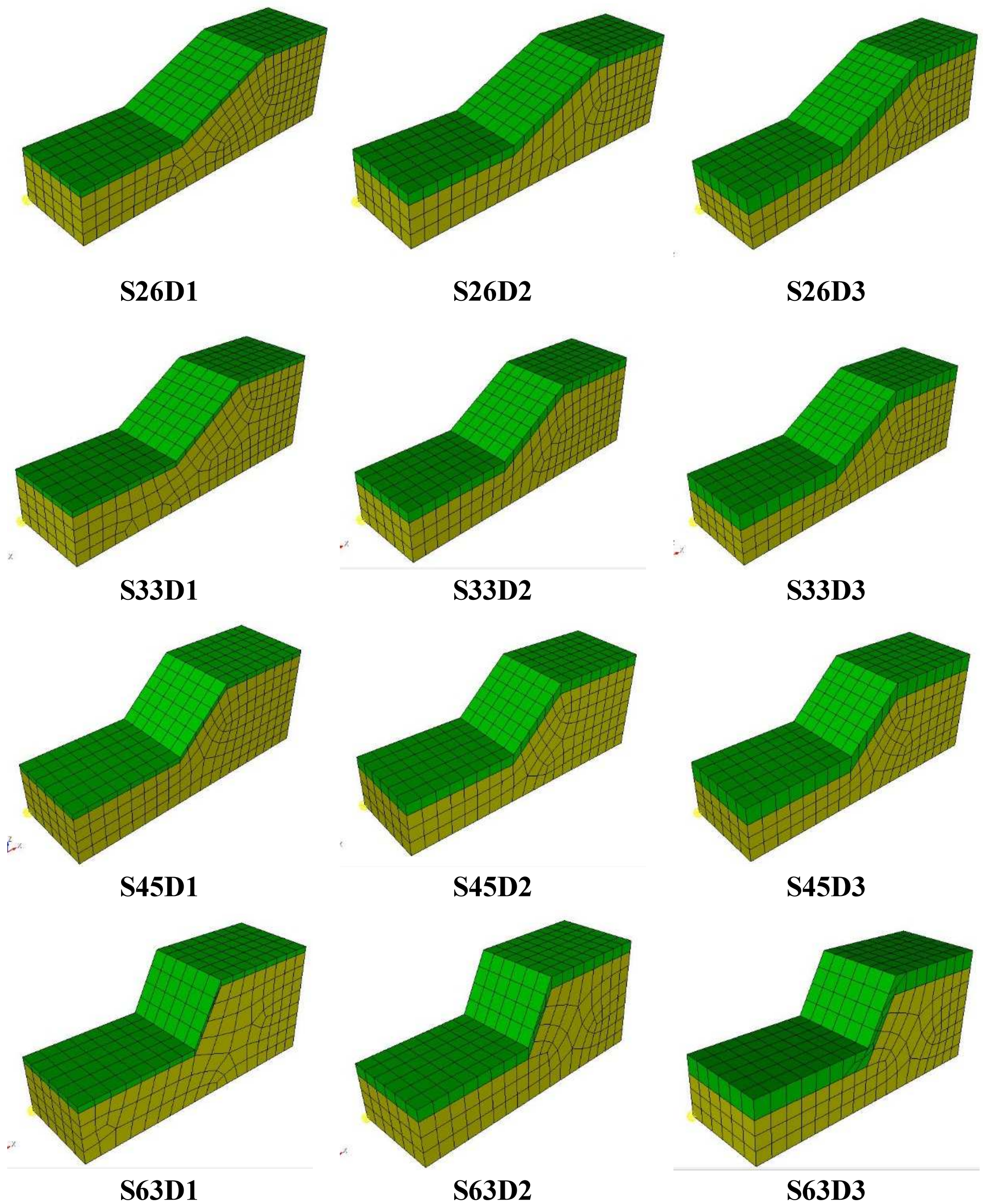


Figure 5 Model geometry with various slope angle & root depth

3.0.4 Load Parameter

Besides body forces, the model are subjected to the horizontal seismic excitation only. Pseudo static seismic coefficient of 0.1g, 0.2g and 0.3g have been adopted in this thesis.

3.0.5 Boundary Condition

2D boundary condition as illustrated below, as per Zhang et.al, 2010 has been adopted.

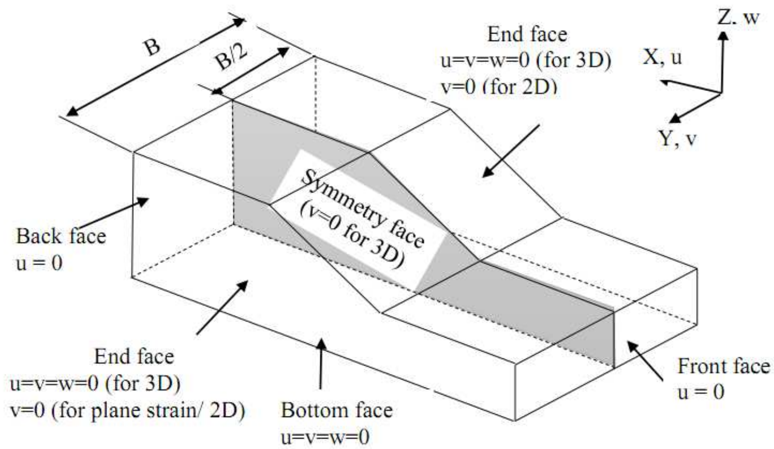


Figure 6 Boundary condition as per Zhang et al. 2010

3.0.6 Failure Criteria

SPECFEM3D_GEOTECH employs Mohr-Columb failure criteria. This criteria is effective for the soil possessing both of the components of cohesion and friction. In terms of principal stresses and assuming a compression- negative sign convention, the criterion can be written as follows:

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

where, σ_1' and σ_3' are major and minor principal effective stresses.

The failure function F can be interpreted as follows:

F<0 stress is inside envelope (elastic)

F=0 stress on failure envelope (yielding)

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

3.0.7 Summary of Model Combinations

Table 2 Summary of model combinations

S	C	ϕ	Cr	D	Kx	
2H:1V	1	5	1	1	0.1	
1.5H:1V	5	10	5	2	0.2	$\gamma = 20$ KN/m^3
1H:1V	10	15	10	3	0.3	E = 10^5 KN/m^2
0.5H:1V	15	20	15			
	20	25	20			$\upsilon = 0.42$ for $\phi \leq 20$
	25	30				$\upsilon = 0.33$ for $\phi > 20$
		35				$\Psi = 0$
		40				
Count						
4	6	8	5	3	3	1
			Total Combinations			8640

3.1 Numerical Tools

Table 3 Numerical Tools

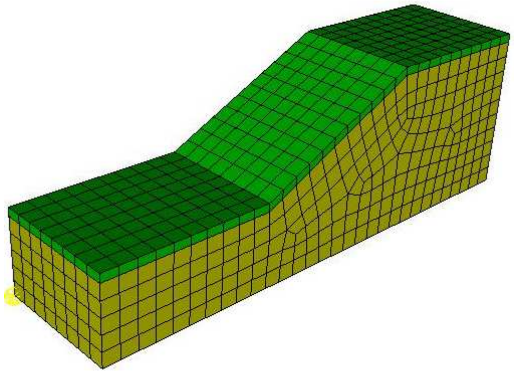
Stage	Tool	Function
Input	Trelis	Create 3D Model Create & refine mesh Assign boundary conditions Export to Exodus file format
Processing	Cygwin, Scotch, MPI SPECFEM3D_ GEOTECH	**Cygwin**: To simulate Unix environment within Windows. **Scotch:** Graph Partitioning **MPI:** Message passing interface for parallel simulations. **Specfem3d_Geotech** Converts Exodus to ASCII Input Format Performs all computations
Output	Tecplot Paraview	**Tecplot:** Preparation of various charts **Paraview:** Visualization of displacement contours

3.2 Model Tests

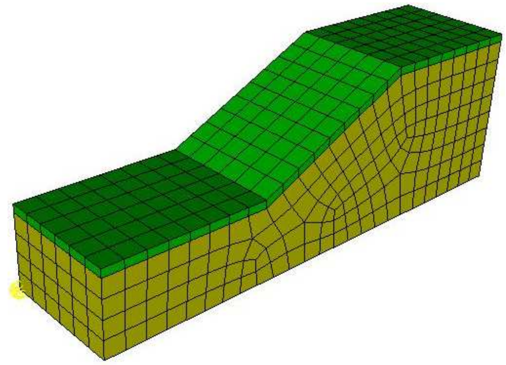
3.2.1 H-Refinement

H-refinement refers to the change in mesh size of a numerical model. In FEM, H-refinement technique is often employed in region having irregular geometry. However Trelis doesn’t have the ability to refine mesh on a particular region. Hence mesh size of entire model has been varied and tested for variation of FOS and computation time.

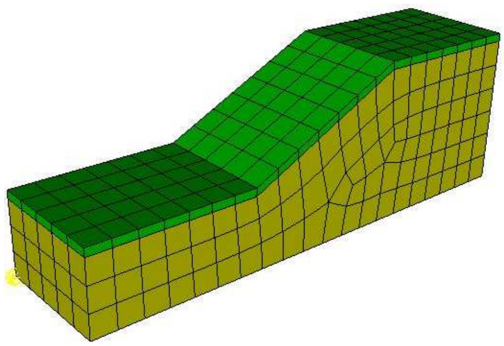
Models with varied mesh size are as illustrated in Figure 7.



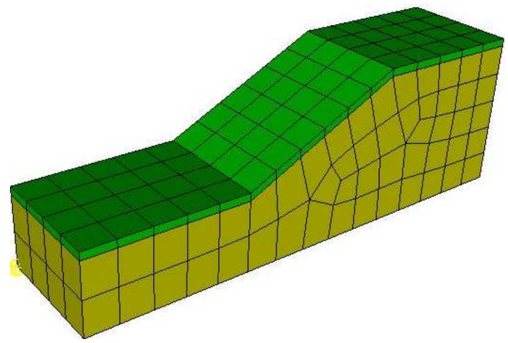
(a)Element Size 2m Number 1968



(b)Element Size 2.5 m Numbers 1074



(c) Element Size 3m Numbers 550



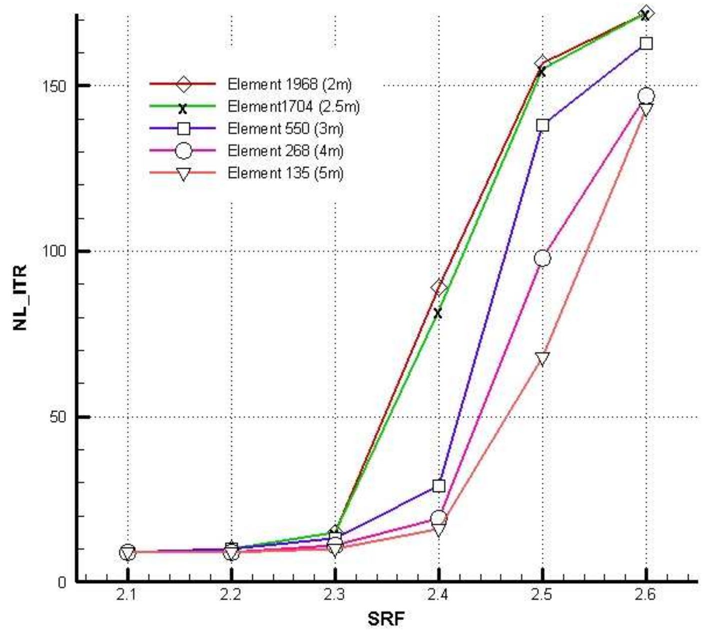
(d)Element Size 4m Numbers 268

Figure 7 Model showing various mesh sizes

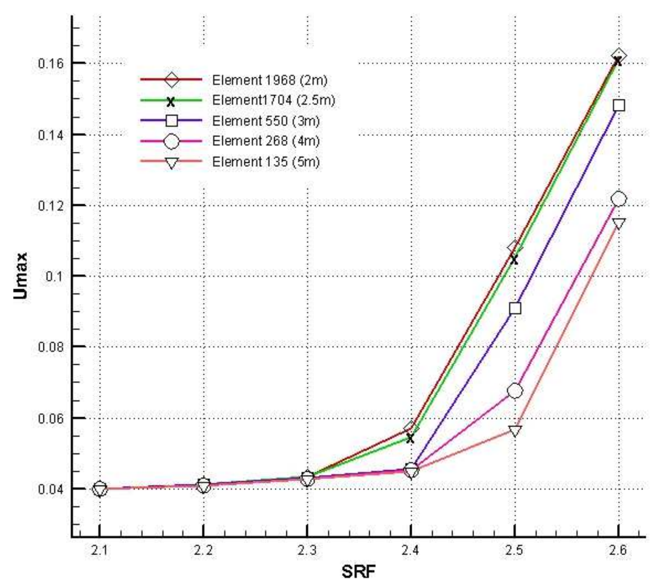
The results from the H-refinement test are as shown below.

Table 4 Computation time for various Element Budgets

Computation time for various element budget					
Element Size	2m	2.5m	3m	4m	5m
/Number	(1968)	(1074)	(550)	(268)	(135)
Time (seconds)	4995	2439	915	334	250



(a) NL_ITR Vs. SRF



(b) Umax Vs. SRF

Figure 8 (a)NL_ITR VS SRF (b) Umax Vs SRF

The test showed that a mesh size of 2.5 m yields FOS accurately with the least computation time. Hence, the mesh size of 2.5m has been adopted in batch processing.

3.2.2 P-Refinement

Accuracy numerical computation can be varied by varying the degree of polynomial of the shape function. P-refinement test was performed to determine the GLL value that yields FOS with reasonable accuracy with the least computation time.

The result obtained from the test are as illustrated below.

Table 5 Variation of Computation Time with GLL Points

Variation of Computation time with GLL points				
GLL	2	3	4	5
Seconds	3.8405	132.4453	2419	24180

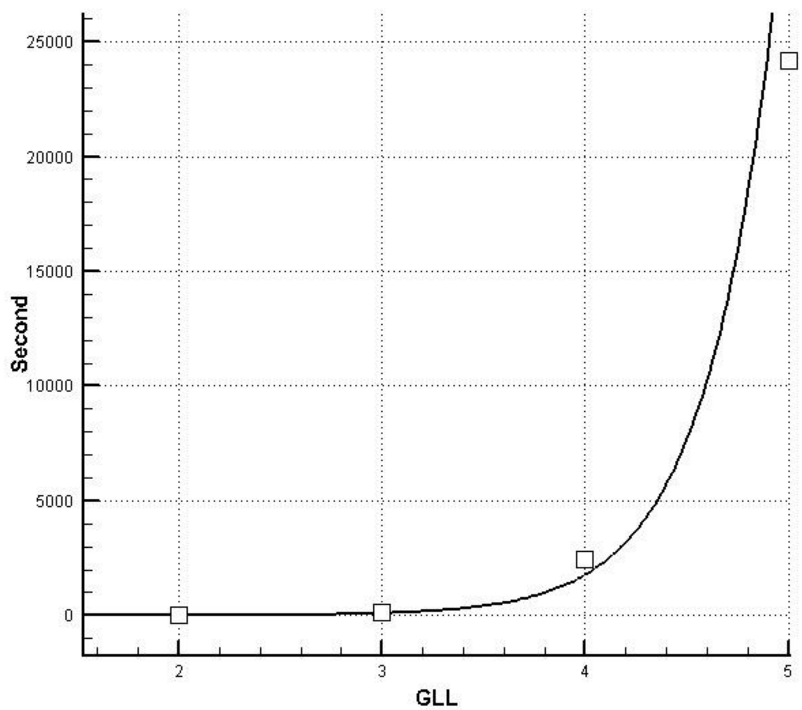


Figure 9 Variation of computation time with increase in GLL points

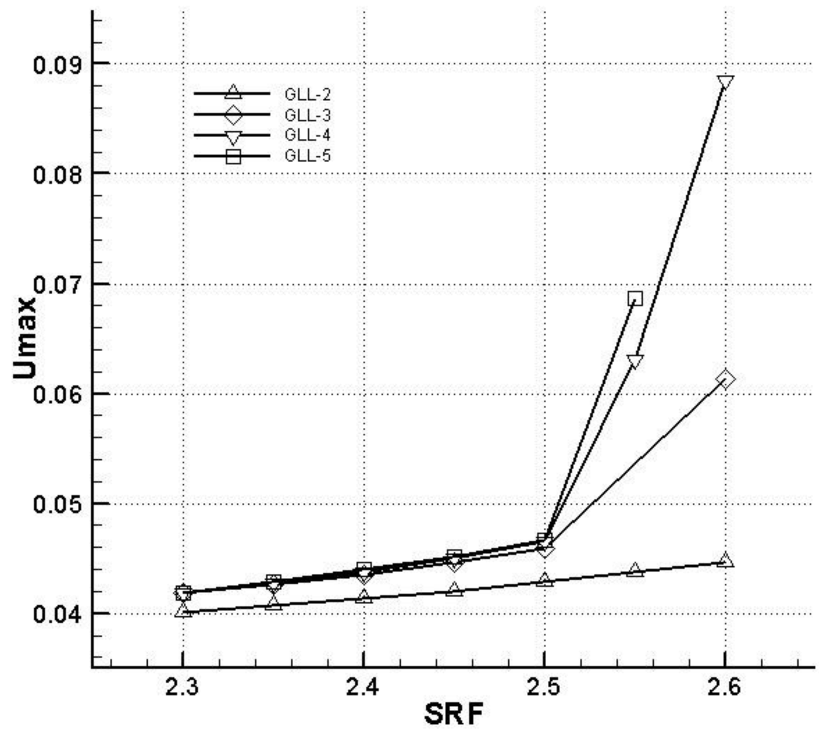


Figure 10 FOS at various GLL points

From the P-refinement test GLL 3 was found to yield FOS with reasonable accuracy in least time. Hence, GLL 3 was adopted batch processing.

3.2.3 Partitioning

To understand the effect of parallel processing on computation time, a domain having 2568 elements is decomposed into various partitions, as visualized in Figure 1. Domain was decomposed such that the number of partitions was equal to the number of cores intended to be used for simulation.

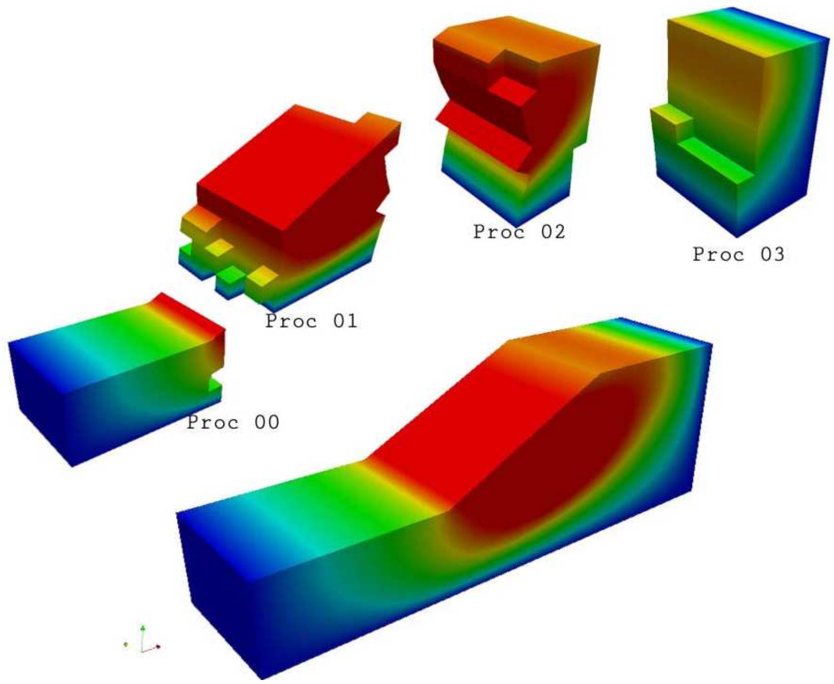


Figure 11 Domain Decomposition for 4 cores visualized using ParaView

The result obtained from the simulation are as follows.

Table 6 Variation of computation time with No. of processors

Variation of computation time with No. of Processors						
Processor(s)	1	4	8	16	20	24
Time (sec)	724.8906	200.0078	138.9648	106.3828	98.9352	106.6576

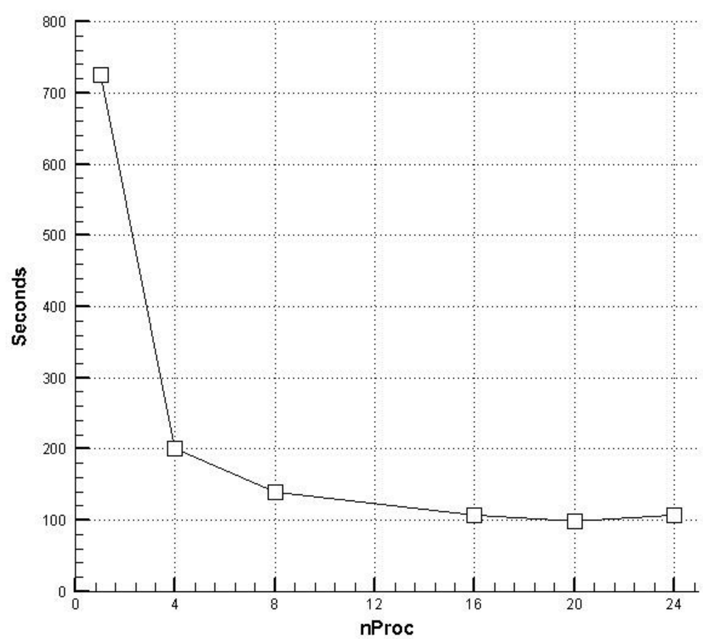


Figure 12 Variation of computation time with No. of Processors

Figure 2 shows that parallel processing is significantly faster than serial processing. There is an almost one forth reduction in computation time while using 4 cores as compared to a single core. However, the rate at which the computation time decreases onwards is very gradual.

It is also worth noting that there is an increase in computation time while using 24 cores as compared to 20 cores. This may be due to Pagefile usage. Pagefile is a space allocated in the HDD to temporarily store the contents of RAM incase the system runs low on RAM. Use of Pagefile involves read & write operations on HDD; which itself is a slower process.

Hence, increase in the number of processors doesn't necessarily mean reduction in computation time. It depends on system configuration and has to be tested independently for each system for optimum results.

3.3 Methodology

Procedure for the computation of factor of safety for all the model combination has been carried out as shown in the flow chart below. The procedure can be divided into two stages. In the first stage the basic slope models were prepared and various tests such as H, P refinements, & quality checks were performed in the local PC. Once the models were found suitable for the purpose of computation of FOS, they were uploaded to the server. The Codes were executed, in the order as shown in flowchart, to generate the simulation files for SPECFEM3D_GEOTECH, to generate batch file for execution of the simulation and to extract FOS after all the simulation were completed.

The function of each code is listed below:

a. Code-1: Generates simulation files SPECFEM3D_Geotech, Generates batch file to execute all simulations without human intervention.
b. Code-2: Checks the results of the completed simulation & determines if models have undergone plastic deformation. Generates Batch File for the models that are yet to undergo plastic deformation.
c. Code-3: Extracts FOS from the results in CSV file format & generates Charts for Tecplot 360 for all models.

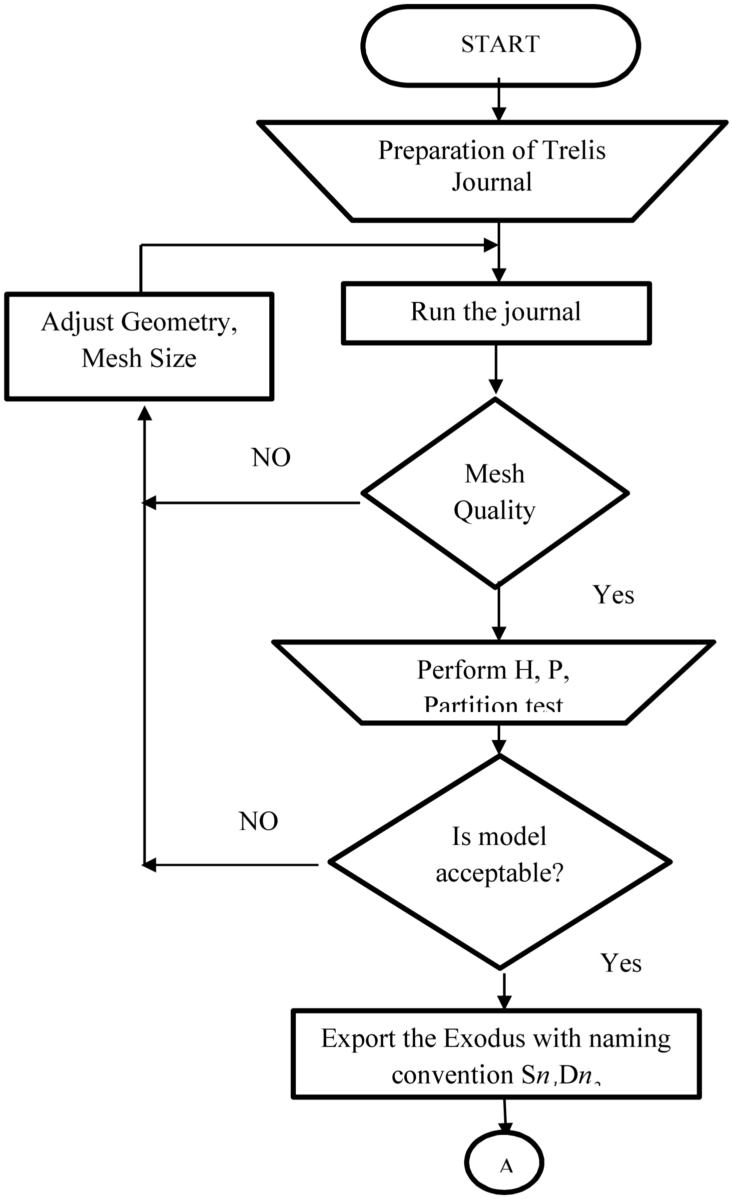


Figure 13. Flow Chart of Procedure carried on Local PC

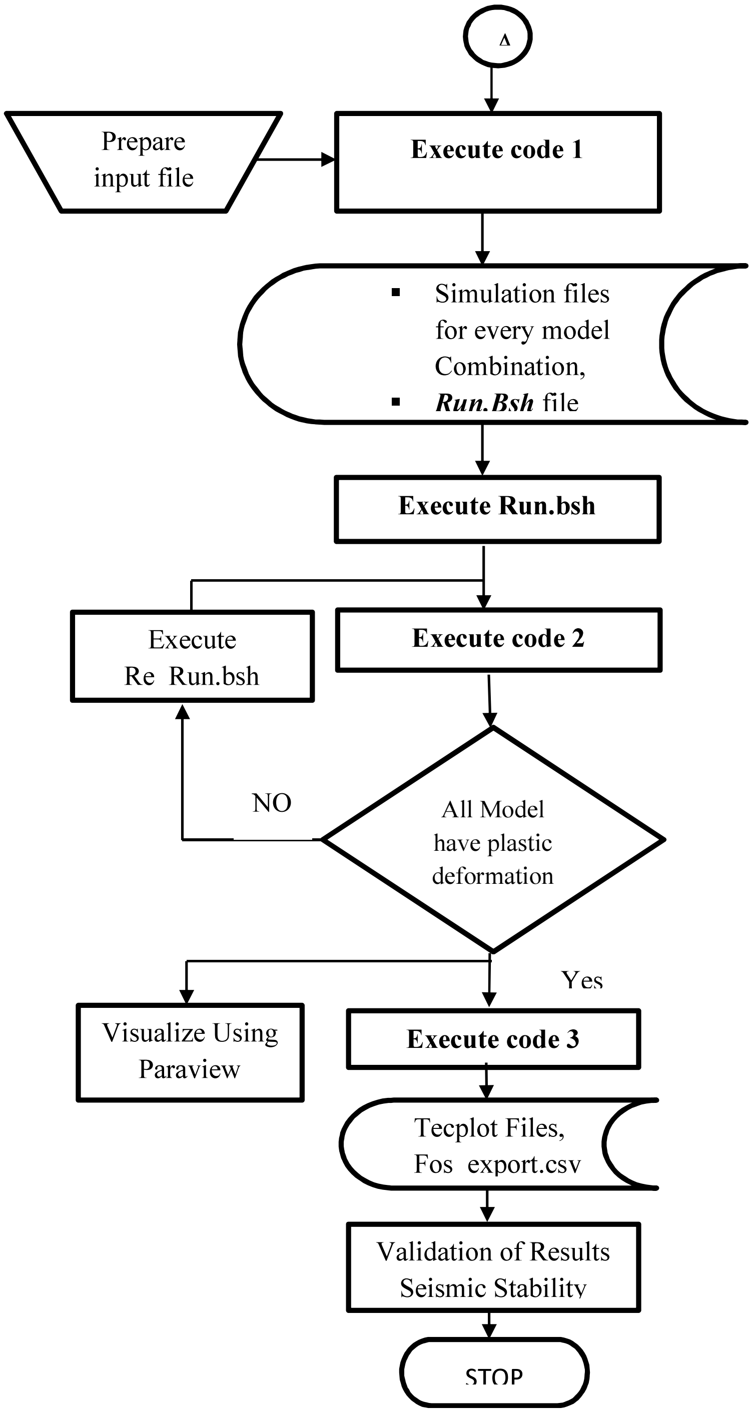


Figure 14 Flowchart of Procedure Carried in Server

CHAPTER FOUR: OUTCOMES

Following the work procedures as per the methodology as descripted in Chapter Three. FOS for all model combinations were determined. All the results have been attached in the appendix. Due to voluminous nature of the work it is not practicable to present all the graphs. So, for illustration purpose, 45° slope having γ=20 KN/m^3, Φ=15, c=10 KN/m^2, Cr = 5 KN/m^{2,} D=1 m subjected to Kx=0.1g, 0.2g and 0.3g has been presented in this section.

4.0 SRF Vs. Displacement

The failure of the material model is defined as the point, from which the material in elastic zone enters the plastic zone. At a factor of 0.7, 0.6 and 0.5 for horizontal seismic load coefficients of 0.1g, 0.2g and 0.3g, the displacement sharply increases and the curve becomes almost vertical. This point of deflection of the plot is the described as the FOS for the slope.

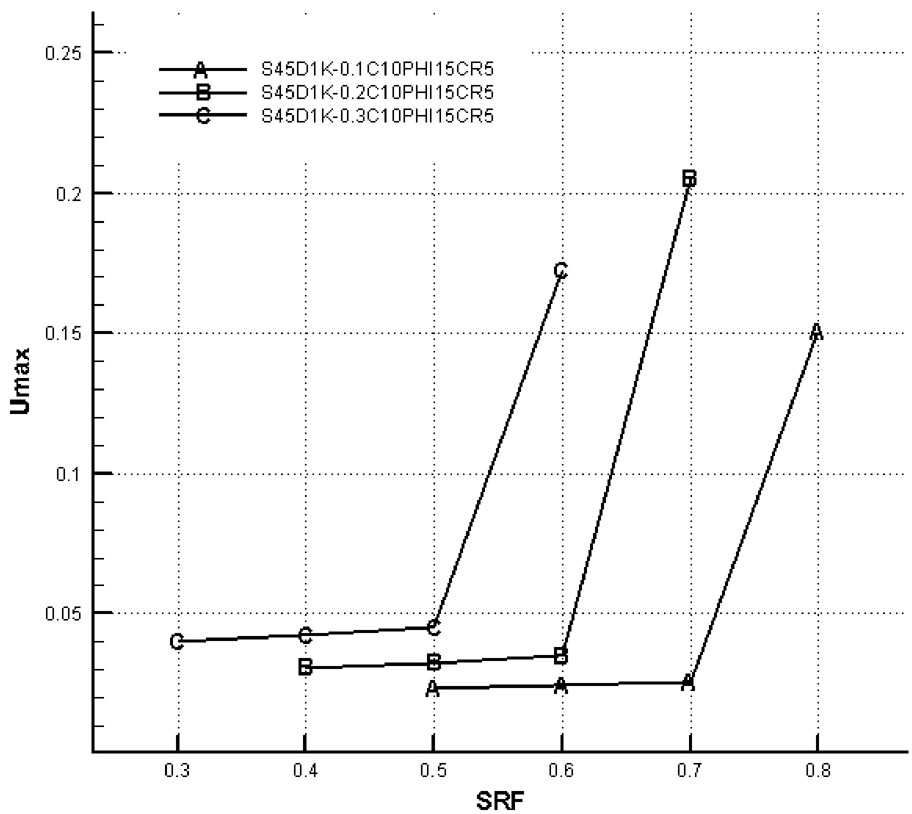


Figure 15 SRF Vs Displacement

4.1 SRF Vs. Nonlinear Iterations

As failure approaches, more Gauss points undergo plastic deformation, requiring a large number of iterations for convergence. Only a few iterations are required to converge to the solution in the elastic range. At a factor of 0.7, 0.6 and 0.5 for horizontal seismic load coefficients of 0.1, 0.2 and 0.3, the number of nonlinear iterations suddenly increases and the curve becomes almost vertical

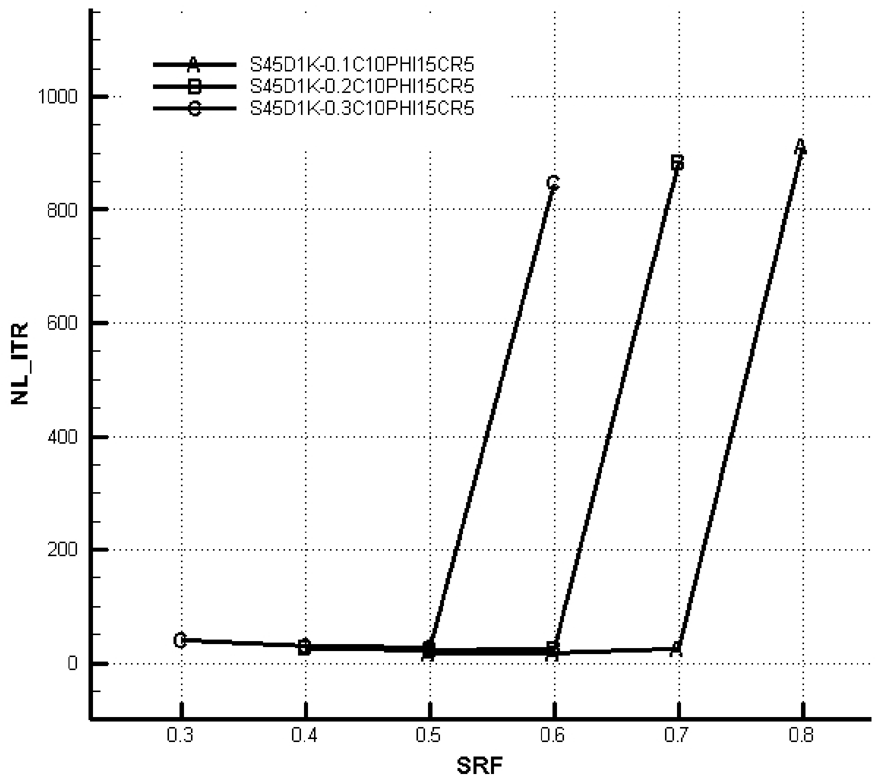
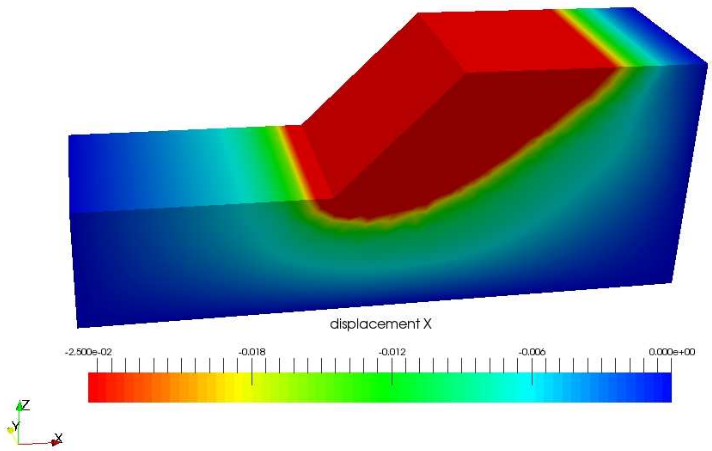


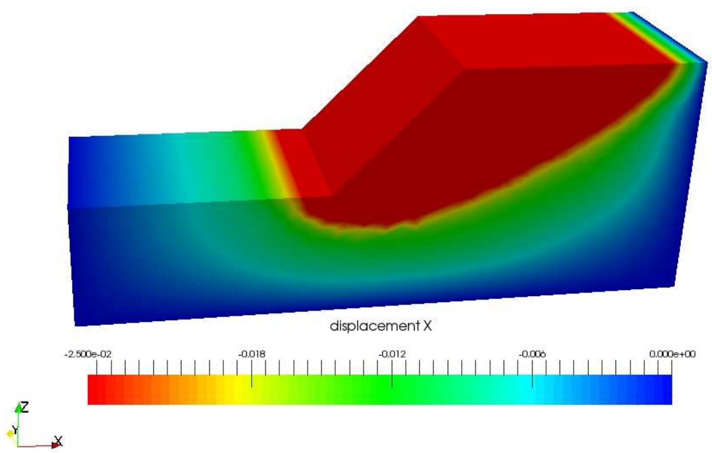
Figure 16 SRF Vs NLITR

4.2 Displacement Contour

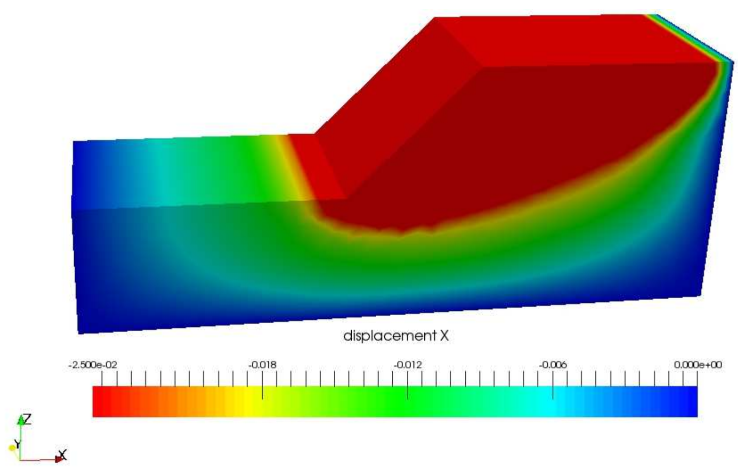
Displacement along the slope direction can be visualized using Paraview as shown below. This helps understand the nature of failure of the slope.



(a) Seismic coefficient 0.1g



(b) Seismic coefficient 0.2g



(c) Seismic coefficient 0.3g

Figure 17 3D visualization of results using Paraview

4.3 Final Outcome

As the final outcome of this thesis work, a set of 9 charts has been prepared as in Annex-2. Each chart has 12 curves representing FOS for root cohesion 1, 10 & 20 KN/m^2 for each slope. The curves are obtained as best fit polynomial of 2^{nd} order having R^2 value 0.987. Curves for Root Cohesion Value 5 & 15 KN/m2 have not been presented due to very small variation in FOS. The charts are based in the format as prescribed by Michalowski (1998) & can be used in similar manner.

However as these charts merely state the FOS of slopes and do not distinguish the effect of vegetation on the stability of slope, additional 3 charts have been prepared by comparing the FOS of the barren slopes & vegetated slopes under seismic excitation. For this purpose, FOS across various C and ϕ are obtained and contour map of FOS is prepared as shown in Annex-4. The contour corresponding to unit FOS for barren slope represents the upper bound and the contour corresponding to unit FOS for vegetated slope represents the lower bound. Thus, each chart is a plot between Stability Number (C/γH) and Friction Angle (ϕ) and for each slope in the chart, an upper bound and a lower bound has been specified. The region above the upper bound is stable even without application of vegetation, the region between upper and lower bound can be stabilized using vegetation. The charts are presented in Annex-3.

In addition to that, a multi variable regression analysis was performed using SPSS. The results of the analysis is presented in the Annex 8. The equation obtained from the regression analysis is:

$$Y = 0.533 + 5.397\frac{c}{\gamma H} + 1.344\ \tan\emptyset - 0.301\ \tan\beta + 0.035\ R_d + 0.006\ c_r - 1.521\ K_x$$

Where Y= Predicted FOS

C=Soil Cohesion

γ = Unit weight of soil

H= Height of slope

ϕ = Friction angle of soil

β = slope angle

R_d= Root depth in meters

C_r= Root Cohesion in KN/m^2

K_x= Seismic Coefficient as fraction of g.

The equation has a regression coefficient R2 of 0.916 and standard error of 0.1372. The standard error shows the wide range of variability of the FOS predicted using this equation. A chart comparing the FOS obtained from various methods is shown below; which shows the over estimation of FOS by the regression equation as compared to other methods.

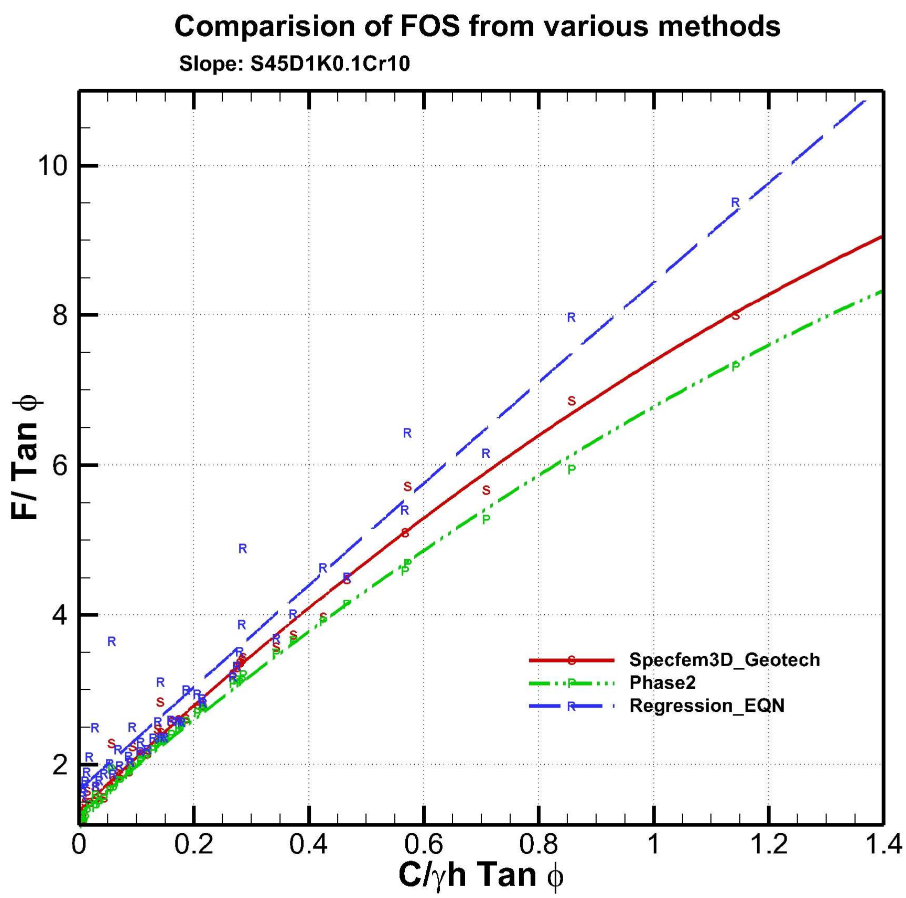


Figure 18 Comparison of FOS from Regression with SPECFEM & Phase2

CHAPTER FIVE: VERIFICATION

Verification of the computation from SPECFEM3D_GEOTECH was verified against the commercially available software Rocscience Phase2. In Rocscience Phase2, computation was carried out on two dimensional model having uniform 6 noded triangle using Gauss Elimination method.

For the verification of the computation, correlation coefficient between the FOS obtained from SPECFEM3D_GEOTECH and Phase2 were computed. Thus obtained correlation coefficients ranges from minimum 0.992 to maximum 0.999 and have mean of 0.997. Hence it can be deemed as satisfactory

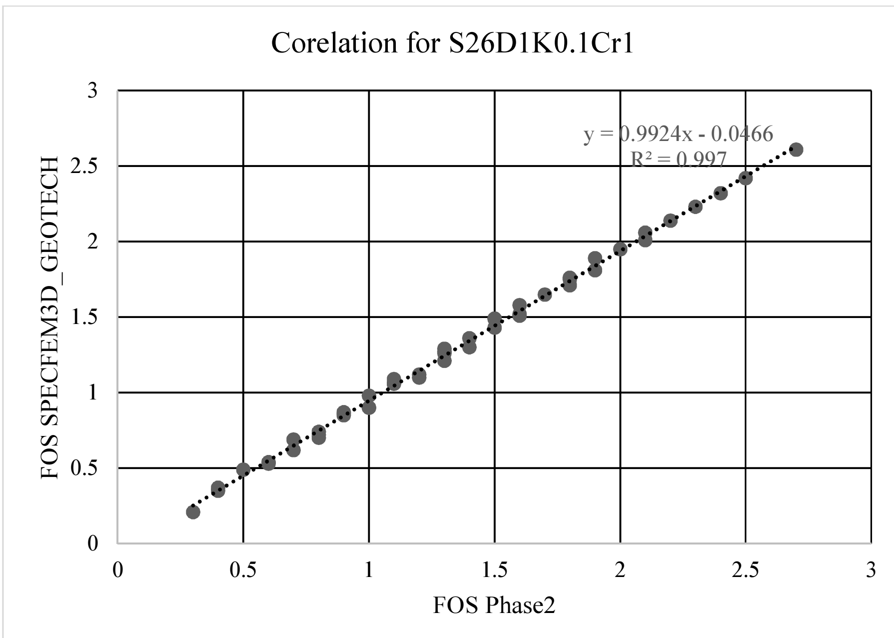


Figure 19 Correlation of FOS from Phase2 and SPECFEM3D_GEOTECH

For the verification of charts, a random model was assumed as follows:

Slope=45 degrees; Height=5m; ∅= 30; c=1; Kx=0.1

Cr=5; Rd=3

The model was simulated with & without vegetation in Phase2 to obtain critical SRF as 0.69 and 1.13 respectively.

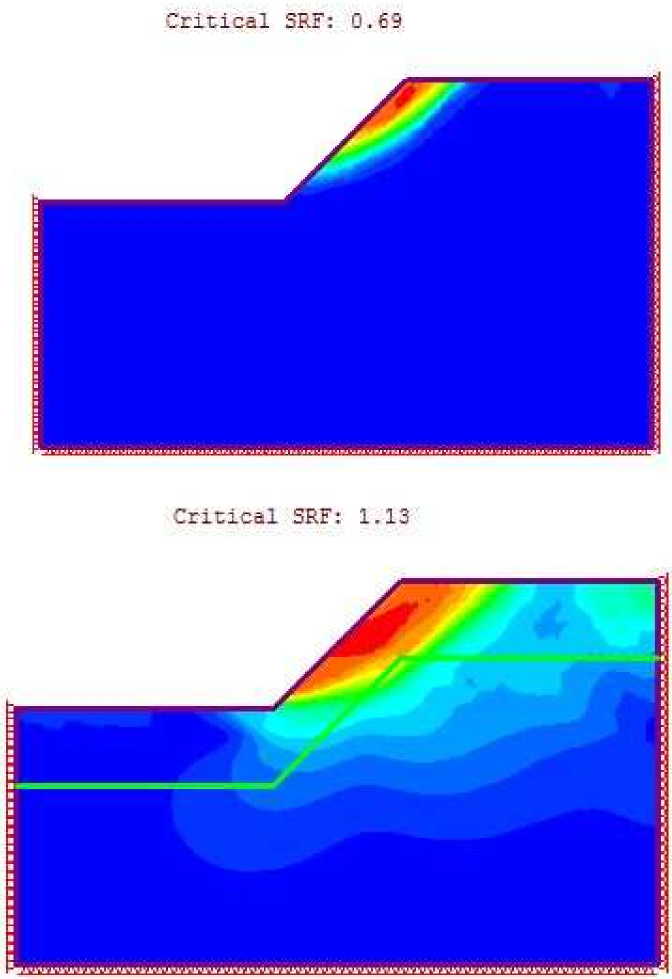


Figure 20 Phase2 models with & without vegetaion for verification

Results from the charts are tabulated and verified against results from Phase 2 as shown:

Table 7 Summary of verification

Chart/Equation	Observation	Remarks
Seismic Stability Chart	FOS: 1.2	Verified
Additional Chart	Slope is unstable without vegetation but can be stabilized with vegetation	Verified!
Regression Equation	FOS: 1.279	Verified in this particular case but the equation on an average has an error of 0.137.

CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Stability Charts are useful for preliminary assessment of stability of slopes having various slope geometry and soil properties. These charts may not be applicable for each & every slope problems which demand site specific analysis. However, these stability charts have a tremendous scope in hazard mapping, where site specific analysis is not possible due to large spatial variability.

In this thesis, Factor of Safety for 8640 model combinations were computed. And, it was observed that FOS of soil slopes having high friction angle and low cohesion are significantly affected due to application of vegetation. Variation in FOS as high as 0.2 was observed upon varying root cohesion from 1 to 20 KN/m^2.

Further, Nine stability charts based on Michalowski (1998) have been prepared; which can be used to determine FOS for vegetated homogenous dry soil slopes subject to varying degree of seismic excitation. Each chart contains four slope values and each slope has three curves corresponding to FOS due to varying root cohesion. Separate charts are presented for variation of root depth and variation of seismic coefficients.

For computation purpose, a mathematical model is more desirable than a chart so a multi variable linear regression equation was developed. However, the standard error of estimate was found to be 0.137; which shows a wide range of variability of FOS predicted by the equation. So the use of this equation without rational judgement isn't recommended.

6.2 Recommendations

Following are the recommendations based on this thesis work;

a. The level of discretization adopted for root cohesion in this thesis work is too fine to capture the variation of FOS; which only varies by 0.2 in the entire range. Thus, sensitivity analysis of each parameter towards FOS is recommended to aid in the discretization of parameters & to reduce computation cost in future works.
b. The charts prepared in this thesis work are applicable only for the assessment of FOS of slope having dry soil condition. In order to capture the variability of site conditions it's recommended that the effect of water be included in the preparation of charts in

future works. However, care must be taken that low cohesion soil with pore pressure subject to seismic excitation may also fail due to liquefaction.

c. This thesis work only deals with the stability of slope during horizontal seismic excitation. It's recommended that the effect of vertical excitation also be included in future works.

d. Due to the limitation of SPECFEM3D_GEOTECH, this thesis work employs pseudo static method to apply effects of ground acceleration; which is a very conservative method. It's recommended that other methods such as Response Spectrum & Time history analysis be researched in future works.

e. Only Root Reinforcement property of vegetation based on Wu. et al has been modelled so far. Other properties of vegetation such as armour, anchor should be subject of research in future works.

f. Root Depth of upto 3 meters and root cohesion of upto 20 KN/m^2 are adopted for the preparation of the stability chart; which are expected to be sufficient to cover every plants used in bioengineering. However, it's mandatory to know the root depth & root cohesion of a particular species of plant to use these charts. It's recommended that list of local plants used in bioengineering be prepared including their actual root cohesion, root depth and their variation with age of plant.

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Gharti, H.N., Dimitri Komatitsch, Volker Oye, Roland Martin, and Tromp Jereon. 2012. *SPECFEM3D_GEOTECH user manual* . Vol. Version 1.1 Beta. Manual.

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Tiwari, R.C., N.P. Bhandary, and R. Yatabe. 2015. "3-D elasto-plastic spectral element application to evaluate the stability of large-scale landslides." *Geomechanics and Geoengineering: An International Journal* (Taylor and Francis) 271-289.

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APPENDICES

ANNEX 1: CUBIT JOURNAL

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Create Vertex 60 0 19
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Create Vertex 0 0 10
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Create Vertex 40 0 20
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Create Curve 2 3
Create Curve 3 4
Create Curve 4 5
Create Curve 5 6
Create Curve 6 1
Create Curve 2 7
Create Curve 7 8
Create Curve 8 9
Create Curve 9 10
Create Curve 10 5
Create Surface 1 2 3 4 5 6
Create Surface 7 8 9 10 11 4 3 2
Sweep Surface 1 Vector 0 -1 0 Distance 15
Surface 9 Size 2.5
Surface 9 Scheme Pave
Volume 1 Size 2.5
Volume 1 Scheme Sweep Source Surface 9 target surface 1
rotate off
Volume 1 sweep smooth Auto
mesh volume 1
Sweep Surface 2 Vector 0 -1 0 Distance 15
Surface 18 Size 2.5
Surface 18 Scheme Pave
Volume 2 Size 2.5
Volume 2 Scheme Sweep Source Surface 18 target surface 2
rotate off
Volume 2 sweep smooth Auto
mesh volume 2
compress all
Imprint all
merge all
compress all
Block 1 Volume 1
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Block 2 Volume 2
Sideset 1 surface 1 2
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Sideset 2 Surface 3 10
Sideset 2 name "left_ssbcux"
Sideset 3 Surface 7 14
Sideset 3 name "right_ssbcux"
Sideset 4 Surface 9 15
Sideset 4 name "back_ssbcuy"
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Sideset 5 name "bottom_ssbcux_ssbcuy_ssbcuz"
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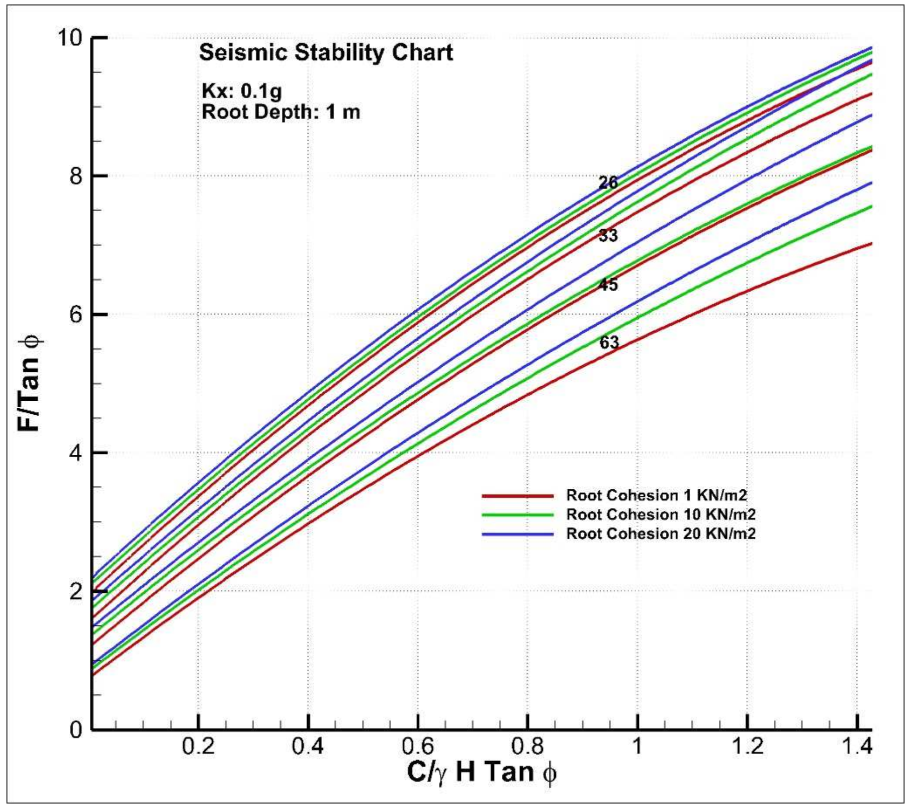
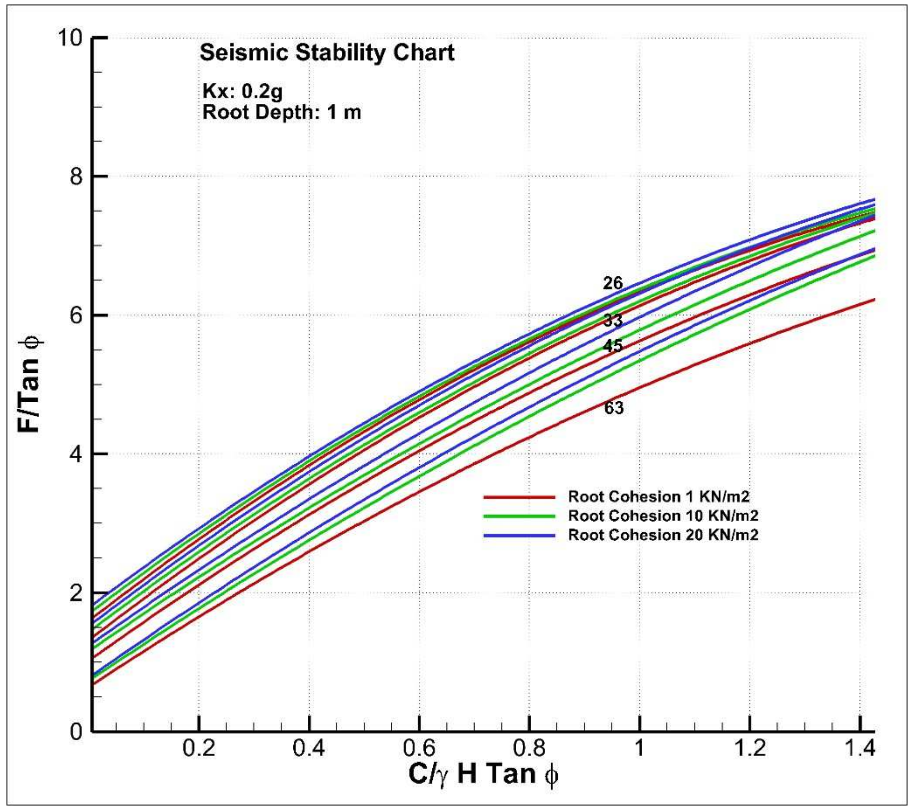
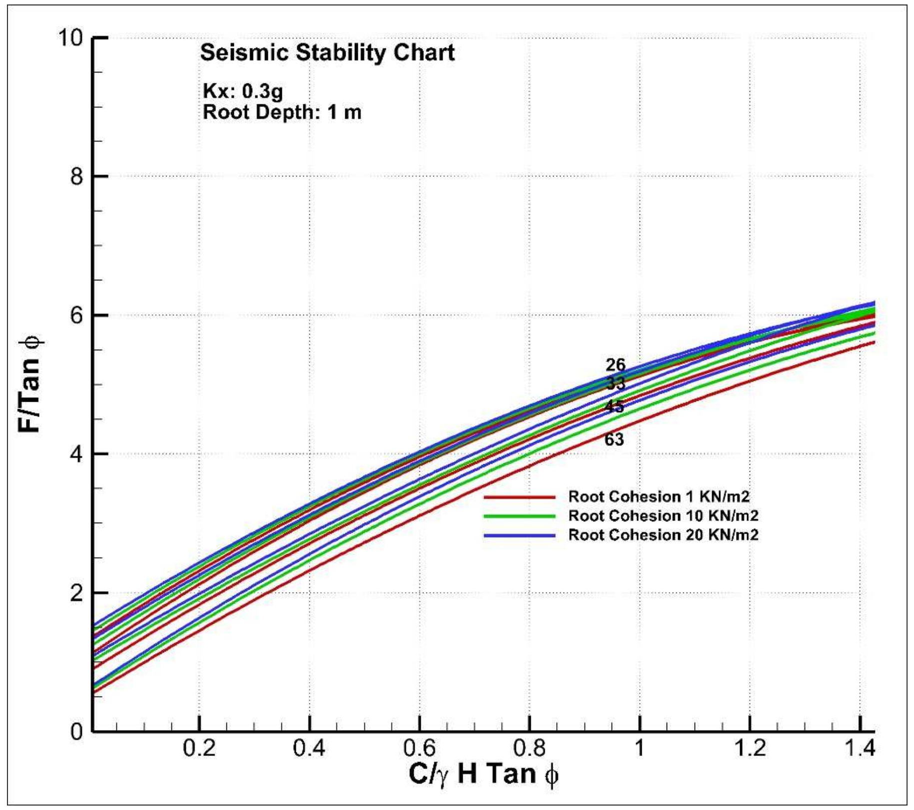
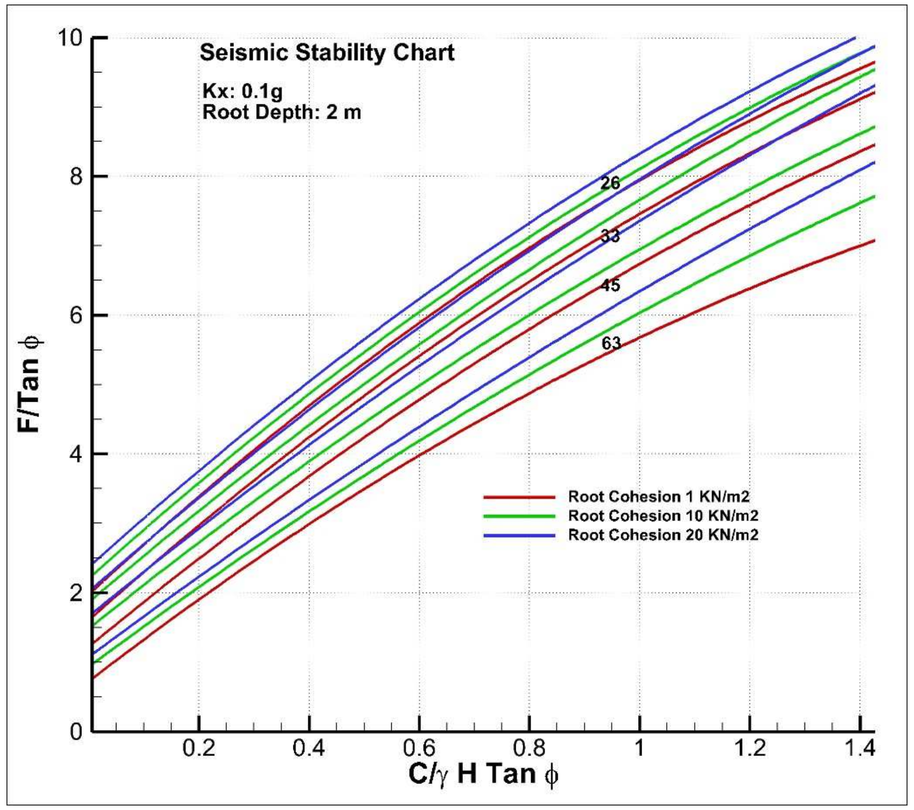
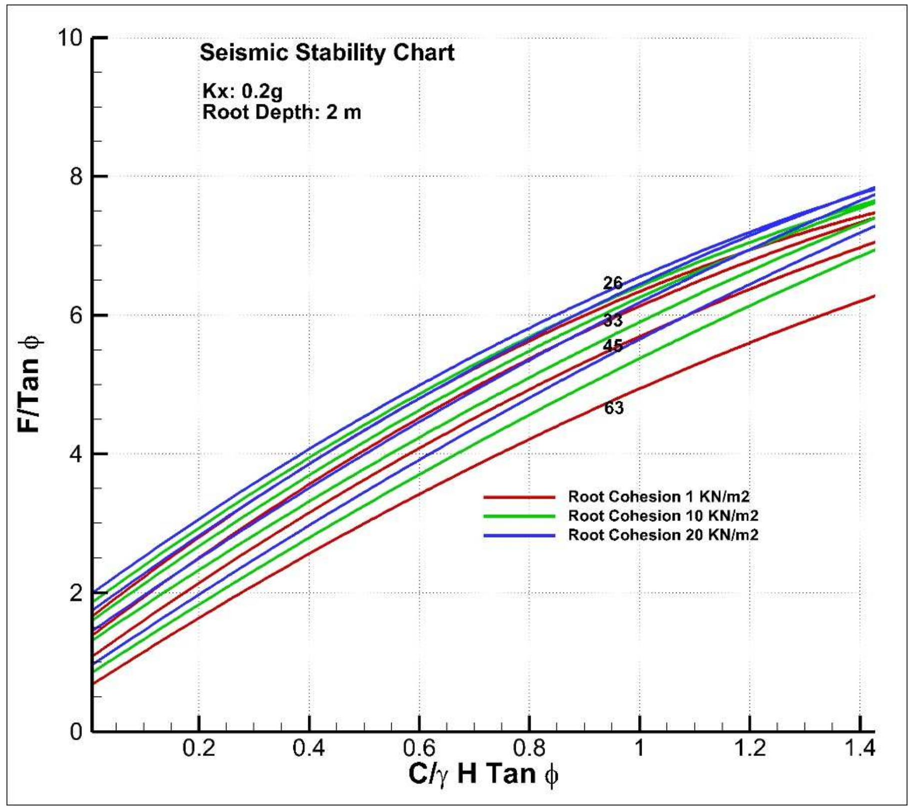
ANNEX 2: SEISMIC STABILITY CHART FOR VEGETATED HOMOGENOUS DRY SOIL SLOPES








Seismic Stability Chart
Kx: 0.1g
Root Depth: 2 m
26
33
45
63
Root Cohesion 1 KN/m2
Root Cohesion 10 KN/m2
Root Cohesion 20 KN/m2
F/Tan ϕ
C/γ H Tan ϕ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33
45
63
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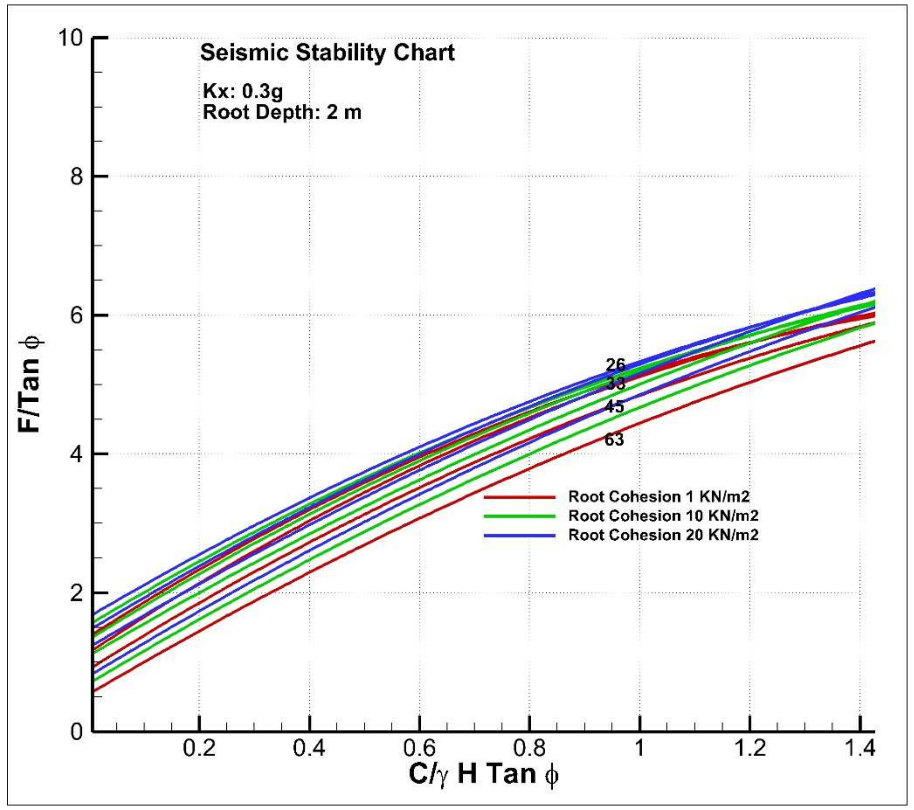
F/Tan ϕ
C/γ H Tan ϕ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Root Depth: 2 m
26
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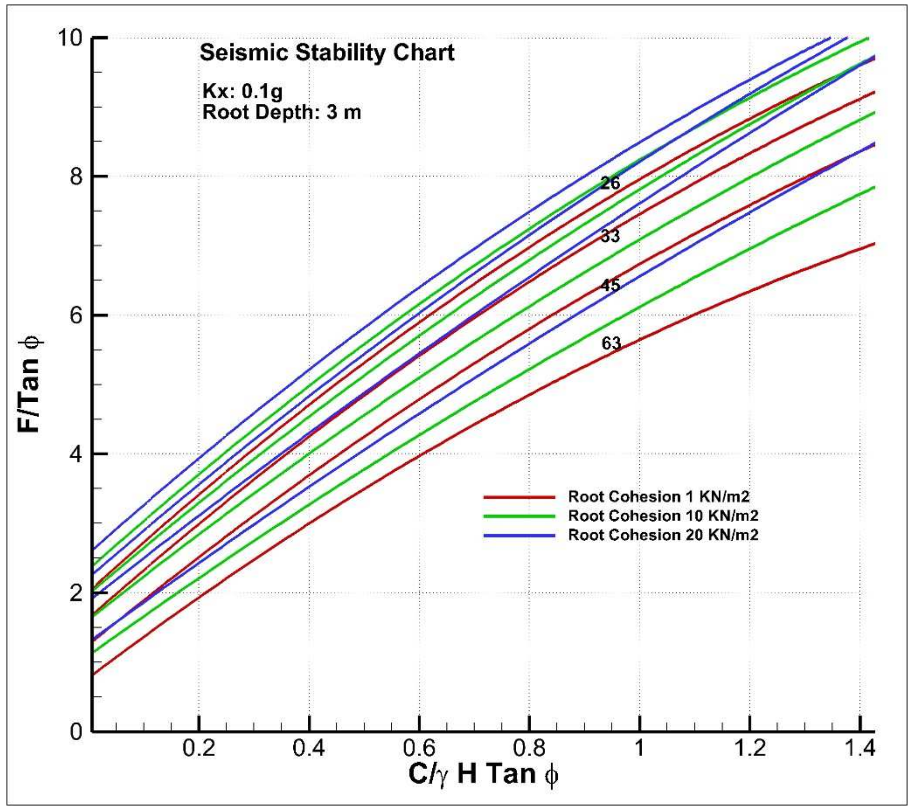
F/Tan ϕ
C/γ H Tan ϕ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Root Depth: 3 m
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33
45
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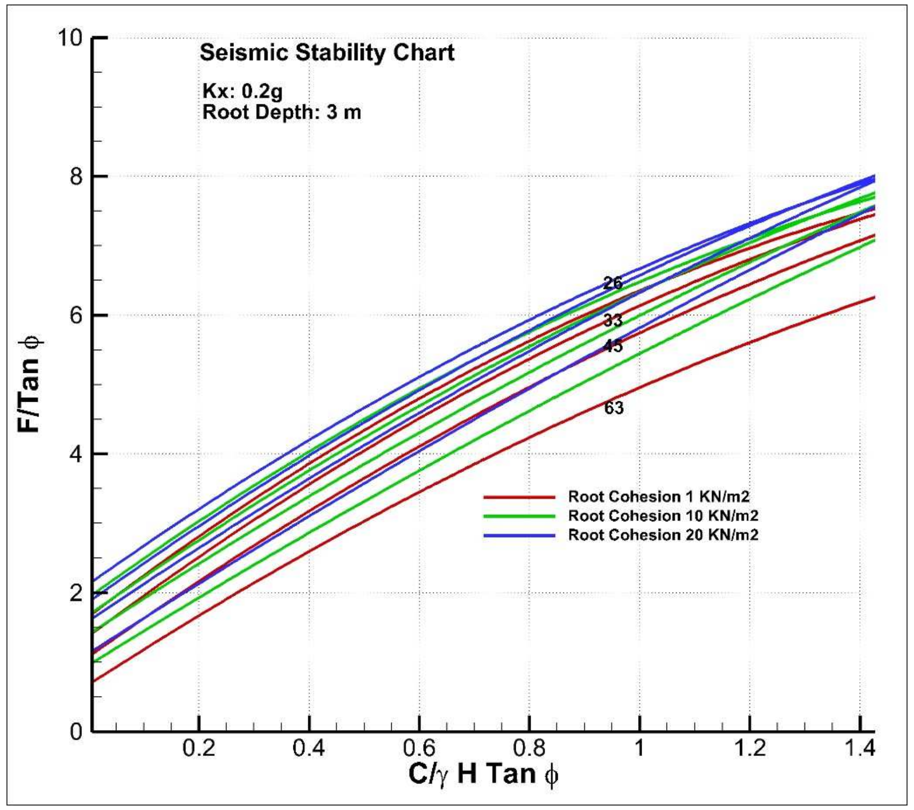
F/Tan φ
C/γ H Tan φ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F/Tan φ
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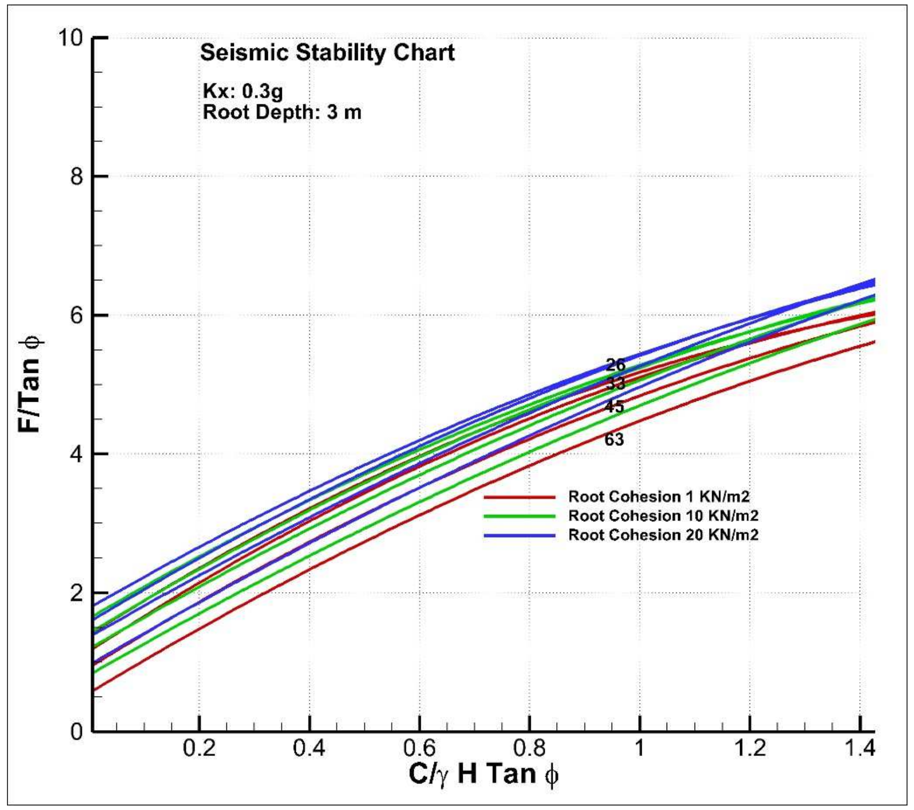
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45
63
Root Cohesion 1 KN/m2
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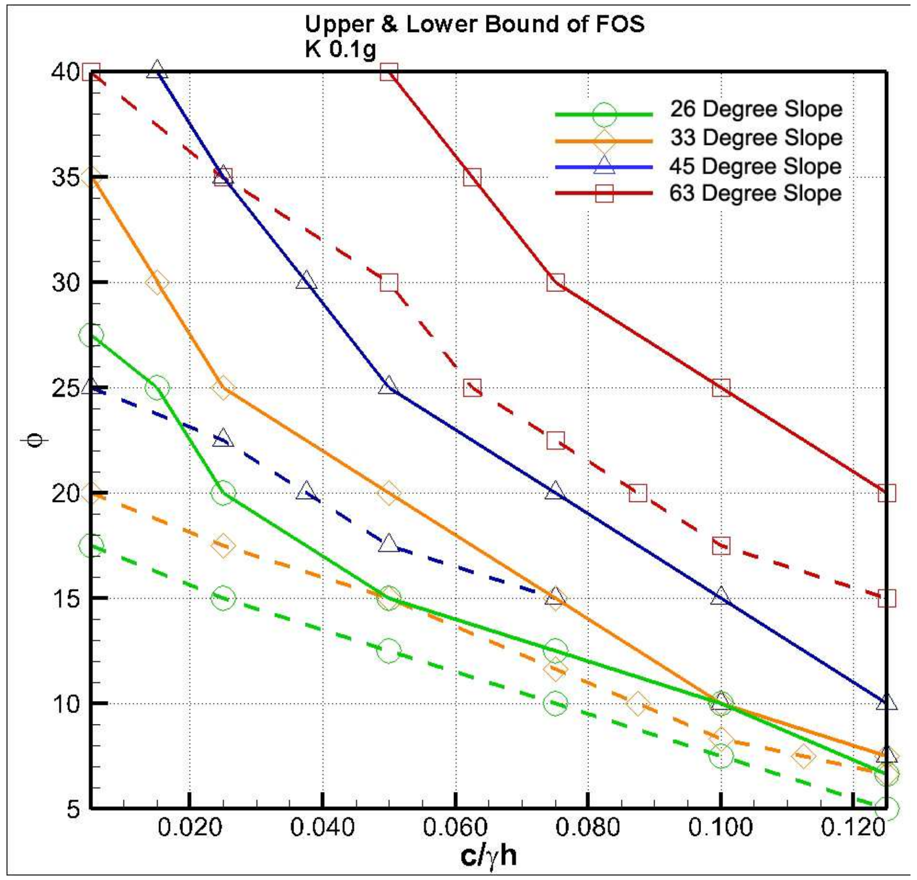
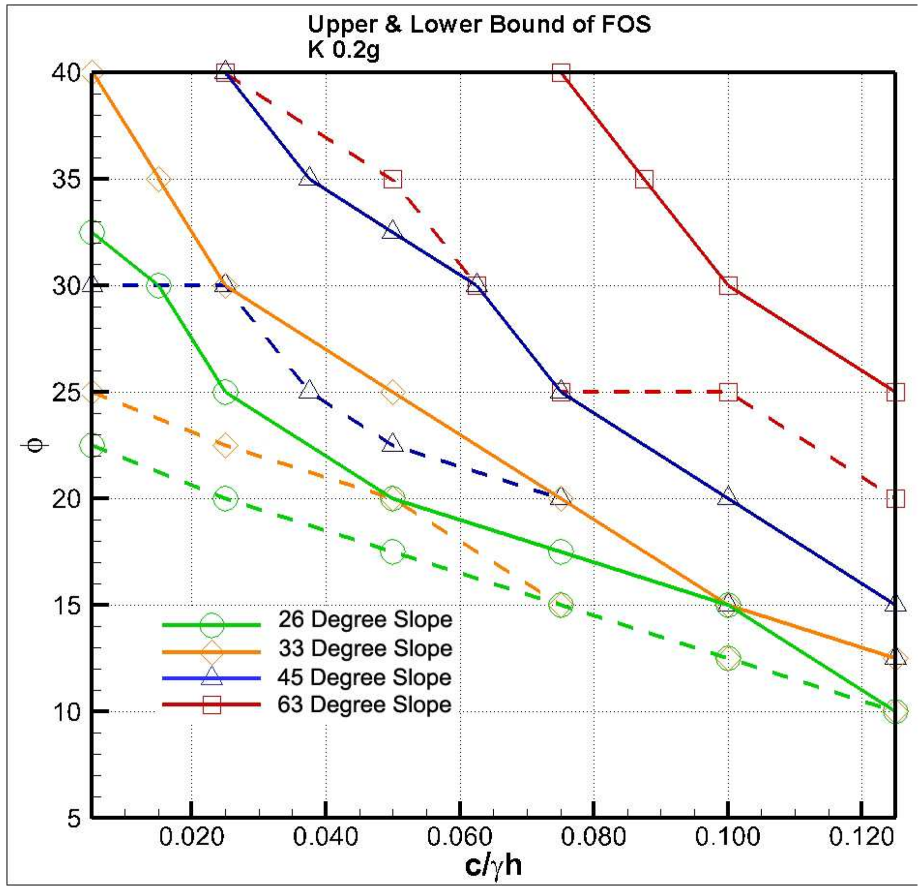
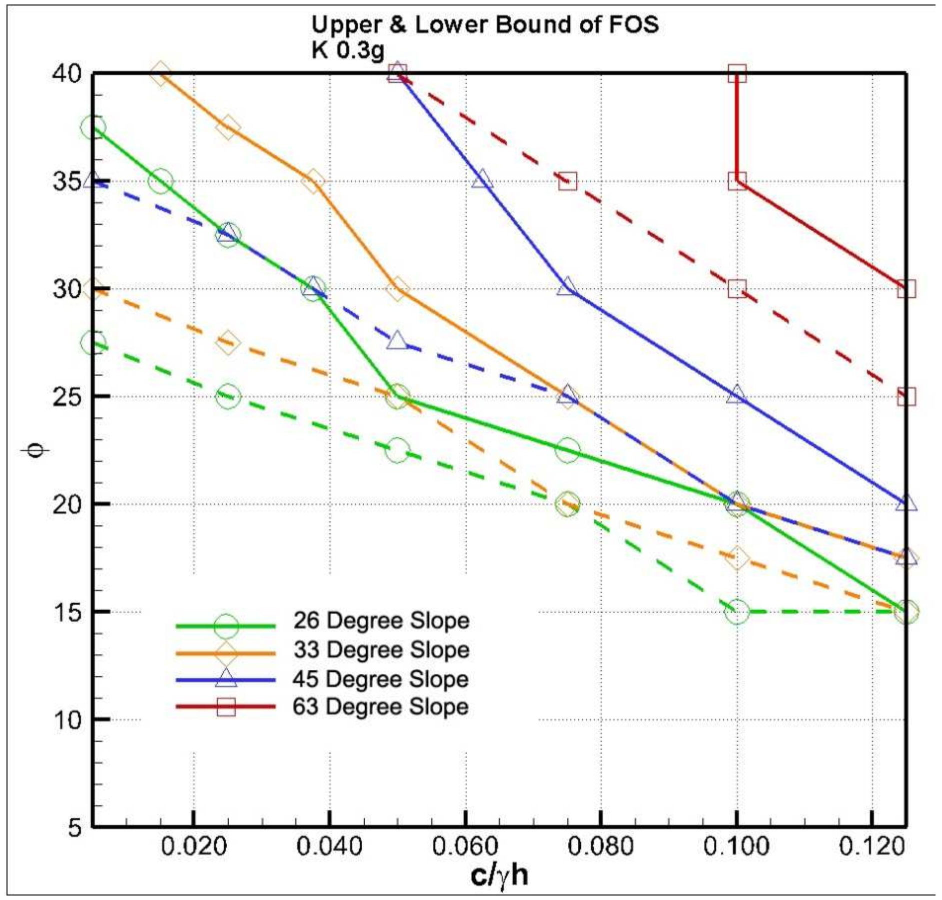
Root Cohesion 20 KN/m2
F/Tan φ
C/γ H Tan φ

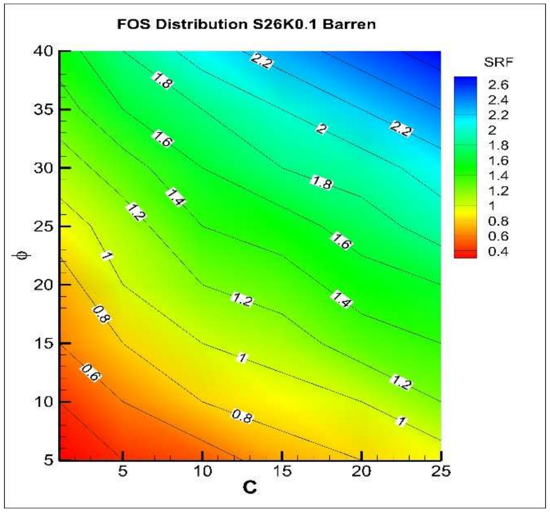
ANNEX 3: UNIT FOS FOR BARREN & VEGETATED SLOPES

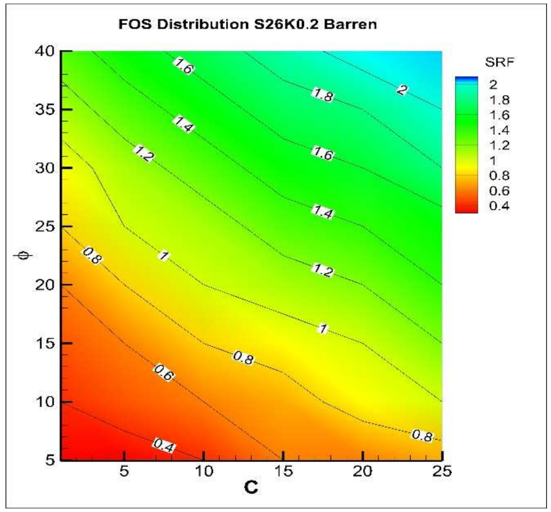


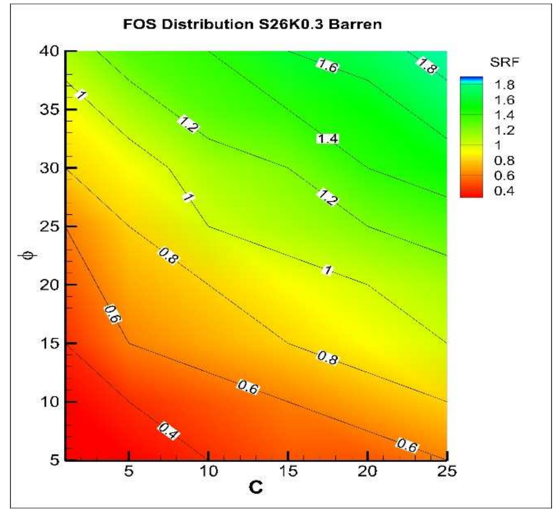


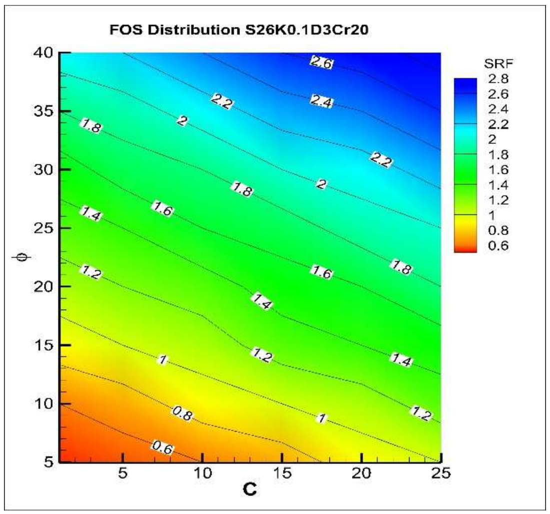


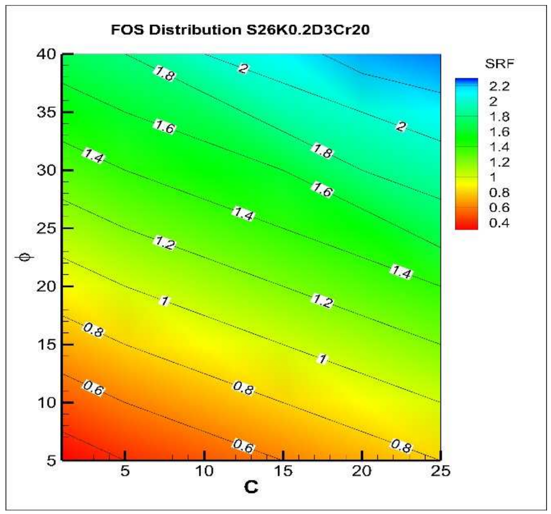
ANNEX 4: COMPARISION OF FOS WITH & WITHOUT VEGETATION

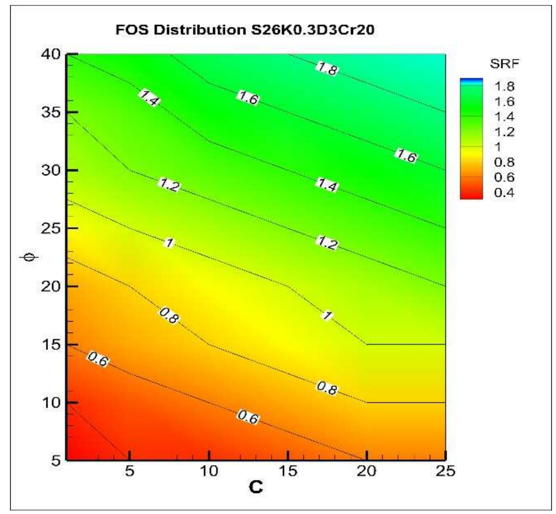


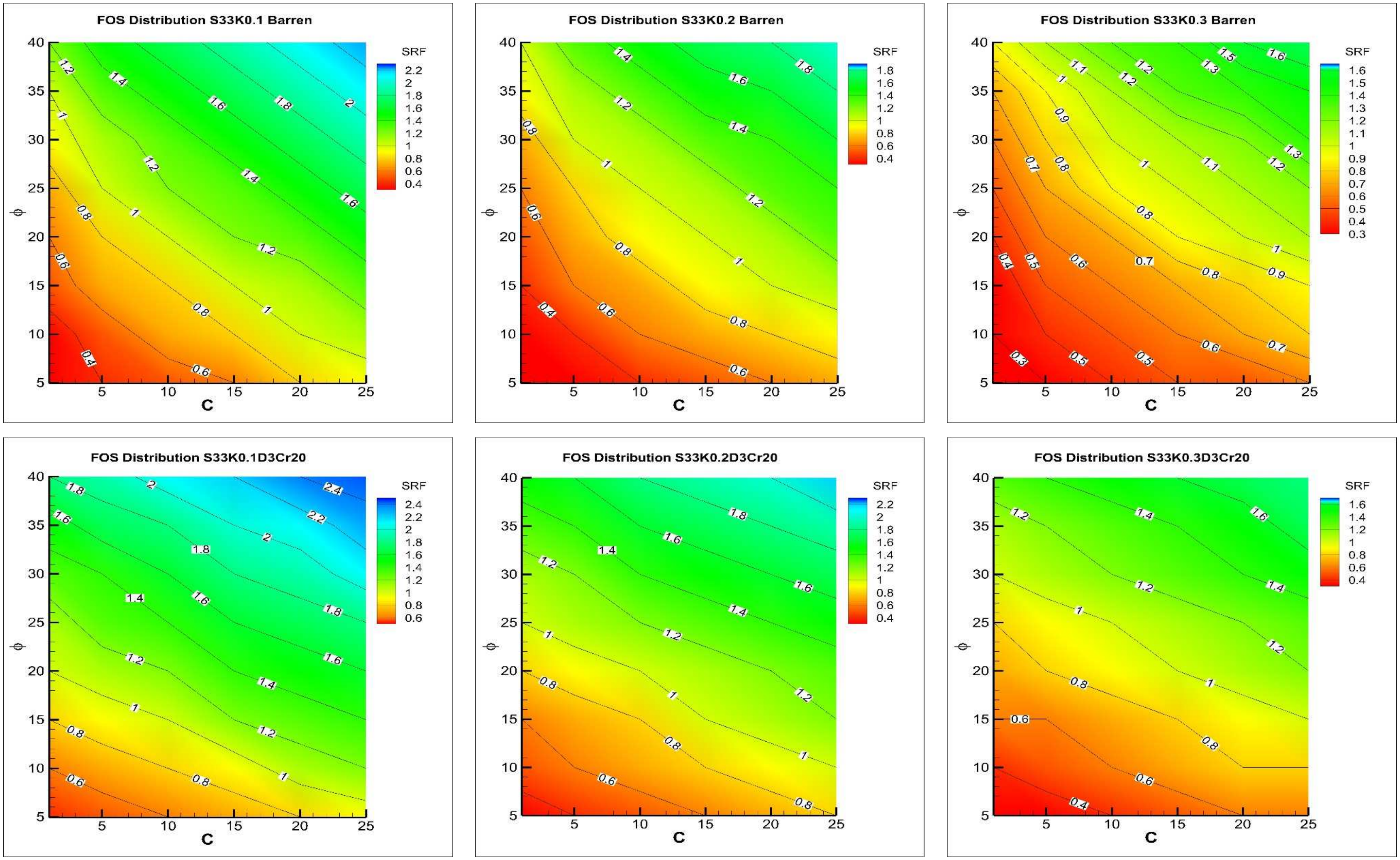








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FOS Distribution S33K0.2 Barren
FOS Distribution S33K0.3 Barren
FOS Distribution S33K0.1D3Cr20
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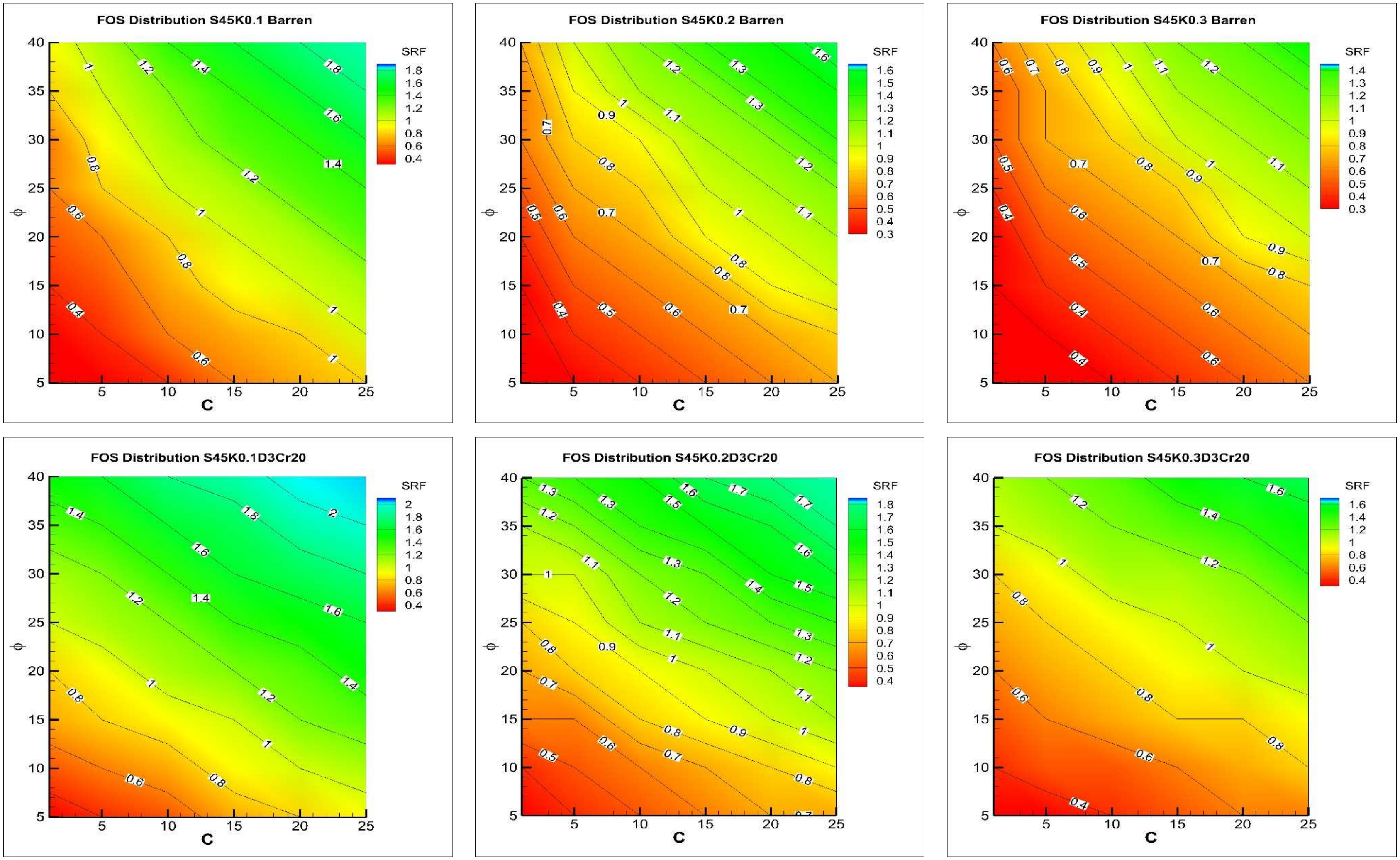
SRF
C
ϕ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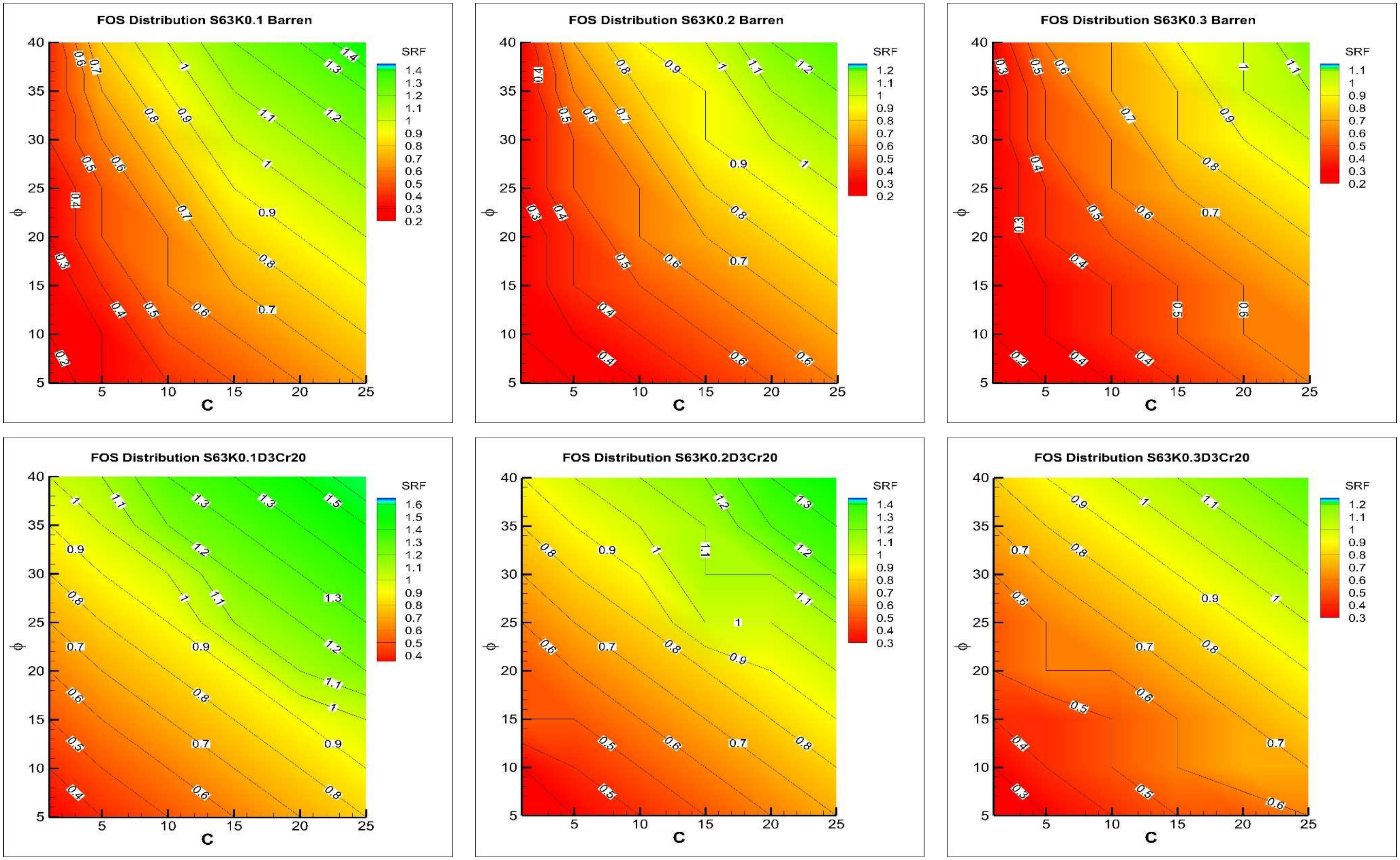
SRF
C
ϕ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FOS Distribution S63K0.2 Barren
FOS Distribution S63K0.3 Barren
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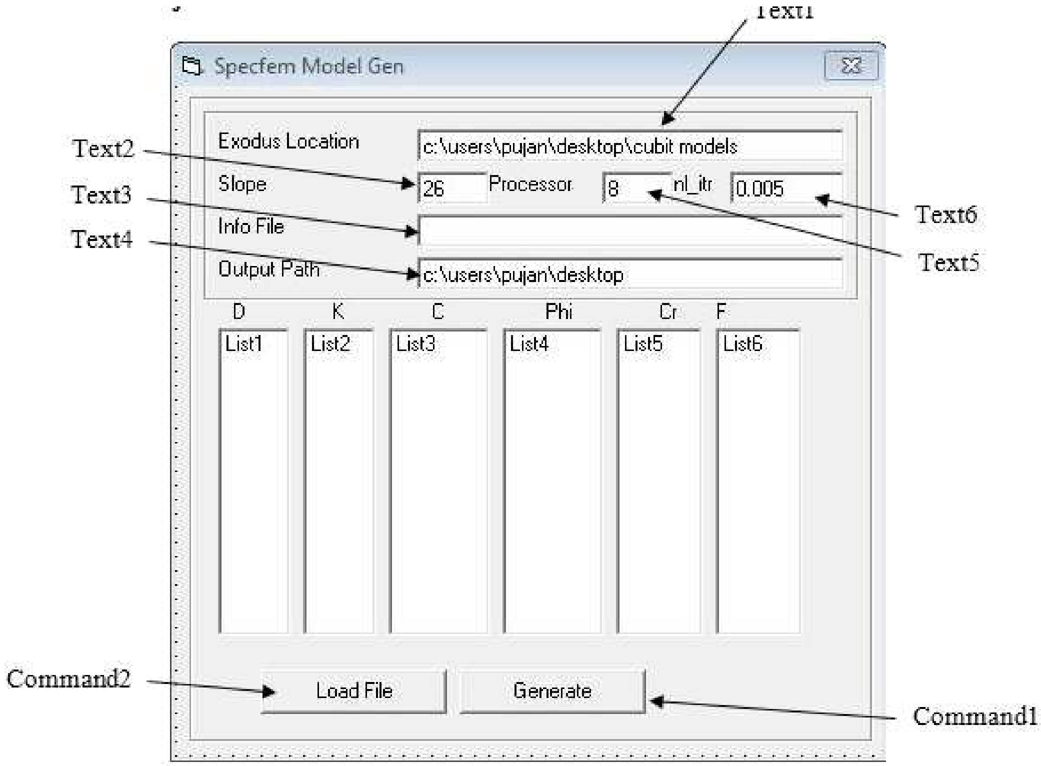
SRF
C
ϕ

ANNEX 5: CODE1

Form-1 Object



Form 1 Code

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Private Sub Command1_Click()
Frame2.Enabled = False
Slopedir = Text4.Text & "\" & Text2.Text & "\"
CreateDir (Slopedir)
Open Text4.Text & "\S" & Text2.Text & ".bsh" For Output As#100
For i = 0 To List1.ListCount - 1
Me.Caption = " Writing " & i & " of " & List1.ListCount
List1.ListIndex = i
DoEvents
List3.Text & "PHI" & List4.Text & "Cr" & List5.Text & "\"
path = Slopedir '& "\" '& "D" & List1.Text & "K" & List2.Text &
"C" & List3.Text & "PHI" & List4.Text & "Cr" & List5.Text & "\"
Call CreateDir(path, True)
Next
Close #100
```

```
Me.Caption = "DONE!"
Frame2.Enabled = True
End Sub

Private Sub CreateDir(ByVal path As String, Optional Copy As Boolean)
On Error Resume Next
path = Replace(path, "\\", "\")
MkDir path
If Copy = False Then Exit Sub
MkDir path & "input\"
MkDir path & "output\"
MkDir path & "partition\"
filesrc = Text1.Text & "\S" & Text2.Text & "D" & List1.Text & ".e"
model = "d" & List1.Text & "k" & List2.Text & "c" & List3.Text & "phi" & List4.Text & "cr" & List5.Text
filedest = path & "input\" & model & ".e"
FileCopy filesrc, filedest
Call CreateSimulations(model)
End Sub

Private Sub CreateSimulations(ByVal path As String)
filnam = path
psem = "#pre information" & vbLf & _
"preinfo: " & "nproc=" & Val(Text5.Text) & ", method='sem', ngllx=3, nglly=3, ngllz=3, nenod=8, ngnod=8, inp_path='../input" & "', part_path='../partition', out_path='../output'" & vbLf & vbLf & _
"#mesh information" & vbLf & _
"mesh: xfile='" & filnam & "_coord_x', yfile='" & filnam & "_coord_y', zfile='" & filnam & "_coord_z', " & _
"confile='" & filnam & "_connectivity', idfile='" & filnam & "_material_id', gfile='" & filnam & "_ghost'" & vbLf & vbLf & _
"#boundary conditions" & vbLf & _
"bc: uxfile='" & filnam & "_ssbcux', uyfile='" & filnam & "_ssbcuy', uzfile='" & filnam & "_ssbcuz'" & vbLf & vbLf & _
"#material list" & vbLf & _
```

```
"material: matfile='" & filnam & "_material_list'" & vbLf & vbLf
psem = psem & "#eathquake loading" & vbLf & _
"eqload: eqkx=" & List2.Text & ", eqky=0, eqkz=0" & vbLf & vbLf
srfx = ""
srfx = Trim(CreateSRF)
tmp = Split(srfx, " ")
nsrfx = UBound(tmp) + 1
tmp = ""
psem = psem & "#control parameters" & vbLf & _
"control: cg_tol=1e-8, cg_maxiter=5000, nl_tol=" & Text6.Text & ", nl_maxiter=2000, phinu=0, " & _
"nsrf=" & nsrfx & ", srf=" & srfx & vbLf & vbLf & _
"#save data options" & vbLf & _
"save: disp=1, porep=0, vmeps=1"
simfile = Text4.Text & "\" & Text2.Text & "\input\" & filnam
Open simfile & ".psem" For Output As #1
Print #1, psem;
Close #1
Open simfile & "_material_list" For Output As #1
Print #1, "# material properties (id,domain,gamma,ym,nu,phi,coh,psi)" & vbLf;
Print #1, "2" & vbLf;
If Val(List4.Text) > 20 Then
Nu = 0.33
Else
Nu = 0.42
End If
Print #1, "1, 1, 20, 1e5, " & Nu & ", " & Val(List4.Text) & ", " & Val(List3.Text) & ", 0" & vbLf;
Print #1, "2, 1, 20, 1e5, " & Nu & ", " & Val(List4.Text) & ", " & Val(List3.Text) + Val(List5.Text) & ", 0";
Close #1
Print #100, "echo " & Chr(34) & "[$(Date)] Running " & filnam & "<" & List1.ListIndex + 1 & " of " & List1.ListCount & ">" & Chr(34) & "| tee -a log.txt" & vbLf;
Print #100, "./exodus2sem ../input/" & filnam & ".e -bin=1" & vbLf;
Print #100, "./partmesh ../input/" & filnam & ".psem" & vbLf;
```

```
Print #100, "mpirun -n " & Val(Text5.Text) & " ./psemgeotech
../input/" & filnam & ".psem" & vbLf;
End Sub

Private Function CreateSRF() As String
ReDim numx(1 To 5) As Double
numx(4) = Round(Val(List6.Text), 1)
numx(5) = numx(4) + 0.1
numx(3) = numx(4) - 0.1
numx(2) = numx(4) - 0.2
numx(1) = numx(4) - 0.3
srfx = ""
For i = 1 To 5
If numx(i) > 0 Then srfx = srfx & " " & CStr(numx(i))
Next
srfx = Trim(srfx)
CreateSRF = srfx
End Function

Private Sub Command2_Click()
Command2.Enabled = False
List1.Clear
List2.Clear
List3.Clear
List4.Clear
List5.Clear
List6.Clear
cnt = 0
Open Text3.Text For Input As 1
While Not EOF(1)
Input #1, a, b, c, d, e, f
If Val(f) <> 0 Then
cnt = cnt + 1
Me.Caption = "Loading: " & cnt
List1.AddItem a
List2.AddItem b
```

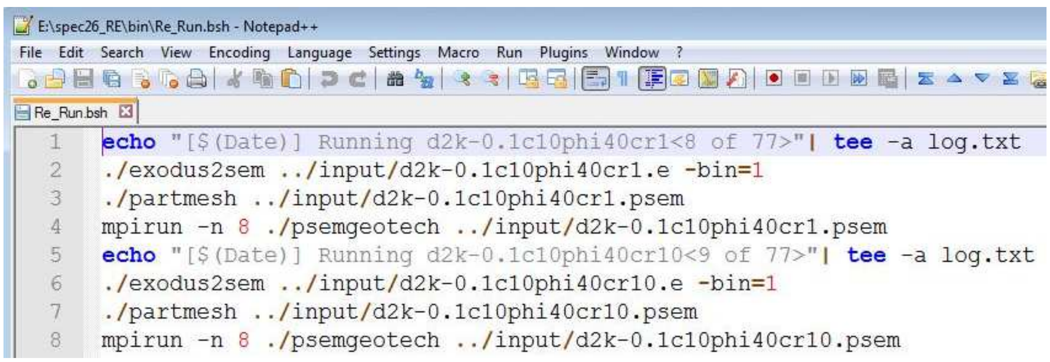
```
List3.AddItem c
List4.AddItem d
List5.AddItem e
List6.AddItem f
End If
Wend
Close #1
DoEvents
If List1.ListCount <> 0 Then Command1.Enabled = True
Command2.Enabled = True
Me.Caption = "DONE!"
End Sub

Private Sub Command3_Click()
Open "Move.bsh" For Output As 1
For i = 0 To 722
model = "s" & Text2.Text & "d" & List1.List(i) & "k" & List2.List(i) & "c" & List3.List(i) & "phi" & List4.List(i) & "cr" & List5.List(i)
Print #1, "mkdir /" & Text2.Text & "/" & model & vbLf;
in_path = "mkdir /" & Text2.Text & "/" & model & "/input"
Print #1, in_path & vbLf;
out_path = "mkdir /" & Text2.Text & "/" & model & "/output"
Print #1, out_path & vbLf;
part_path = "mkdir /" & Text2.Text & "/" & model & "/partition"
Print #1, part_path & vbLf;
Print #1, "mv /input/" & model & "* /" & Text2.Text & "/" & model & "/input/" & vbLf;
Print #1, "mv /output/" & model & "* /" & Text2.Text & "/" & model & "/output/" & vbLf;
Print #1, "mv /partition/" & model & "* /" & Text2.Text & "/" & model & "/partition/" & vbLf;
Next
Close #1
End Sub

Private Sub List1_Click()
```

```
List2.ListIndex = List1.ListIndex
List3.ListIndex = List1.ListIndex
List4.ListIndex = List1.ListIndex
List5.ListIndex = List1.ListIndex
List6.ListIndex = List1.ListIndex
End Sub

Private Sub Text2_Change()
Text3.Text = App.path & "\s" & Text2.Text & "_final.csv"
End Sub
```

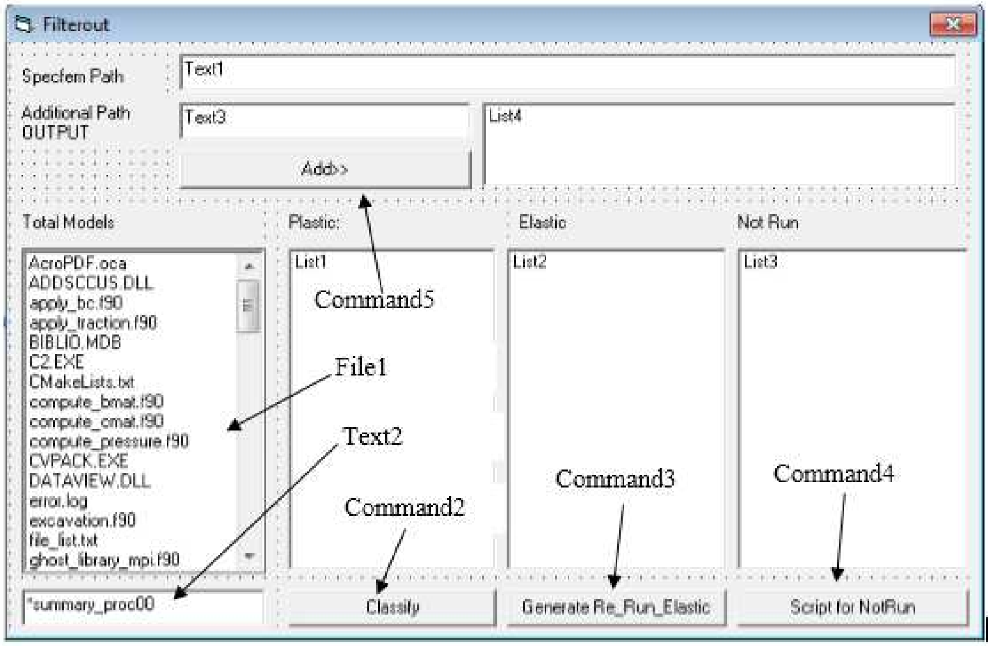



```
echo "[$(Date)] Running d2k-0.1c10phi40cr1<8 of 77>"| tee -a log.txt
./exodus2sem ../input/d2k-0.1c10phi40cr1.e -bin=1
./partmesh ../input/d2k-0.1c10phi40cr1.psem
mpirun -n 8 ./psemgeotech ../input/d2k-0.1c10phi40cr1.psem
echo "[$(Date)] Running d2k-0.1c10phi40cr10<9 of 77>"| tee -a log.txt
./exodus2sem ../input/d2k-0.1c10phi40cr10.e -bin=1
./partmesh ../input/d2k-0.1c10phi40cr10.psem
mpirun -n 8 ./psemgeotech ../input/d2k-0.1c10phi40cr10.psem
```

Sample Bash File Generated by Code-1

ANNEX 6: CODE2

Form-1 Object



Form-1 Code

```
Private Sub Command1_Click()
Open App.Path & "\Plastic.txt" For Output As 1
For i = 0 To List1.ListCount - 1
List1.ListIndex = i
tmp = Split(List1.List(i))
Print #1, tmp(0)
Next
Close #1
Open App.Path & "\Elastic.txt" For Output As 1
For i = 0 To List2.ListCount - 1
List2.ListIndex = i
tmp = Split(List2.List(i))
Print #1, tmp(0)
Next
Close #1
Open App.Path & "\NotRun.txt" For Output As 1
For i = 0 To List3.ListCount - 1
List3.ListIndex = i
tmp = Split(List3.List(i))
Print #1, tmp(0)
Next
Close #1
MsgBox "OK"
End Sub
```

```
Private Sub Command2_Click()
Dim x As Integer
Dim diffumax As Double
Dim plastic As Boolean
List1.Clear
List2.Clear
List3.Clear
min_itr = InputBox("Rerun If Last Iteration is less or equal
to ", "Enter", "1")
fx = InputBox("Plastic if Umax is greater or equal to ",
"Enter", "0.08")
For i = 0 To File1.ListCount - 1
ReDim SRF(0) As Double
ReDim nitr(0) As Integer
ReDim umax(0) As Double
Call ReadMultiSRF(File1.List(i), SRF, nitr, umax)

'-This is a criteria to check using umax>Prescribed Value-----
plastic = False
For j = 0 To UBound(SRF)
If umax(j) >= Val(fx) Then
plastic = True
Exit For
End If
Next
'------------Criteria Ends---------------------
'---- CRITERIA TO CHECK FOS using Change in Average Slope-----
'For j = 0 To UBound(SRF)
'If umax(j) <= 0 Then MsgBox "umax = " & umax(j) & "@ " & j
'Next
'itrdiff = 0
'curdiff = 0
'diffumax = 0
'diffnitr = 0
'cnt = 0
'plastic = False
'For j = 0 To UBound(SRF) - 1
'    If cnt <> 0 Then
'    cur_diff = umax(j + 1) - umax(j)
'        If cur_diff > Val(fx) * diffumax / cnt Then
'            plastic = True
'            Debug.Print File1.List(i) & ": " & j + 1
'            Exit For
'        End If
'    End If
'
'    cnt = cnt + 1
```

```
'    diffumax = diffumax + umax(j + 1) - umax(j)
'    diffnitr = diffnitr + nitr(j + 1) - nitr(j)
'Next
'-------CRITERIA ENDS----------------------------------------
If UBound(SRF) = 1 Then plastic = True 'to ensure single line
passess
If UBound(SRF) = 0 Then
List3.AddItem File1.List(i)
ElseIf nitr(UBound(nitr)) > Val(min_itr) And plastic = True
Then '(lastumax >= 6 * diffumax / cnt) Then
List1.AddItem File1.List(i)
Else
List2.AddItem File1.List(i)
End If
a = List1.ListCount
b = List2.ListCount
c = List3.ListCount
tot = a + b + c
Label1.Caption = "Plastic: " & a
Label2.Caption = "Elastic: " & b
Label3.Caption = "Not Run: " & c
Label5.Caption = "Total: " & tot
Next

MsgBox "Complete: " & a & vbCrLf & "Partial: " & b & vbCrLf &
"Rerun: " & c & vbCrLf & vbCrLf & "Total: " & tot,
vbInformation
End Sub

Private Sub Command3_Click()
Dim txt As String
On Error GoTo 1
If List2.ListCount = 0 Then Exit Sub
suffix = InputBox("Enter the Suffix for this batch of file",
"Folder_suffix", "_RE")
MkDir Text1.Text & suffix
Target = Text1.Text & suffix & "\input"
MkDir Target
MkDir Text1.Text & suffix & "\bin"
MkDir Text1.Text & suffix & "\output"
MkDir Text1.Text & suffix & "\partition"

Open Text1.Text & suffix & "\bin\Re_Run.bsh" For Output As#100
For i = 0 To List2.ListCount - 1
Me.Caption = i & " of " & List2.ListCount
List2.ListIndex = i
tmp2 = Split(List2.List(i), "_")
'----------READ EXISTING SIM FILE------------------------'
```

```
    simfile = Text1.Text & "\input\" & tmp2(0) & ".psem"
    Open simfile For Binary As #1
    txt = Space(LOF(1))
    Get #1, , txt
    Close #1
'------------ Read SRF & ADD 2 ADDITIONAL SRFs---------
ReDim SRF(0) As Double
ReDim nitr(0) As Integer
ReDim umax(0) As Double
Call ReadMultiSRF(List2.List(i), SRF, nitr, umax)
srf1 = SRF(UBound(SRF)) + 0.1
srf2 = srf1 + 0.1
a = InStr(1, txt, "nproc=")
b = InStr(a, txt, ",")
nproc = Val(Mid(txt, a + 6, b - a - 6))
a = InStr(1, txt, "nsrf=")
b = InStr(a, txt, vbLf)
cur_txt = Mid$(txt, a, b - a)
If InStr(1, LCase(tmp2(0)), "phi40", vbTextCompare) <> 0 Then
rep_txt = "nsrf=2, srf=" & CStr(srf1) & " " & CStr(srf2)
txt = Replace(txt, cur_txt, rep_txt)
Else
rep_txt = "nsrf=1, srf=" & CStr(srf1)
txt = Replace(txt, cur_txt, rep_txt)
End If
'-------------Write the new Simulation file-------------------
Open Target & "\" & tmp2(0) & ".psem" For Output As #1
Print #1, txt;
Close #1
'Copy Other Files
FileCopy Text1.Text & "\input\" & tmp2(0) & "_material_list",
Target & "\" & tmp2(0) & "_material_list"
FileCopy Text1.Text & "\input\" & tmp2(0) & ".e", Target & "\"
& tmp2(0) & ".e"
'copy binary files
FileCopy Text1.Text & "\bin\exodus2sem.exe", Text1.Text &
suffix & "\bin\exodus2sem.exe"
FileCopy Text1.Text & "\bin\partmesh.exe", Text1.Text & suffix
& "\bin\partmesh.exe"
FileCopy Text1.Text & "\bin\psemgeotech.exe", Text1.Text &
suffix & "\bin\psemgeotech.exe"

Print #100, "echo " & Chr(34) & "[$(Date)] Running " & tmp2(0)
& "<" & List2.ListIndex + 1 & " of " & List2.ListCount & ">" &
Chr(34) & "| tee -a log.txt" & vbLf;
Print #100, "./exodus2sem ../input/" & tmp2(0) & ".e -bin=1" &
vbLf;
Print #100, "./partmesh ../input/" & tmp2(0) & ".psem" & vbLf;
```

```
Print #100, "mpirun -n " & nproc & " ./psemgeotech ../input/"
& tmp2(0) & ".psem" & vbLf;
Next
Close #100
MsgBox "GENERATION COMPLETE @ " & Text1.Text & suffix,
vbInformation
Exit Sub
1:
MsgBox Err.Description, vbExclamation
End Sub

Private Sub Command4_Click()
Dim nproc As Integer
nproc = CInt(InputBox("Enter the Number of Processors",
"NProc", "4"))
If nproc = 0 Then
MsgBox "Invalid Number of processor", vbExclamation, "Exit"
Exit Sub
End If

Path = Text1.Text
Open Path & "\Rerun.bsh" For Output As #1
For i = 0 To List3.ListCount - 1
tmp = Split(List3.List(i), "_")

filnam = tmp(0)
Print #1, "echo " & Chr(34) & "[$(Date)] Running " & filnam &
"<" & i & " of " & List3.ListCount & ">" & Chr(34) & "| tee -a
log.txt" & vbLf;
Print #1, "./exodus2sem ../input/" & filnam & ".e -bin=1" &
vbLf;
Print #1, "./partmesh ../input/" & filnam & ".psem" & vbLf;
Print #1, "mpirun -n " & nproc & " ./psemgeotech ../input/" &
filnam & ".psem" & vbLf;
Next
Close #1
MsgBox "Written to " & Path & "\rerun.bsh", vbInformation
End Sub

Private Sub Command5_Click()
For i = 0 To List4.ListCount - 1
If List4.List(i) = LCase(Trim(Text3.Text)) Then
MsgBox "Already Exists", vbExclamation
Exit Sub
End If
Next
List4.AddItem LCase(Trim(Text3.Text))
End Sub
```

```
Private Sub Form_Load()
File1.Pattern = "*_summary_proc00"
Padding = 200
End Sub

Private Sub Form_Unload(Cancel As Integer)
End
End Sub

Private Sub List1_Click()
txt = List1.List(List1.ListIndex)
Me.Caption = txt & "(" & Len(txt) & ")"
If Form2.Visible = True Then
Call Display(txt)
Me.SetFocus
End If
End Sub
Private Sub List2_Click()
txt = List2.List(List2.ListIndex)
Me.Caption = txt & "(" & Len(txt) & ")"
If Form2.Visible = True Then
Call Display(txt)
Me.SetFocus
End If
End Sub

Private Sub List2_KeyDown(KeyCode As Integer, Shift As
Integer)
If KeyCode = 46 And Abs(List2.ListIndex) = List2.ListIndex
Then List2.RemoveItem (List2.ListIndex)
End Sub

Private Sub List3_Click()
txt = List3.List(List3.ListIndex)
Me.Caption = txt & "(" & Len(txt) & ")"
End Sub

Private Sub List1_DblClick()
Display (List1.List(List1.ListIndex))
End Sub

Private Sub List2_DblClick()
Display (List2.List(List2.ListIndex))
End Sub

Private Sub ReadMultiSRF(ByVal filename As String, ByRef S()
As Double, ByRef N() As Integer, ByRef U() As Double)
```

```
Call GetSRF(File1.Path & "\" & filename, S(), N(), U())
For i = 0 To List4.ListCount - 1
    fil = List4.List(i) & "\" & filename
    If Fileexists(fil) = True Then
        ReDim srf_2(0) As Double
        ReDim N_itr_2(0) As Integer
        ReDim umax_2(0) As Double
        Call GetSRF(fil, srf_2(), N_itr_2(), umax_2())
        If srf_2(0) = 0 Then
        Clipboard.Clear
        Clipboard.SetText fil
        MsgBox fil
        End If

       For j = 0 To UBound(srf_2)
       If srf_2(j) <> 0 Then
       ReDim Preserve S(UBound(S) + 1)
       ReDim Preserve N(UBound(N) + 1)
       ReDim Preserve U(UBound(U) + 1)
       S(UBound(S)) = srf_2(j)
       N(UBound(N)) = N_itr_2(j)
       U(UBound(U)) = umax_2(j)
       End If
       Next
   End If
Next
End Sub

Private Sub Display(ByVal filename As String)
Dim data As String
Form2.Caption = filename
Form2.Show
Open File1.Path & "\" & filename For Binary As #1
data = Space(LOF(1))
Get #1, , data
Close #1
data = Replace(data, vbLf, vbCrLf)
Form2.Text1.Text = data
data = ""
For i = 0 To List4.ListCount - 1
fil = List4.List(i) & "\" & filename
If Fileexists(fil) = True Then
Open fil For Binary As #1
    data = Space(LOF(1))
    Get #1, , data
    Close #1
data = Replace(data, vbLf, vbCrLf)
```

```
Form2.Text1.Text = Form2.Text1.Text & vbCrLf & "[" &
UCase(fil) & "]" & vbCrLf
Form2.Text1.Text = Form2.Text1.Text & vbCrLf & data
End If
Next
ReDim SRF(0) As Double
ReDim N_Itr(0) As Integer
ReDim u_max(0) As Double
Call ReadMultiSRF(filename, SRF, N_Itr, u_max)
Form3.Show
Call Graph.Set_PicBox(Form3.Picture1)
Graph.User_Xmax = SRF(UBound(SRF)) - SRF(0)
Graph.User_Ymax = u_max(UBound(u_max)) - u_max(0)
Graph.Clear
For i = 0 To UBound(SRF) - 1
Call Graph.Draw_Line(SRF(i) - SRF(0), u_max(i) - u_max(0),
SRF(i + 1) - SRF(0), u_max(i + 1) - u_max(0), 20, vbGreen)
Next

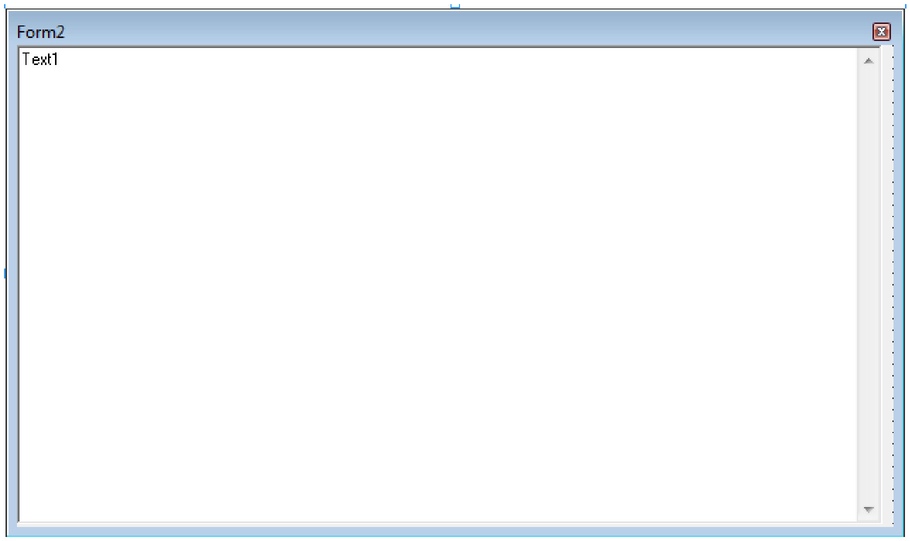
End Sub
Private Sub List3_DblClick()
Shell "notepad " & Chr(34) & File1.Path & "\" &
List3.List(List3.ListIndex) & Chr(34), vbNormalFocus
End Sub

Private Sub List4_KeyDown(KeyCode As Integer, Shift As
Integer)
If KeyCode = 46 And List4.ListIndex >= 0 Then List4.RemoveItem
List4.ListIndex
End Sub

Private Sub Text1_Change()
On Error Resume Next
File1.Path = Text1.Text & "\output"
List4.Clear
Text3.Text = Text1.Text & "_RE\Output"
End Sub

Private Sub Text2_Change()
File1.Pattern = Text2.Text
End Sub
```

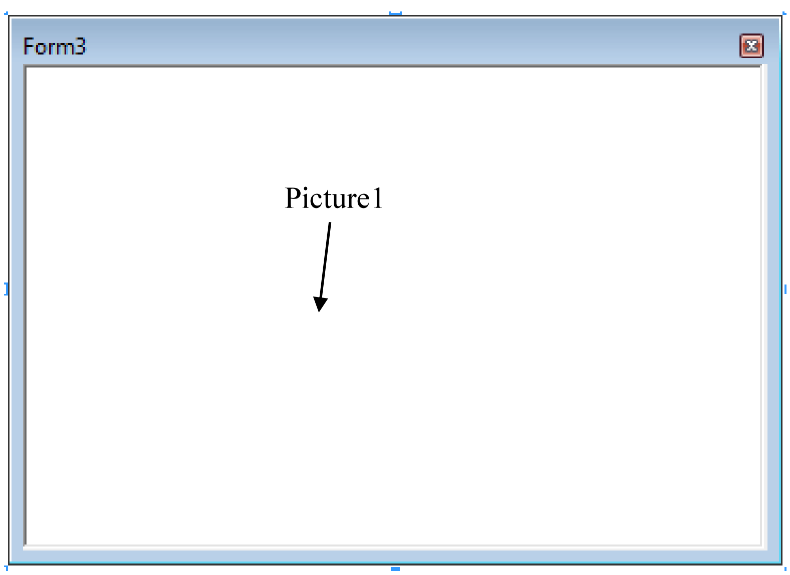
Form-2 Object



Form-2 Code

```
Private Sub Form_Resize()
On Error Resume Next
Text1.Height = Me.Height
Text1.width = Me.width - 100
End Sub
```

Form-3 Object



Form-3 Code

```
Private Sub Form_Resize()
On Error Resume Next
Picture1.Left = 0
Picture1.Left = 0
Picture1.Height = Me.Height - 500
Picture1.width = Me.width - 300
End Sub
```

Module (Graph)

```
Public User_Xmax As Double
Public User_Ymax As Double
Public Padding As Double
Dim PicBox As PictureBox

Public Sub Set_PicBox(ByRef pic As PictureBox)
Set PicBox = pic
End Sub

Public Function Get_UserX(Picture_X) As Single
Get_UserX = ((Picture_X - Padding) * User_Xmax) /
(PicBox.width - 2 * Padding)
End Function

Public Function Get_PictureX(User_X) As Single
Get_PictureX = ((PicBox.width - 2 * Padding) * User_X /
User_Xmax) + Padding
End Function

Public Function Get_UserY(Picture_Y) As Single
Get_UserY = (PicBox.Height - Picture_Y - Padding) * User_Ymax
/ (PicBox.Height - 2 * Padding)
Debug.Print Get_UserY
End Function

Public Function Get_PictureY(User_Y)
Get_PictureY = PicBox.Height - (User_Y * (PicBox.Height - 2 *
Padding) / User_Ymax + Padding)
End Function

Public Sub Draw_Line(ByVal x1 As Double, ByVal y1 As Double,
ByVal x2 As Double, ByVal Y2 As Double, Optional ByVal radius
As Integer, Optional ByVal colorx As ColorConstants, Optional
ByVal Style As DrawStyleConstants, Optional ByVal width As
Integer)
If IsNull(colorx) = True Then
colorx = vbWhite
```

```
End If
If IsNull(Style) = True Then
Style = vbSolid
End If
If width <= 0 Then
width = 1
End If
PicBox.ForeColor = colorx
PicBox.DrawStyle = Style
PicBox.DrawWidth = width
If radius <> 0 Then
Call Draw_point(x1, y1, radius, colorx)
Call Draw_point(x2, Y2, radius, colorx)
End If

PicBox.Line (Get_PictureX(x1), Get_PictureY(y1))-
(Get_PictureX(x2), Get_PictureY(Y2))
End Sub

Public Sub Clear()
PicBox.Cls
PicBox.Refresh
End Sub

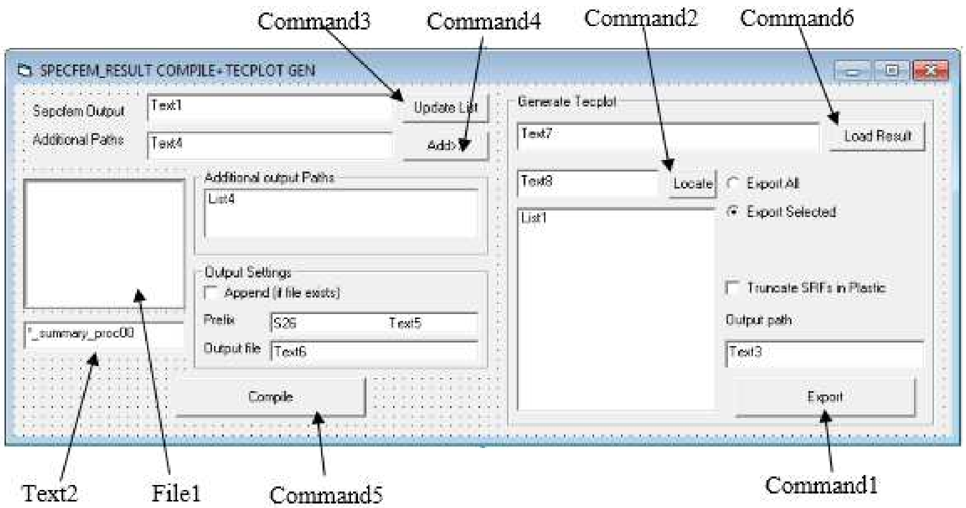
Public Sub Draw_point(ByVal x1 As Double, ByVal y1 As Double,
ByVal radius As Integer, Optional ByVal colorx As
ColorConstants, Optional ShowLabel As Boolean)
If IsNull(colorx) = True Then
colorx = vbWhite
End If
PicBox.ForeColor = colorx
PicBox.FillColor = colorx
PicBox.Circle (Get_PictureX(x1), Get_PictureY(y1)), radius
If ShowLabel = True Then
Label = "(" & x1 & "," & y1 & ")"
If PicBox.CurrentX + PicBox.TextWidth(Label) > PicBox.width
Then
PicBox.CurrentX = PicBox.CurrentX - PicBox.TextWidth(Label) -
100
Else
PicBox.CurrentX = Get_PictureX(x1) + 100
End If
PicBox.CurrentY = Get_PictureY(y1) - 100
PicBox.Print "(" & x1 & "," & y1 & ")"
'PicBox.ForeColor = colorx
End If
End Sub
```

Module (Specfem)

```
Public Function Fileexists(ByVal filename As String) As
Boolean
On Error GoTo 1
a = FileLen(filename)
Fileexists = True
Exit Function
1:
Fileexists = False
End Function
Public Sub GetSRF(ByVal filename As String, ByRef SRF() As
Double, ByRef N_Itr() As Integer, ByRef umax() As Double)
Dim data As String
Open filename For Binary As #1
data = Space(LOF(1))
Get #1, , data
Close #1
b = InStr(1, data, "fmax")
c = InStr(1, data, "ELAPSED TIME")
If b = 0 Then GoTo Last
If c <> 0 Then
data = Trim(Mid(data, b + 4, c - b - 4))
Else
data = Trim(Mid(data, b + 4))
End If
Do While final <> data
 final = Replace(data, Chr(32) & Chr(32), Chr(32))
 data = final
 final = Replace(data, Chr(32) & Chr(32), Chr(32))
 DoEvents
Loop
tmp = Split(final, vbLf)
If UBound(tmp) < 2 Then GoTo Last
ReDim SRF(UBound(tmp) - 2)
ReDim N_Itr(UBound(tmp) - 2)
ReDim umax(UBound(tmp) - 2)
cnt = 0
For i = 0 To UBound(tmp)
    If tmp(i) <> "" Then
    tmp2 = Split(tmp(i), " ")
    SRF(cnt) = tmp2(1)
    N_Itr(cnt) = tmp2(3)
    umax(cnt) = tmp2(5)
    cnt = cnt + 1
    End If
Next
Last:
End Sub
```

ANNEX 7: CODE 3

Form1 Object



Form1 Code

```
'/***Coded By : Pujan Giri, 070 MSC_GEOTECH IOE, 2015***/
Dim Fil_Data As String
Dim Write_FOS As Boolean
Private Sub Command1_Click()
If Option2.Value = True Then
    Write_FOS = False
    If Label2.Caption <> "" Then ExportFile
Else
Write_FOS = True
Open Text3.Text & "\FOS_Export.csv" For Output As #500
Print #500, "S,D,K,C,Phi,Cr,F"
Open Text3.Text & "\Generate_JPG.mcr" For Output As #300
Print #300, "#!MC 1300"
Print #300, "# Created by Tecplot 360 build 13.1.1.16309"
Print #300, "$!EXPORTSETUP EXPORTFORMAT = JPEG"
Print #300, "$!EXPORTSETUP EXPORTREGION = ALLFRAMES"
Print #300, "$!EXPORTSETUP IMAGEWIDTH = 1000"

For i = 0 To List1.ListCount - 1
List1.ListIndex = i
Me.Caption = "Exporting " & i + 1 & " of " & List1.ListCount
Call ExportFile
DoEvents
Next
Close #500
Close #300
End If
```

```
MsgBox "Export Complete!", vbInformation, "Pujan"
End Sub
Private Sub ReadMultiSRF(ByVal filename As String, ByRef S()
As Double, ByRef N() As Integer, ByRef U() As Double)
Call GetSRF(File1.Path & "\" & filename, S(), N(), U())
For i = 0 To List4.ListCount - 1
    fil = List4.List(i) & "\" & filename
    If Fileexists(fil) = True Then
        ReDim srf_2(0) As Double
        ReDim N_itr_2(0) As Integer
        ReDim umax_2(0) As Double
        Call GetSRF(fil, srf_2(), N_itr_2(), umax_2())
        If srf_2(0) = 0 Then
        Clipboard.Clear
        Clipboard.SetText fil
        MsgBox "Empty " & fil
        End If
       For j = 0 To UBound(srf_2)
       If srf_2(j) <> 0 Then
       ReDim Preserve S(UBound(S) + 1)
       ReDim Preserve N(UBound(N) + 1)
       ReDim Preserve U(UBound(U) + 1)
       S(UBound(S)) = srf_2(j)
       N(UBound(N)) = N_itr_2(j)
       U(UBound(U)) = umax_2(j)
       End If
        Next
    End If
Next
End Sub
Private Sub DecodeName(ByVal modelx As String, ByRef Valx() As
Double)
On Error Resume Next
'S26D2K-0.1C10PHI15CR10   <---File Must have name in this
format
orderx = Array("S", "D", "K", "C", "PHI", "CR")
For i = 0 To UBound(orderx) - 1
a = InStr(1, modelx, orderx(i), vbTextCompare)
b = InStr(a, modelx, orderx(i + 1), vbTextCompare)
Valx(i) = Val(Mid(modelx, a + Len(orderx(i)), b - a -
Len(orderx(i))))
Next
Valx(i) = Val(Mid(modelx, b + Len(orderx(i))))
End Sub
Private Sub ExportFile()
Dim data As String
Dim plastic As String
Dim diffumax As Double
```

```
Dim cnt As Integer
Dim fos As Double
Dim Coeff As Double
a = InStr(1, Fil_Data, "#" & Label2.Caption, vbTextCompare)
b = InStr(a + 1, Fil_Data, "#")
If b = 0 Then b = Len(Fil_Data)
codex = Mid(Fil_Data, a + Len(Label2.Caption) + 1, b - a -
Len(Label2.Caption) - 1)
tmp = Split(codex, vbCrLf)
srf_txt = Trim(Replace(tmp(1), ",", " "))
nl_txt = Trim(Replace(tmp(2), ",", " "))
umax_txt = Trim(Replace(tmp(3), ",", " "))

Dim Valx(0 To 5) As Double
Call DecodeName(Label2.Caption, Valx())
    plastic = ""
    diffumax = 0
    cnt = 0
    fos = 0
    tmp2 = Split(umax_txt, " ")
'----COEFFICIENT FOR VARIOUS PHI VALUES
If Valx(4) <= 20 Then
Coeff = 10
ElseIf Valx(4) <= 30 Then
Coeff = 5
Else
Coeff = 3
End If
'---------------Coefficent Ends
    For j = 0 To UBound(tmp2) - 1
        If cnt <> 0 And plastic = "" Then
            cur_diff = Val(tmp2(j + 1)) - Val(tmp2(j))
            If cur_diff > Coeff * diffumax / cnt Then
'<=====THIS COEFFICIENT MAY BE OF YOUR INTEREST
                plastic = CStr(j)
                Exit For
            End If
        End If
        cnt = cnt + 1
        add_diff = Val(tmp2(j + 1)) - Val(tmp2(j))
        If add_diff < 0 Then add_diff = 0
        diffumax = diffumax + add_diff
    Next
    cnt = UBound(tmp2) + 1

    If plastic <> "" Then
        tmp1 = Split(srf_txt, " ")
        fos = Val(tmp1(Val(plastic)))
```

```
        If Check2.Value = vbChecked Then
            cnt = Val(plastic) + 2
            tmp3 = Split(nl_txt, " ")
            srf_txt = ""
            nl_txt = ""     '<-- reset existing value to null
            umax_txt = ""
            For j = 0 To Val(plastic) + 1
                srf_txt = srf_txt & " " & tmp1(j)
                nl_txt = nl_txt & " " & tmp3(j)
                umax_txt = umax_txt & " " & tmp2(j)
            Next
            srf_txt = Trim(srf_txt)
            nl_txt = Trim(nl_txt)
            umax_txt = Trim(umax_txt)
        End If
    End If


Open Text3.Text & "\NL_" & Label2.Caption & ".dat" For Output
As #1
Print #1, "TITLE=" & Label2.Caption
Print #1, "Variables=" & Chr(34) & "SRF" & Chr(34) & "," &
Chr(34) & "NL_ITR" & Chr(34)
Print #1, "ZONE DATAPACKING=BLOCK, T=" & Label2.Caption & ",
I=" & cnt
Print #1, srf_txt
Print #1, nl_txt
Close #1
Open Text3.Text & "\Umax_" & Label2.Caption & ".dat" For
Output As #1
Print #1, "TITLE=" & Label2.Caption
Print #1, "Variables=" & Chr(34) & "SRF" & Chr(34) & "," &
Chr(34) & "Umax" & Chr(34)
Print #1, "ZONE DATAPACKING=BLOCK, T=" & Label2.Caption & ",
I=" & cnt
Print #1, srf_txt
Print #1, umax_txt
Close #1

Open App.Path & "\base.lay" For Binary As #1
data = Space(LOF(1))
Get #1, , data
Close #1

data = Replace(data, "%NLITR_HERE%", "NL_" & Label2.Caption &
".dat")
```

```
data = Replace(data, "%UMAX_HERE%", "Umax_" & Label2.Caption &
".dat")
data = Replace(data, "%SRFX_MIN%", srf_min - 0.05)
data = Replace(data, "%SRFX_MAX%", srf_max + 0.05)
data = Replace(data, "%NLITR_MIN%", nl_min - nl_min)
data = Replace(data, "%NLITR_MAX%", Nl_max + nl_min)
data = Replace(data, "%UMAX_MIN%", umax_min - umax_min)
data = Replace(data, "%UMAX_MAX%", umax_max + umax_min)
tmp_txt = "Slope = " & Valx(0) & _
" K<sub>x</sub> = " & Abs(Valx(2)) & _
" C = " & Valx(3) & _
" <greek>f</greek> = " & Valx(4) & _
" D <sub>r</sub> = " & Valx(1) & " m." & _
" C <sub> r </sub> = " & Valx(5)
If Write_FOS = True Then
    fos_fil = ""
    For i = 0 To 5
    fos_fil = fos_fil & Valx(i) & ","
    Next
    fos_fil = fos_fil & fos
Print #500, fos_fil
Print #300, "$!OPENLAYOUT  " & Chr(34) & "|macrofilepath|\" &
Label2.Caption & ".lay" & Chr(34)
Print #300, "$!EXPORTSETUP EXPORTFNAME = '|macrofilepath|\" &
Label2.Caption & ".jpg'"
Print #300, "$!EXPORT"
Print #300, "  EXPORTREGION = ALLFRAMES"
End If
data = Replace(data, "%MODELID%", tmp_txt)
data = Replace(data, "%FOS%", "FOS=" & fos)
Open Text3.Text & "\" & Label2.Caption & ".lay" For Output As
#1
Print #1, data
Close #1

End Sub
Private Function Fileexists(ByVal filename As String) As
Boolean
On Error GoTo 1
a = FileLen(filename)
Fileexists = True
Exit Function
1:
Fileexists = False
End Function

Private Sub Command2_Click()
Dim a As Integer
```

```
a = List1.ListIndex + 1
If a = -1 Or a = List1.ListCount - 1 Then a = 0
For i = a To List1.ListCount - 1
If InStr(1, UCase(List1.List(i)), UCase(Text8.Text),
vbTextCompare) <> 0 Then
List1.ListIndex = i
Option2.Value = True
Exit Sub
End If
Next
End Sub

Private Sub Command3_Click()
On Error GoTo 1
File1.Path = Text1.Text
Me.Caption = File1.Path
Me.Caption = "Loading Files..."
File1.Refresh
Me.Caption = "File Count: " & File1.ListCount
Command5.Enabled = True
Exit Sub
1:
Me.Caption = Err.Description
End Sub

Private Sub Command4_Click()
For i = 0 To List4.ListCount - 1
If List4.List(i) = LCase(Trim(Text4.Text)) Then
MsgBox "Already Exists", vbExclamation
Exit Sub
End If
Next
List4.AddItem LCase(Trim(Text4.Text))
End Sub

Private Sub Command5_Click()
If File1.ListCount = 0 Then Exit Sub
If Check1.Value = vbChecked Then
Open Text6.Text For Append As #200
Else
Open Text6.Text For Output As #200
End If
Text7.Text = Text6.Text
For j = 0 To File1.ListCount - 1
File1.ListIndex = j
ReDim SRF(0) As Double
ReDim nitr(0) As Integer
ReDim umax(0) As Double
```

```
Call ReadMultiSRF(File1.List(j), SRF(), nitr(), umax())
tmp2 = Split(File1.List(j), "_")
modelx = "#" & UCase(Trim(Text5.Text) & tmp2(0))
UL = UBound(umax)
umaxx = CStr(umax(0))
For i = 1 To UL
umaxx = umaxx & "," & CStr(umax(i))
Next
srfx = CStr(SRF(0))
For i = 1 To UL
srfx = srfx & "," & CStr(SRF(i))
Next
nitrx = CStr(nitr(0))
For i = 1 To UL
nitrx = nitrx & "," & CStr(nitr(i))
Next
Print #200, modelx
Print #200, srfx
Print #200, nitrx
Print #200, umaxx
Me.Caption = j + 1 & " of " & File1.ListCount
Next
Close #200
MsgBox "Export Completed", vbInformation
Me.Caption = "Complete!"
End Sub

Private Sub Command6_Click()
On Error GoTo 1
Open Text7.Text For Input As #1
List1.Clear
While Not EOF(1)
Line Input #1, a
If Left(a, 1) = "#" Then List1.AddItem Mid(a, 2)
Wend
Close #1
If List1.ListCount <> 0 Then
Open Text7.Text For Binary As #1
Fil_Data = Space(LOF(1))
Get #1, , Fil_Data
Close #1
List1.ListIndex = 0
End If
Exit Sub
1:
MsgBox Err.Description, vbCritical, "Failed"
End Sub
```

```
Private Sub File1_Click()
File1.ToolTipText = File1.List(File1.ListIndex)
End Sub

Private Sub List1_Click()
Label2.Caption = List1.List(List1.ListIndex)
End Sub

Private Sub List1_KeyDown(KeyCode As Integer, Shift As
Integer)
If KeyCode = 46 And List1.ListIndex >= 0 Then List1.RemoveItem
List1.ListIndex
End Sub

Private Sub List4_DblClick()
If List4.ListIndex >= 0 Then Text4.Text = List4.List(i)
End Sub

Private Sub List4_KeyDown(KeyCode As Integer, Shift As
Integer)
If KeyCode = 46 And List4.ListIndex >= 0 Then List4.RemoveItem
List4.ListIndex
End Sub

Private Sub Text1_Change()
List4.Clear
Command5.Enabled = False
End Sub

Private Sub Text2_Change()
File1.Pattern = Text2.Text
File1.Refresh
End Sub

Private Sub Text3_Change()
If Text3.Text = "" Then
Command1.Enabled = False
Else
Command1.Enabled = True
End If
End Sub
```

Module (Specfem)

Ref. Code2 Module (specfem)

ANNEX 8: RESULT OF REGRESSION FROM SPSS

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	K, Cr, Rd, TanBeta, TanPhi, StabilityNum[b]	.	Enter

a. Dependent Variable: F

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.957[a]	.916	.916	.1372

a. Predictors: (Constant), K, Cr, Rd, TanBeta, TanPhi, StabilityNum

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1772.564	6	295.427	15687.569	.000[b]
	Residual	162.576	8633	.019		
	Total	1935.140	8639			

a. Dependent Variable: F

b. Predictors: (Constant), K, Cr, Rd, TanBeta, TanPhi, StabilityNum

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.533	.007		73.673	.000
	StabilityNum	5.397	.036	.473	151.720	.000
	TanPhi	1.344	.006	.692	221.880	.000
	TanBeta	-.301	.003	-.364	-116.671	.000
	Rd	.035	.002	.060	19.338	.000
	Cr	.006	.000	.089	28.495	.000
	K	-1.521	.018	-.262	-84.129	.000

a. Dependent Variable: F