University of Southern Queensland

Faculty of Health, Engineering & Sciences

Geotechnical Stability Analysis Using Student Versions of FLAC, PLAXIS and SLOPE/W

A dissertation submitted by

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towards the degree of

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Abstract

Slope stability analysis is of particular importance to Geotechnical Engineers as slope failures can have devastating social and economic impacts. There are several software packages developed for stability analysis which utilise the Limit Equilibrium (LE) Method, Finite Element (FE) method and Finite Difference (FD) method.

The majority of published information is in regards to the slope stability analysis methods of Limit Equilibrium, Finite Element and Finite Difference and not the software packages themselves. Several studies have suggested that the FE and FD methods provide greater benefits than the LE method; however other studies have suggested that the simplicity of the LE method outweighs the complexity of the FE and FD methods.

The purpose of this research project is to compare the student versions of FLAC, PLAXIS and SLOPE/W and their use in Geotechnical stability analysis. FLAC is a software package using the FD method; PLAXIS the FE method and SLOPE/W the LE method.

From this report it can be concluded that for software packages using the FE or FD method the type of 'mesh' generated and utilised in calculating the FOS value has a significant effect on accuracy of the results. Due to the limit in the amount of zones allowed within the FLAC student version and in general only allowing a coarse mesh analysis it can be considered that the FOS values calculated are less accurate compared to the student versions of PLAXIS and SLOPE/W.

Each package has its own benefits and limitations and it is recommended that the users choose the package that best suits the models requirements and its complexity. The student versions should be used as an indication only and any detailed analysis requires the use of a full licensed version of the chosen software package.

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19TH OCTOBER 2013

Date

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Contents

List of Figures

List of Tables

Nomenclature

FOS	Factor of safety
LE	Limit Equilibrium
FE	Finite Element
FD	Finite Difference
SRF	Strength Reduction Factor
Z	Depth
s	Shear strength
τ	Shear stress
σ	Normal stress
σ'	Effective normal stress
ρ	Density
γ_{unsat}	Unsaturated unit weight
γ_{sat}	Saturated unit weight
u	Pore water pressure
c'	Drained cohesion
ϕ'	Drained friction angle
c	Undrained cohesion
ϕ	Undrained friction angle
E'	Drained Elastic (Young's) modulus
E	Undrained Elastic (Young's) modulus
v'	Poisson's ratio

Chapter 1: Introduction

1.1 Introduction

The purpose of this report is to compare the student versions of FLAC, PLAXIS and SLOPE/W and their use in Geotechnical stability analysis.

The instability of a slope is an ongoing concern in most construction and infrastructure projects, as slope failures can result in significant repair and maintenance costs and can endanger both the workers and the general public. There are a number of software packages that have been developed for geotechnical stability analysis which utilise the Limit Equilibrium (LE) Method, Finite Element (FE) method and Finite Difference (FD) method. The LE method is the most widely used approach; however it does contain several limitations and inconsistencies. With the advancement in technology software packages utilising the FE and FD methods have increased in popularity as they tend to possess a wider range of features (Hammouri et al. 2008).

This research project intends to compares three software packages and their respective methods of stability analysis.

LE method:

- SLOPE/W is a software package created by GEO-SLOPE International Ltd. as part of their GeoStudio bundle.

FE/FD methods:

- PLAXIS is a software package created by Plaxis bv..
- FLAC is a software package created by ITASCA Consulting Group Inc.

1.2 Background

Over the years there has been an increase in construction and infrastructure projects and consequently a growth in the requirements for excavation, footings and road design. Engineers must take into account all geotechnical aspects affecting their design including soil material properties, slope stability and possible natural disasters which can have devastating social and economic impacts. Incorporating the analysis of slope stability within the design will help in the prevention of any geotechnical failures throughout construction and the life of the design (Bromhead 1992).

Slope stability is important throughout all aspects of construction and a small difference in the calculated Factor of Safety (FOS) can result in a significant increase in costs both in construction and ongoing maintenance. For many years the LE method has been the most common approach due to its simplicity and requiring minimal properties; however with the advancement in technology there has been an increase in the use of the FE and FD methods; as they are able to accommodate a wider range of geometries and can progressively calculate the deformation and stresses on the model up to and including the FOS. Currently there is no evidence into which software packages produce the most acceptable results. This research project intends to assist the engineering industry in comparing the student versions of SLOPE/W, PLAXIS & FLAC; three packages widely used (Aryal 2008).

1.3 Methodology

The methodology employed in addressing this report involves:

i) Studying the background into the methodology of the 3 software packages; PLAXIS, FLAC & SLOPE/W. i.e. Finite Element Method, Finite Difference Method & Limit Equilibrium Method.

ii) Familiarise with each package and their capabilities.

iii) Understand the limitations of the student versions.

iv) Research scenarios of geotechnical stability in which the software packages can be used.

v) Create concepts for each scenario to analyse.

vi) Research each scenario's parameters and soil properties.

vii) Create detailed scenarios including the geometry, details or actions and soil properties.

viii) Analyse each scenario using FLAC, PLAXIS & SLOPE/W and discuss the results.

ix) From all the above steps discuss the limitations and benefits of each of the software packages and make recommendations.

1.4 Objectives

The objectives of this report include:

- Gain a better understanding of factors that cause slope instability and their importance in the geotechnical analysis.
- Gain a better understanding of the student versions of FLAC, PLAXIS and SLOPE/W.
- Discuss the benefits and limitations of each packages student version.
- Evaluate my own personal experiences and preferences in the packages.

1.5 Report Structure

This report details background information of slope stability analysis through reviewing literature, analysing slope stability methods, experimental techniques, results and recommendations on the student versions of FLAC, PLAXIS and SLOPE/W software programs. These are outlined in the following sections:

Chapter 1: Introduction	Outlines the problem explored within the report.
Chapter 2: Literature Review	Reviews the current literature that has been published.
Chapter 3: Software Packages	Outlines the software packages used for the report.
Chapter 4: Scenario 1 - Simple Homogeneous Soil Slope at Varying Heights.	Outlines the scenario and results.
Chapter 5: Scenario 2 - Simple reservoir embankment with a clayey soil of varying plasticity.	Outlines the scenario and results.
Chapter 6: Scenario 3 - Earth Dam suffering rapid drawdown.	Outlines the scenario and results.
Chapter 7: Results and Discussion	Analysis of the results and discussion of the software used.
Chapter 8: Conclusion	Conclusion and recommendations for further work.

Chapter 2: Literature Review

2.1 Introduction

This chapter serves to review the current literature that has been published regarding FLAC, PLAXIS and SLOPE/W and their corresponding stability analysis methods. The majority of published information is in regards to the analysis methods of Limit Equilibrium, Finite Element and Finite Difference and not the software packages themselves. This literature review intends to establish an understanding of each of these methods.

2.2 Limit Equilibrium (LE) Method

Currently the LE method is the most widely used approach within the geotechnical industry in solving modern day slope stability scenarios. The LE method requires the plastic Mohr-Coulomb criterion where a materials failure is due not from the maximum normal or shear stress alone but a combination of both. The LE method establishes the required soil properties; slope geometry and then using the Mohr-Coulomb criterion calculates the stability of the slope by comparing the forces causing failure against the resisting forces. Throughout this procedure an FOS is computed using the equations of static equilibrium. "The fundamental assumption…is that failure occurs through sliding of a block or mass along a slip surface" (RocScience 2004a, p.2) and in order to compute the appropriate FOS a number of slip surfaces need to be postulated to find the *critical slip surface.* (Duncan & Wright 2005; Hammouri et al. 2008; Chen & Liu 1990, Das 2010).

The LE method requires the following assumptions:

i) "The soil behaves as a Mohr-Coulomb material.

ii) The FOS of the cohesive component of strength and the frictional component of strength are equal for all soils involved" (GEO-SLOPE International 2004, p.427).

iii) Each block within the slip surface has the same FOS.

iv) Inter-slice forces are assumed; to deem the problem determinate (Griffiths & Lane 1999; Cheng & Lau 2008; Aryal 2008).

2.2.1 Vertical Slices

The LE method utilises the method of vertical slices, the vertical slices method is where "the entire sliding mass is divided into a reasonable number of slices and the inter-slice forces are computed based on an assumed inter-slice force functional relationship" (Aryal 2008, p.4509). Slip surfaces are assumed and the static equilibrium equations are used to calculate the stresses and FOS on each slice (Chen & Lau 2008).

The static equilibrium conditions are:

1. "Equilibrium of forces in the vertical direction,
2. Equilibrium of forces in the horizontal direction, and
3. Equilibrium of moments about any point" (Duncan & Wright 2005, p.56).

The slip surface is a surface where sliding is assumed to occur; this slip surface may be circular, or a shape defined by straight lines. Duncan and Wright, 2005 states that when using the LE method the *Morgenstern-Price* procedure should be adopted as it satisfies all requirements for static equilibrium requirements for both forces and moments. The *Morgenstern-Price* procedure creates '*blocks'* dividing the soil above the slip surface.

Fine – Civil Engineering Software (2013) states that "Forces acting on individual blocks are displayed in the following figure:

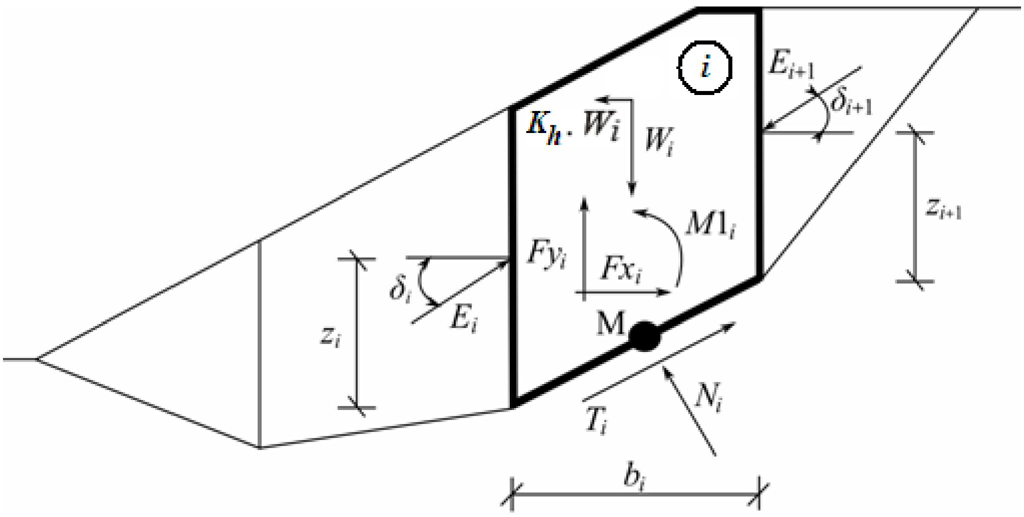


Figure 1 Static Scheme – *Morgenstern-Price* Method (Fine-Civil Software Package 2013).

The following assumptions are introduced in the *Morgenstern-Price* method to calculate the limit equilibrium of forces and moment on individual blocks:

- dividing planes between blocks are always vertical;
- the line of action of weight of block W_i passes through the center of the i^{th} segment of slip surface represented by point M;
- the normal force N_i is acting in the center of the i^{th} segment of slip surface, at point M;
- inclination of forces E_i acting between blocks is different on each block (δ_i) at slip surface end points is $\delta = 0$." (Fine-Civil Software Package, 2013)

An assumption is then made that each 'block' along the slip surface is believed to have the same FOS value, representing the average FOS for the slip surface and is taken as the appropriate value for that slip surface. The minimum or critical FOS is determined by calculating the FOS for all assumed slip surfaces and the smallest value being accepted; this is identified as the *critical slip surface*. Failure should not occur if the design is based on this calculated FOS (Duncan & Wright 2005; Hammouri et al. 2008).

2.2.2 Benefits

The LE method has the following benefits:

- It is a simplistic approach.
- Requires minimal soil properties and slope geometry.
- An adequate design based upon the calculated FOS ensures that sliding along the slip surface should not occur.

2.2.3 Limitations

The LE method has several limitations, including:

- Numerical inconsistencies.
- The analysis method is the same for all scenarios; i.e. the same method is used for a "slope of a newly constructed embankment, a slope of a recent excavation, or an existing natural slope" (Zheng et.al. 2008, p.629).
- Neglects the stress-strain behaviour of the material.
- The user needs an understanding of the geotechnical and slope stability principals involved within the analysis i.e. the direction of the slip surface.
- Unable to model the progressive failure and deformation of the surface without assumptions being made. (Cheng & Lau 2008; Hammouri et al. 2008; RocScience 2004a).

2.2.4 Factor of Safety (FOS)

The FOS provides a "quantitative indication of slope stability" (Duncan & Wright 2005, p.199). A calculated FOS value equal to 1 represents the forces on the slope being in equilibrium; that is the forces within the slope causing stablility (resisting forces) are in balance with those which cause the slope to be unstable (driving forces). A calculated FOS value greater than 1.0 represents the slope being stable under the given conditions (resisting forces > driving forces), and a FOS value less than 1.0 represents that the slope is unstable (failing); that is the driving forces out way the resisting forces (Duncan & Wright 2005).

The FOS is considered the magnitude the soils ultimate shear strength must be reduced by in order for failure to occur (Cheng & Lau 2008; Zheng et.al. 2008; Griffiths & Lane 1999; GEO-SLOPE International 2004).

According to Duncan & Wright (2005), the most extensively used definition of FOS for slope stability is:

$$FOS = \frac{shear\ strength\ of\ the\ soil}{shear\ stress\ required\ for\ equilibrium} = \frac{s}{\tau}$$

Using the Mohr-Coulomb equations, the shear strength can be expressed in terms of total stresses or effective stresses.

Total stress analysis: $\tau = \frac{c + \sigma tan\phi}{FOS}$

Effective stress analysis: $\tau = \frac{c' + (\sigma - u) tan\phi'}{FOS}$

Cheng & Lau (2008) states the LE method assumes the FOS to be constant along a slip surface and can be defined with respect to either the force or moment equilibrium:

1. *Moment Equilibrium:* used for rotational analysis (i.e. landslides).

$$FOS_m = \frac{M_r}{M_d}$$

Where;

FOS_m = factor of safety defined with respect to moment

M_r = summation of the resisting moments

M_d = summation of the driving moment

2. *Force equilibrium:* applies to translational or rotational failure (i.e. planar slip surfaces).

$$FOS_f = \frac{F_r}{F_d}$$

Where;
FOS_f = factor of safety defined with respect to force
F_r = summation of the resisting forces
F_d = summation of the driving forces

2.3 Finite Element (FE) Method

"The FE method is a numerical technique for solving differential equations or boundary value problems in science and engineering" (Hammouri et al. 2008, p.472). The FE method has been adapted for geotechnical engineering; however there is a perception by professionals in the geotechnical industry that the FE method is too complex and there is criticism in its necessity compared to the simpler LE method considering the poor quality of materials properties often used in the analysis (Griffiths & Lane 1999).

The FE method involves transferring the slopes geometry and soils properties into a mesh with a finite number of elements and nodes. Approximations are made for the continuity of displacements, the stresses between elements and the connectivity of the elements through theoretical analysis and mathematical formulations namely finite difference technique (Potts & Zdravkovic 1999; Huat & Mohammad 2006).

2.3.1 Finite Difference (FD) Technique

With regards to geotechnical engineering it can be considered that the Finite Difference (FD) technique is a special case of the FE approach. Both methods involve differential equations being transformed into matrix equations for each element; even though the equations are derived using two different methods the resulting equations are identical. The FD technique involves replacing the given continuous derivative terms with an "algebraic express written in terms of field variables (e.g. stress or displacement) at discrete points in space" (Itasca Consulting Group 2011a, p.1). These newly formed equations relate unknown dependent variables to given initial values and/or boundary conditions. There are 3 different possible techniques. Below is an example of all three (Wikipedia 2013; Itasca Consulting Group 2011a; Stephenson & Meados 1986).

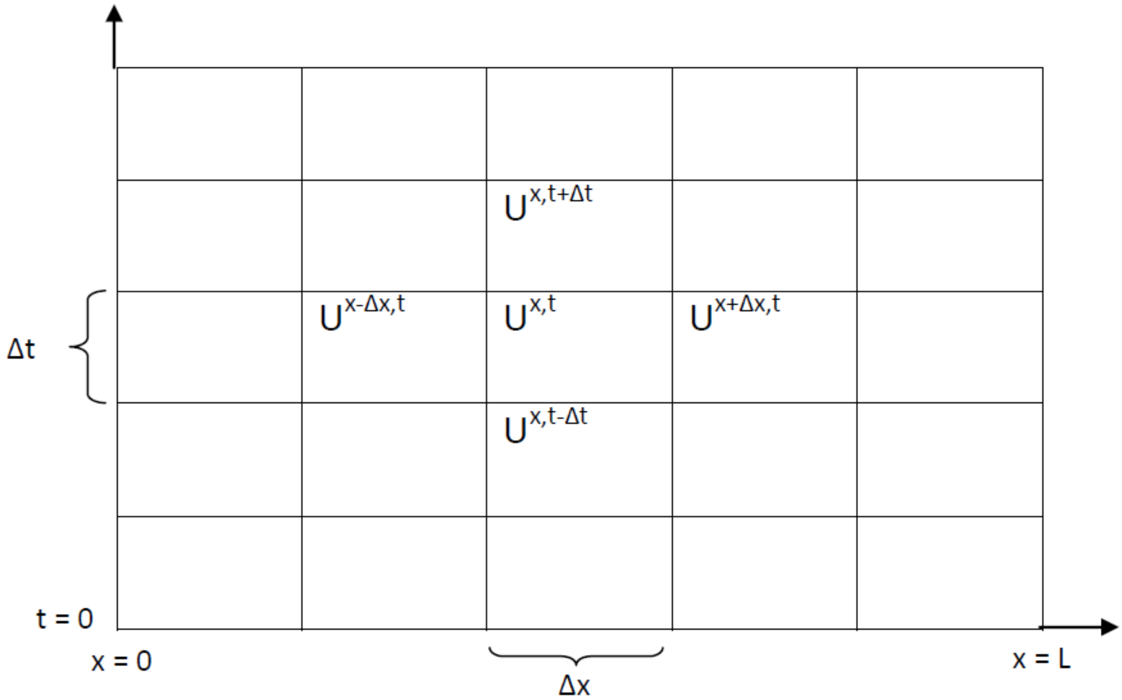


Figure 2 Rectangular mesh showing nodal points used in the finite difference technique.

Forward difference in x-direction

$$\frac{\partial U}{\partial x} = \frac{\mathrm{U}^{x+\Delta x,t} - \mathrm{U}^{x,t}}{\Delta x}$$

Backward difference in x-direction

$$\frac{\partial U}{\partial x} = \frac{U^{x,t} - U^{x-\Delta x,t}}{\Delta x}$$

Central difference in x-direction

$$\frac{\partial U}{\partial x} = \frac{U^{x+\Delta x,t} - U^{x-\Delta x,t}}{2\Delta x}$$

Once the differential equations have been manipulated so they rely on known nodal points it can be seen from the above three examples that it is relatively easy to find the corresponding unknown values. This is an example using a simplistic rectangular mesh however this technique can be used for any shaped mesh.

For the FE and FD approach the element matrices for an elastic material are identical (Itasca Consulting Group 2011a).

2.3.2 Benefits

With the advancement of technology there has been a large increase in the use of the FE and FD methods specifically in slope stability analysis. The FE and FD methods have the following benefits:

- The analysis can run relatively quickly.
- The FD method is a simple approach.Able to monitor progressive failure of the soil up to and including the FOS.
- Can accommodate a wide range of slope geometries and problems.
- The failure occurs within the slope where the resisting forces are outweighed by the driving forces. That is no assumptions are required regarding the location and direction of the slip surface models.

- Is able to calculate deformation, stresses and pore pressures within the slope (Desai & Christian 1977; Griffiths & Lane 1999; Hammouri et al. 2008).

2.3.3 Limitations

Although many believe the FE and FD methods overcome the LE method's deficiencies, it has its limitations, including:

- Calculated FOS can be dependent of the relative conditions chosen
- An inexperienced user may not be aware of meshing errors, boundary conditions or time restrictions involved in the analyses.
- The FD technique can run analysis slower than the FE method, particularly for linear problems.
- The FE and FD method are considered more complex compared to the LE method. Within the industry this complexity can be considered unnecessary – due to the relative inaccuracy of field data. (Zheng et.al. 2008; Griffiths & Lane 1999; Itasca Consulting Group 2011a; Wikipedia 2013).

2.3.4 Factor of Safety (FOS)

To determine the FOS the *shear strength reduction technique* is incorporated and extends off the FE and FD methods. "The factored shear strength parameters c'_f and Φ'_f are therefore given by:

$$c'_f = \frac{c'}{SRF}$$

$$\Phi'_f = \arctan(\frac{tan\Phi'}{SRF})$$

where SRF is a 'Strength Reduction Factor'. (Griffiths & Lane 1999, p.3)

A systematic iterative approach is undertaken to determine the SRF that applies to both terms. The ‘true’ FOS is equal to the SRF at the first instance of failure. That is FOS = SRF (Griffiths & Lane 1999).

Figure 3 Image of the Las Colinas Landslide (U.S. Geology Survey 2010).

Chapter 3: Software Packages

3.1 Overview

This research project compares three of the more predominant software packages used within the Geotechnical Engineering industry for slope stability analyses. Due to licensing requirements of each software package this project compares the student (demonstration) version of each package.

The software packages and their respective methods of stability analysis are:

LE method:

- GEO-SLOPE International Ltd, SLOPE/W 2012 Version 8.0 – Student License.
  - Operating system Microsoft Windows 7.

FE/FD methods:

- ITASCA Consulting Group Inc, FLAC 2011 Version 7.0 – Demonstration Mode.
  - Operating system Microsoft Windows 7.

- Plaxis bv., PLAXIS Version 2010 – Introductory Version.
  - Operating system Microsoft Windows 7.

3.2 SLOPE/W

"SLOPE/W is a software product that uses LE theory to compute the FOS of earth and rock slopes" (GEO-SLOPE International 2004, p.13). The user of SLOPE/W must have knowledge of the geotechnical principles involved in the analysis and judgment is required to ensure that realistic soil properties are used to calculate an accurate FOS. (GEO-SLOPE International 2004).

3.2.1 Required Soil Properties

SLOPE/W requires soil properties that satisfy the Mohr-Coulomb Criterion. The properties required to produce a valid soil model are presented in Table 1.

Property	Symbol	Units	Definition
Unit Weight	γ	kN/m^3	Soil's Total Unit Weight
Cohesion	*c*	kPa	Soil's Cohesion
Phi	ϕ	°	Soil's Friction Angle

Table 1 SLOPE/W Mohr-Coulomb Model Properties

3.2.2 Slip Surface Entry & Exit

The *Entry and Exit* command allows the user to identify slip surfaces by specifying the assumed portion of the surface where the slip surface will enter and exit. (GEO-SLOPE International 2012).

"The entry and exit ranges are used to determine a group of circular trial slip surfaces." (GEO-SLOPE International 2012). The slip surface with the smallest FOS is taken as the *critical slip surface.* This method is considered more intuitive than the '*Grid & Radius'* approach; however consideration must be made for the direction of the slip surface and if the *critical slip surface* extends beyond the entry and exit range specified (GEO-SLOPE International 2012).

3.2.3 SOLVE Process

SLOPE/W uses the SOLVE process to calculate the FOS. Each slip surface is processed in 3 steps:

1. Initially no forces are considered between the slices.
2. Normal forces are then considered, with no shear. An iterative process is used to calculate the FOS within a specified convergence.

3. Then normal and shear force relationship is considered. In the case of the *Morgenstern-Price* method, where the moment and force FOS are calculated within a specified convergence (GEO-SLOPE International 2004).

3.2.4 Morgenstern-Price Method

Cheng (2008) states that the different methods derived for LE (such as *Morgenstern-Price*, Spencer, Janbu, etc) should achieve similar FOS results. However, the *Morgenstern-Price* method is considered the most popular approach as it satisfies both force and moment equilibrium and applies to almost all soil profiles and slope geometries. The method involves dividing the sliding mass into vertical slices, which requires assumptions regarding the inter-slice shear forces (Zhu et al. 2005; GEO-SLOPE International 2004; Duncan & Wright 2005; Bromhead 1992).

Figure 4 presents the plot of FOS against lambda (λ) for various methods. The relationship between shear and normal inter-slice forces is represented by λ and the two curves illustrate the FOS with respect to moment equilibrium compared to the FOS with respect to force equilibrium. It can be seen that there is a variation in FOS for a range of λ values (GEO-SLOPE International 2004).

It can be seen that the *Morgenstern-Price* method satisfies both the force and moment equilibrium.

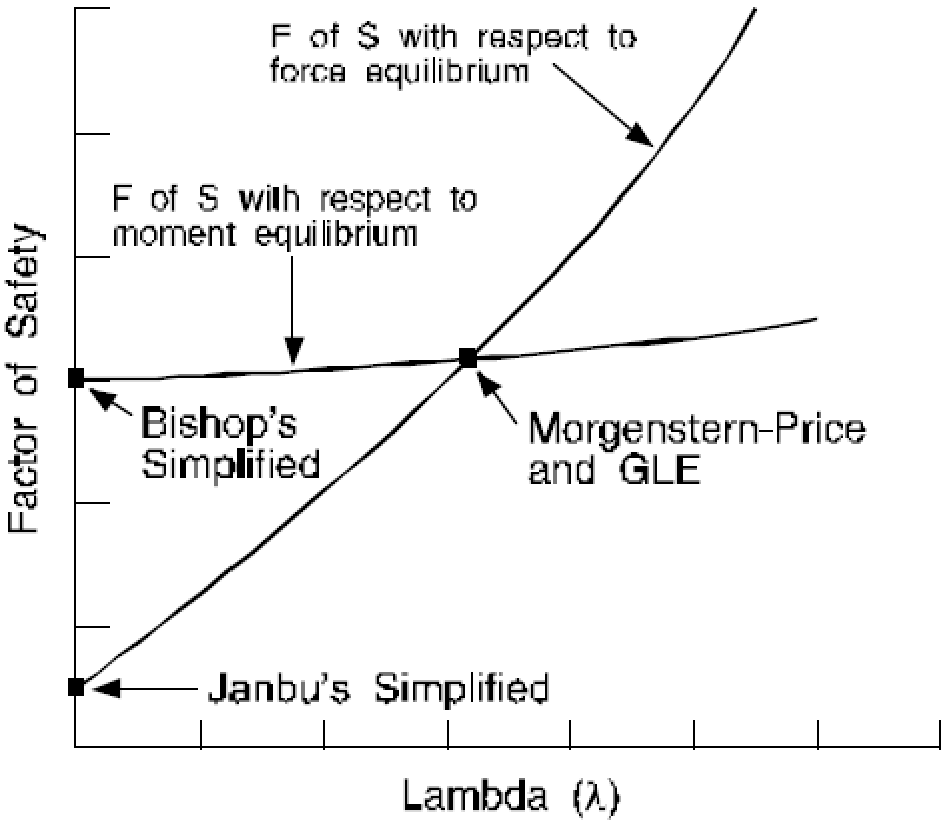


Figure 4 Moment and Force FOS as a Function of the Inter-slice Shear Force (GEO-SLOPE International 2004)

3.3 FLAC

"FLAC is a two-dimensional explicit finite difference program for engineering mechanics computation. This program simulates the behaviour of a structure built of soil, rock, or other materials that may undergo plastic flow when their yields limits are reached" (ITASCA Consulting Group 2011a, p.1). FLAC finds the static solutions for a problem using the two-dimensional *plane-strain* model. However, the dynamic equations of motion are included in the formulation to help model the stable and unstable forces within the model; this ensures that the scenario of a sudden collapse within the model is accounted for.

Presented in Figure 5 is the basic explicit calculation cycle used in FLAC; every cycle is considered one time step. The equations of motion are utilised to derive the velocities and displacements; then the new stresses and strain rates are calculated and so forth until failure is achieved. Note that a relatively small time step is chosen to ensure that the stress changes of each element do not influence its neighbours (ITASCA Consulting Group 2011b).

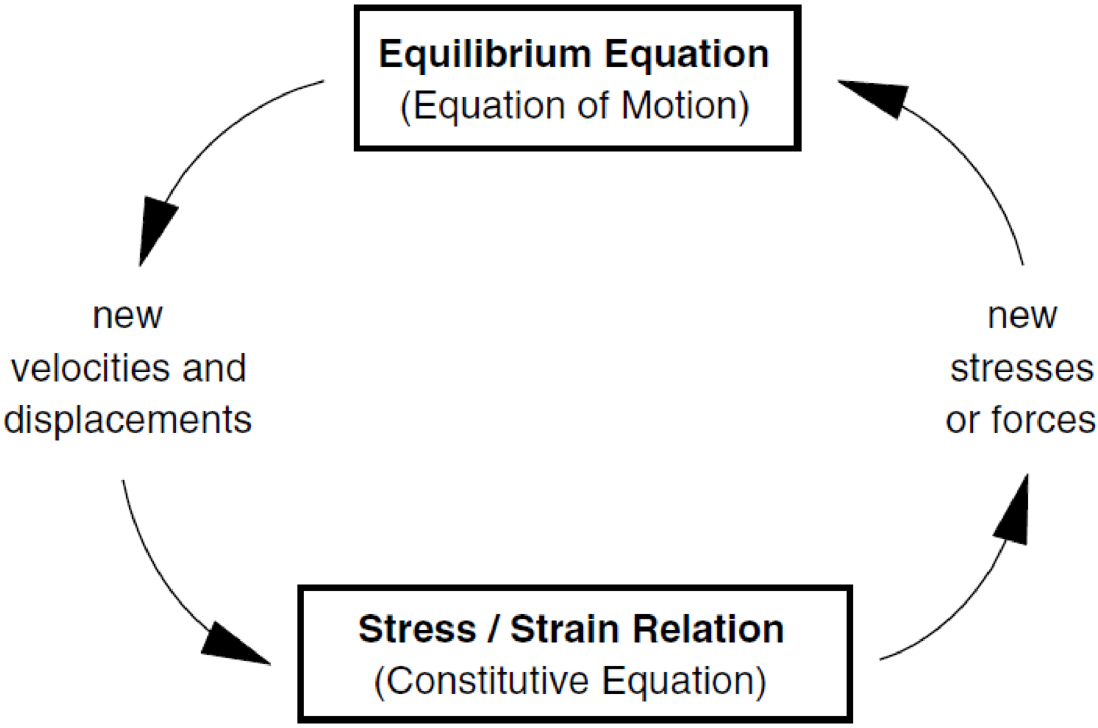


Figure 5 Basic explicit calculation cycle (ITASCA Consulting Group 2011b).

3.3.1 Required Soil Properties

FLAC requires basic soil parameters to simulate the shear strength characteristic of a soil. In addition to the basic parameters, advanced properties may be provided when using the Mohr-Coulomb model. The properties required for the Mohr-Coulomb model used in this analysis are outlined in Table 2 and Table 3.

Property	Symbol	Units	Definition
Density	*p*	kg/m^3	Density of the soil
Cohesion	*c*	Pa	The cohesion component of the shear strength
Phi	ϕ	°	Friction angle of the soil

Table 2 FLAC Mohr-Coulomb Model Basic Properties

Property	Symbol	Units	Definition
Tension	*t*	Pa	The tensile component of the shear strength
Psi	*Ψ*	°	Dilation angle of the soil

Table 3 FLAC Mohr-Coulomb Model Advanced Properties

Note that for a basic Mohr-Coulomb model it is assumed that the dilation angle is equal to the friction angle (Φ = Ψ) and the tensile strength is high enough to prevent tension cut-off. (ITASCA Consulting Group 2011a)

3.3.2 FLAC/Slope

"FLAC/Slope is a mini-version of FLAC that is designed specifically to perform factor-of-safety calculations for slope stability." (ITASCA Consulting Group 2011b, p.1).

FLAC/Slope allows for quick analysis of relatively basic scenarios, with certain model templates already loaded and properties of certain materials pre-loaded. The FLAC/Slope manual states that the FD method is a practical alternative to the LE method software packages and provides the following benefits:

1. "Any failure mode develops naturally; there is no need to specify a range of trial surfaces in advance.

2. No artificial parameters (e.g., functions for interslice force angles) need to be given as input.
3. Multiple failure surfaces (or complex internal yielding) evolve naturally, if the conditions give rise to them.
4. Structural interaction (e.g., rockbolt, soil nail or geogrid) is modelled realistically as fully coupled deforming elements, not simply as equivalent forces.
5. The solution consists of mechanisms that are kinematically feasible. (Note that the limit equilibrium method only considers forces, not kinematics.)" (ITASCA Consulting Group 2011b, p.1).

In addition to the FOS being calculated; FLAC/Slope creates a plot indicating the shear-strain rate of the elements which outline the failure surface and indicates the failure mode.

FLAC/Slope will be used for all analysis of the FLAC component within this report.

3.4 PLAXIS

PLAXIS is described as a FE package for geotechnical analysis that can utilise both two-dimensional and three-dimensional analysis in determining the stability and deformation experienced by slopes. PLAXIS lends itself to modeling more complex geotechnical scenarios as it has the capabilities to simulate inhomogeneous soil properties and time-dependent scenarios (Brinkgreve 2002; Hammouri et al. 2008; Plaxis bv. 2012a).

The models produced by PLAXIS can be considered a qualitative representation of the soil's behaviour. However the models "simulation of reality remains an approximation, which implicitly involves some inevitable numerical and modelling errors" (Plaxis bv. 2012c, p.7). It is critical that the user appropriately models the scenario; selecting the correct soil parameters, understanding the "staged construction" process and its limitations in order to make an appropriately judgement on the reliability of the results obtained (Plaxis bv. 2012c).

3.4.1 Required Soil Properties

In addition to the basic Mohr-Coulomb parameters, several advanced properties may be utilised. These properties are outlined in Table 4.

Property	Symbol	Units	Definition
Saturated Unit Weight	γ_{sat}	kN/m^3	Unit weight of soil below phreatic level
Unsaturated Unit Weight	γ_{unsat}	kN/m^3	Unit weight of soil above phreatic level
Phi	ϕ	°	Friction angle of the soil
Poisson's Ratio	ν	-	The ratio of lateral strain to linear strain
Reference Elastic Modulus	E_{ref}	kN/m^2	Elastic modulus at the reference depth
Reference Cohesion	c_{ref}	kN/m^2	Cohesion at the reference depth

Table 4 PLAXIS Mohr-Coulomb Model Properties

3.4.2 Elastic Modulus (E)

E is used in PLAXIS as the basic stiffness modulus in the Elastic and Mohr-Coulomb model. In general *E* tends to increase with confining pressure; that is, as the soil layer deepens the apparent stiffness of the soil increases and is generally stiffer in undrained conditions compared to drained conditions. In addition, the stress path influences the observed stiffness (Plaxis bv. 2012b).

3.4.3 Staged Construction

The staged construction approach intends to simulate the various stages throughout the slopes construction. This involves activating and/or deactivating the appropriate loads, geogrids, interfaces or soil layers throughout the analysis. The benefit of this approach is that it has the ability to take time into account (Plaxis bv. 2012b).

3.4.4 Phi-c Reduction

To determine an appropriate FOS value the *Phi-c reduction* approach is utilised. This process involves the strength parameters tanϕ and *c* of the soil being reduced until the slope fails (Hammouri et al. 2008; Plaxis bv. 2012b).

Chapter 4: Scenario 1 – Simple Homogeneous Soil Slope at Varying Heights

4.1 Geotechnical Model

The geotechnical model adopted in this analysis is illustrated in Figure 6. The soil is classified as unsaturated sand and comprises of the properties in Table 5, kept constant throughout all analyses.

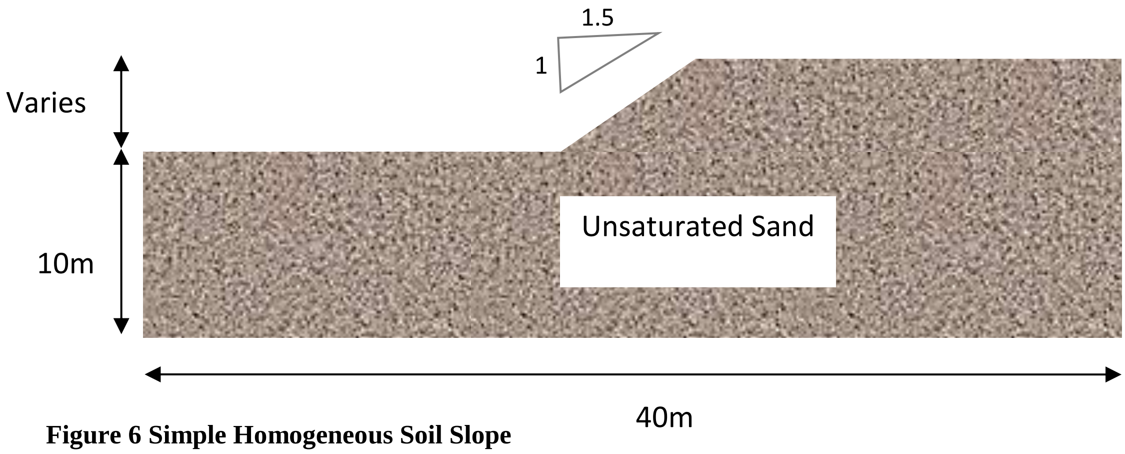


Figure 6 Simple Homogeneous Soil Slope

The slope considered has an embankment batter of 1:1.5, producing a slope angle equal to 33.7˚. The embankment height varies from 4m to 8m, with each case increasing in 2m increments, totalling 3 cases. No water table has been considered.

Figure 7 Image of a Road Embankment (Terracon 2013)

4.1.1 Material Properties

The properties of the unsaturated sand material are presented in Table 5. These properties are adequate for the Mohr-Coulomb approach. The embankment will be analysed for 3 cases at varying heights, presented in Table 6.

Material	Unit Weight (kN/m^3)	Elastic Modulus (MPa)	Poisson's Ratio	Cohesion (kPa)	Friction Angle (°)
Unsaturated Sand	17	13	0.3	1	30

Table 5 Unsaturated Sand Material Properties - Simple Homogeneous Soil Slope

Case	Embankment Height (m)
Case 1	4
Case 2	6
Case 3	8

Table 6 Cases and corresponding Embankment Heights - Simple Homogeneous Soil Slope

4.1.2 Units

PLAXIS, FLAC/Slope and SLOPE/W are all capable of using Metric units. However, FLAC/Slope uses different units to PLAXIS and SLOPE/W. The basic parameters and their units required in the analysis are outlined in Table 7. Gravity is taken as 9.81m/s^{-2}.

Property	Symbol	Units PLAXIS & SLOPE/W	Units FLAC/Slope
Unit Weight / Density	γ / *p*	kN/m^3	kg/m^3
Cohesion	*c*	kPa	Pa
Friction angle	ϕ	°	°
Elastic Modulus	*E*	MPa = 10^3 kN/m^2	-
Poisson's Ratio	*v*	-	-

Table 7 Parameters for Analysis

4.2 FLAC/Slope Analysis

4.2.1 Methodology

i) Upon starting FLAC/Slope a model name and embankment form needs to be chosen. This model is a simple embankment.

ii) The slope parameters need to be entered. The slope parameters for Case 1 are presented in Figure 8.

iii) The material properties need to be created and assigned. It must be noted that FLAC requires the Density of the material and the Cohesion inputted in Pascals as presented in Figure 9. The material is then assigned to the embankment. Note that a standard porosity of 0.5 is assigned but is not relevant as there is no water table.

iv) A mesh needs to be assigned to the embankment. Due to the limitations of the student package of FLAC/Slope a coarse mesh is used, presented in Figure 10. This may affect the accuracy of the results.

v) The embankment is cloned with the slope parameters changed for the corresponding Case's. Each case is solved giving an estimate for the FOS and a plot of the corresponding critical slip surfaces. Figure 11 to Figure 13 illustrate these critical slip surfaces.

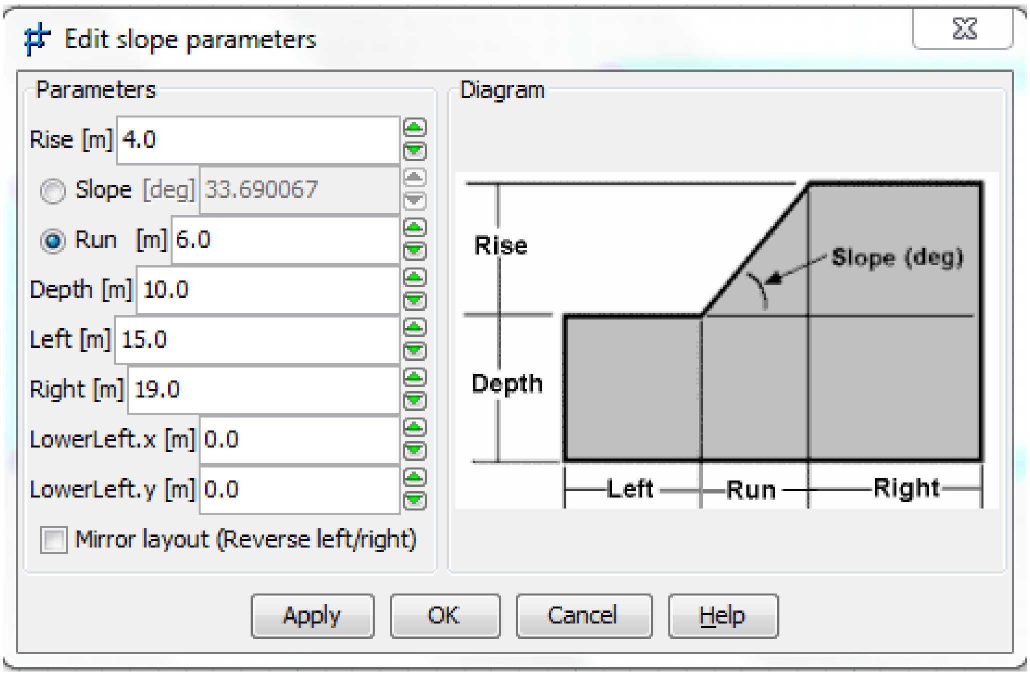


Figure 8 FLAC/Slope Slope Parameters for Case 1 - Simple Homogeneous Soil Slope

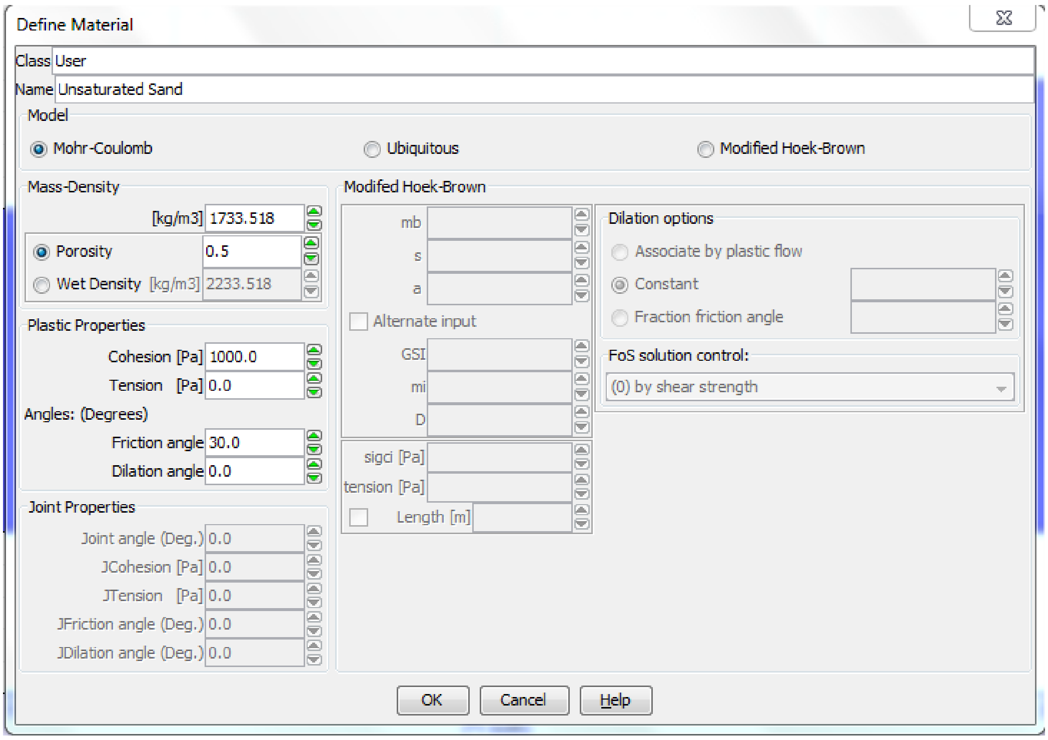


Figure 9 FLAC/Slope Material Properties - Simple Homogeneous Soil Slope

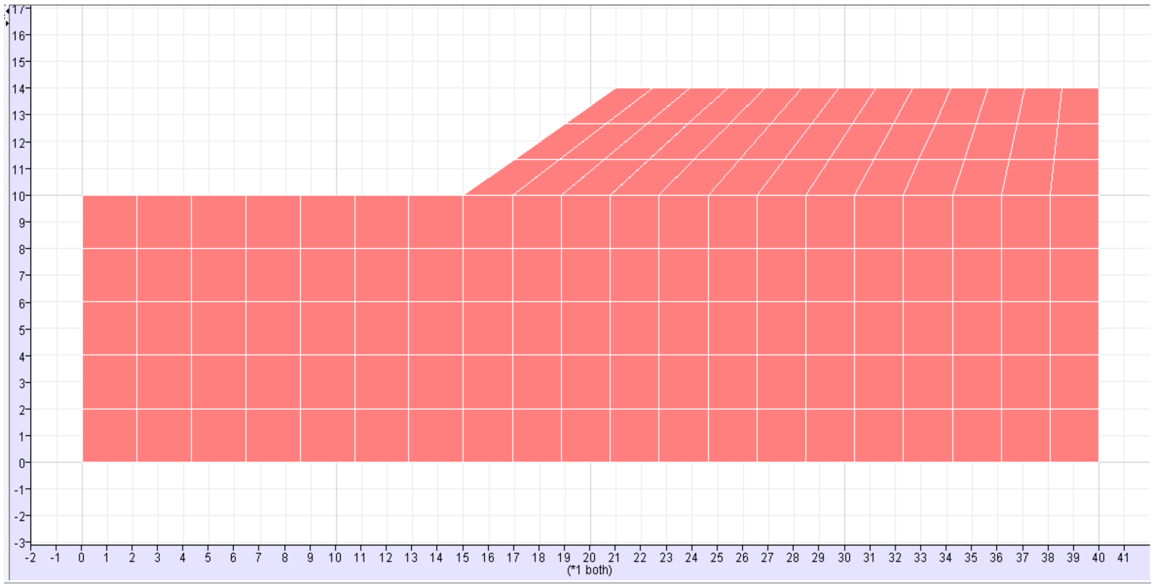


Figure 10 FLAC/Slope Finite Element Mesh for Case 1 - Simple Homogeneous Soil Slope

4.2.2 Results

Figure 11 to Figure 13 illustrate the critical slip surfaces for Cases 1 to 3 respectively using FLAC/Slope. Table 8 summarises the FOS results using FLAC/Slope. Note that due to the restrictions of a coarse mesh the contour plot is not very accurate.

Figure 11 FLAC/Slope Critical Slip Surface for Case 1 - Simple Homogeneous Soil Slope

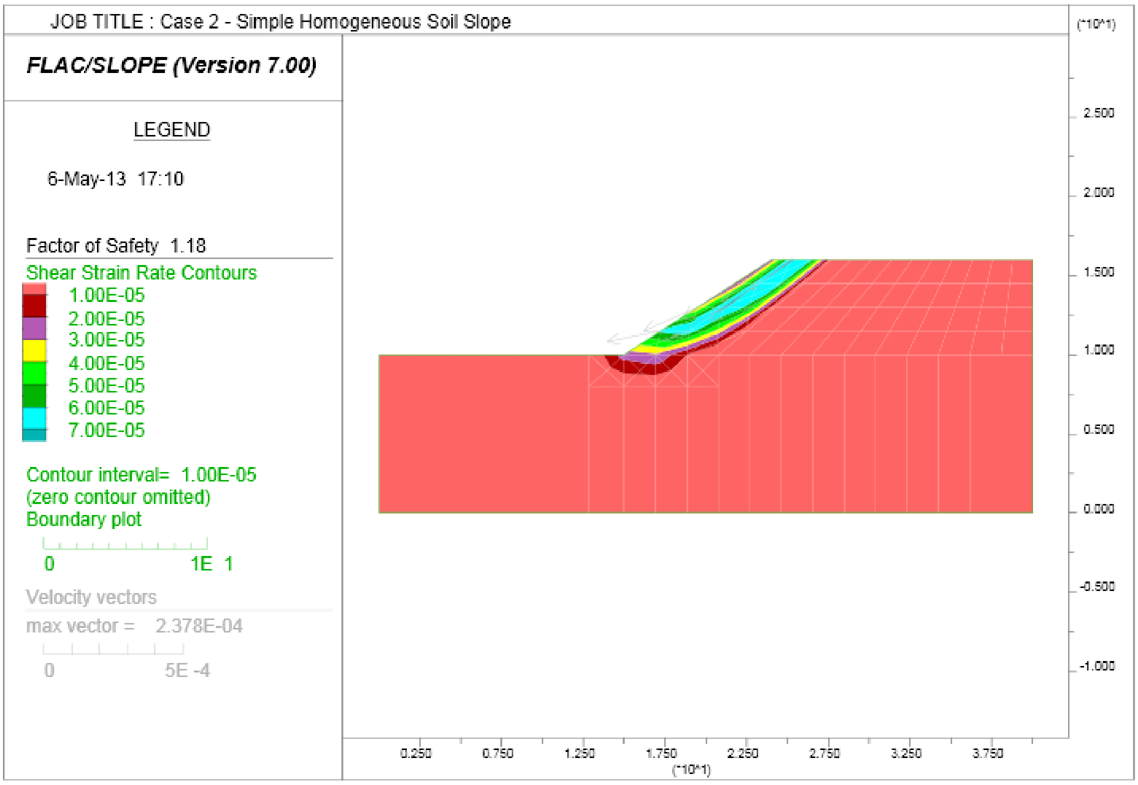


Figure 12 FLAC/Slope Critical Slip Surface for Case 2 - Simple Homogeneous Soil Slope

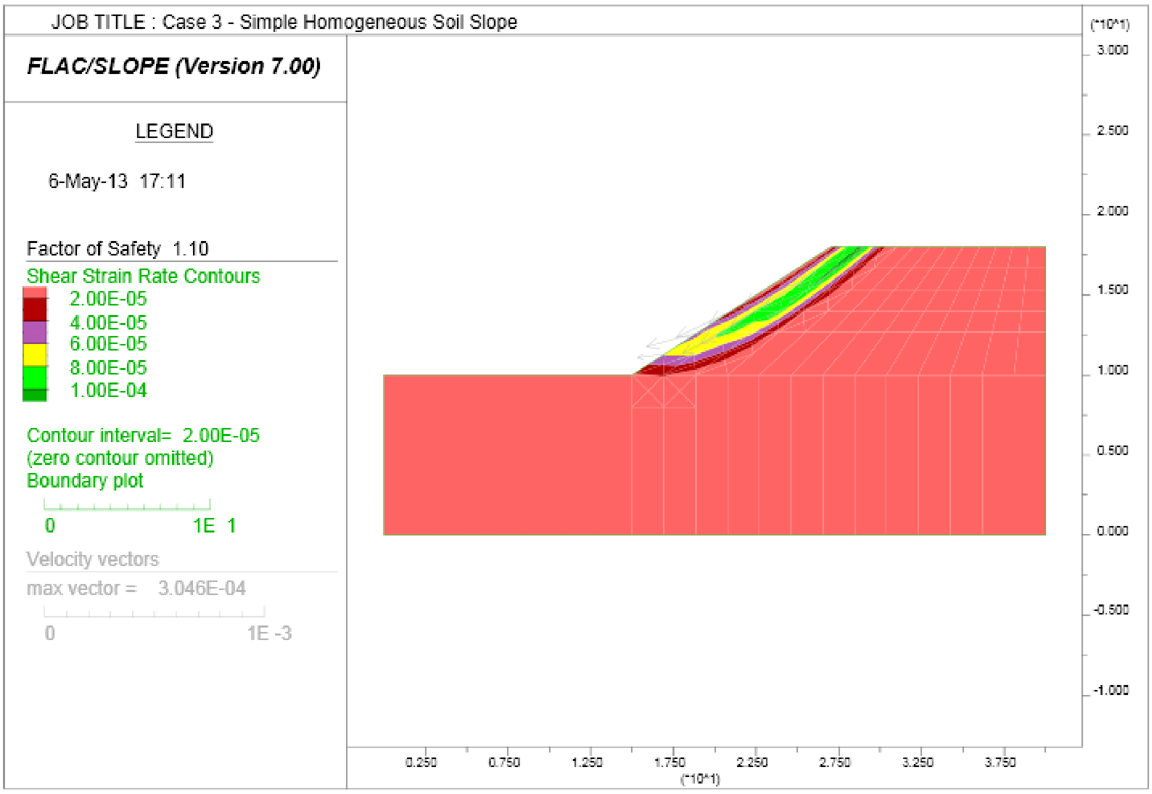


Figure 13 FLAC/Slope Critical Slip Surface for Case 3 - Simple Homogeneous Soil Slope

Table 8 outlines the FOS results from the FLAC/Slope analysis using a coarse mesh.

Case	FOS
Case 1	1.38
Case 2	1.18
Case 3	1.10

Table 8 FLAC/Slope FOS Results - Simple Homogeneous Soil Slope

4.3 SLOPE/W Analysis

4.3.1 Methodology

i) Upon starting SLOPE/W the first step is to set the units and scale for the model, then axes can be drawn.

ii) The model is drawn using the inbuilt CAD interface. Alternatively a model drawing can be imported from such programs as AutoCAD. As this is a simple slope with one region sketching the model with the region function is relatively simple. For models with multiple regions and materials using the Sketch polylines function then applying the region function of the appropriate areas can be more functional.

iii) The material properties need to be created and assigned, presented in Figure 14. The material is then assigned to the embankment.

iv) The slip surface is selected, and then the model can be solved.

v) This process is done for each case. Figure 15 to Figure 17 illustrate the critical slip surfaces for the 3 cases.

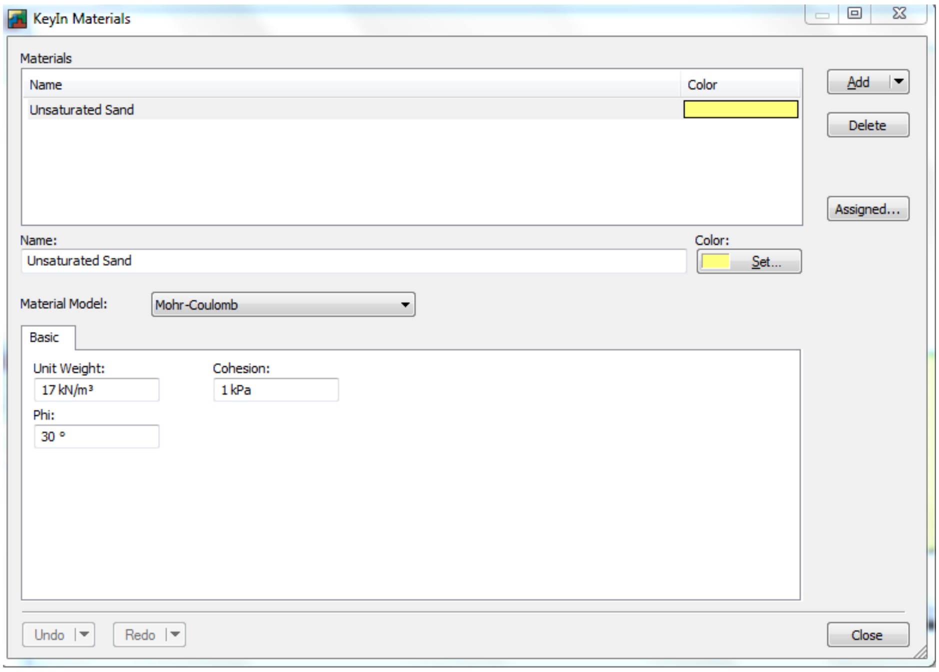


Figure 14 SLOPE/W Material Properties - Simple Homogeneous Soil Slope

4.3.2 Results

Figure 15 to Figure 17 illustrate the critical slip surfaces for Cases 1 to 3 respectively using SLOPE/W. Table 9 summarises the FOS results using SLOPE/W.

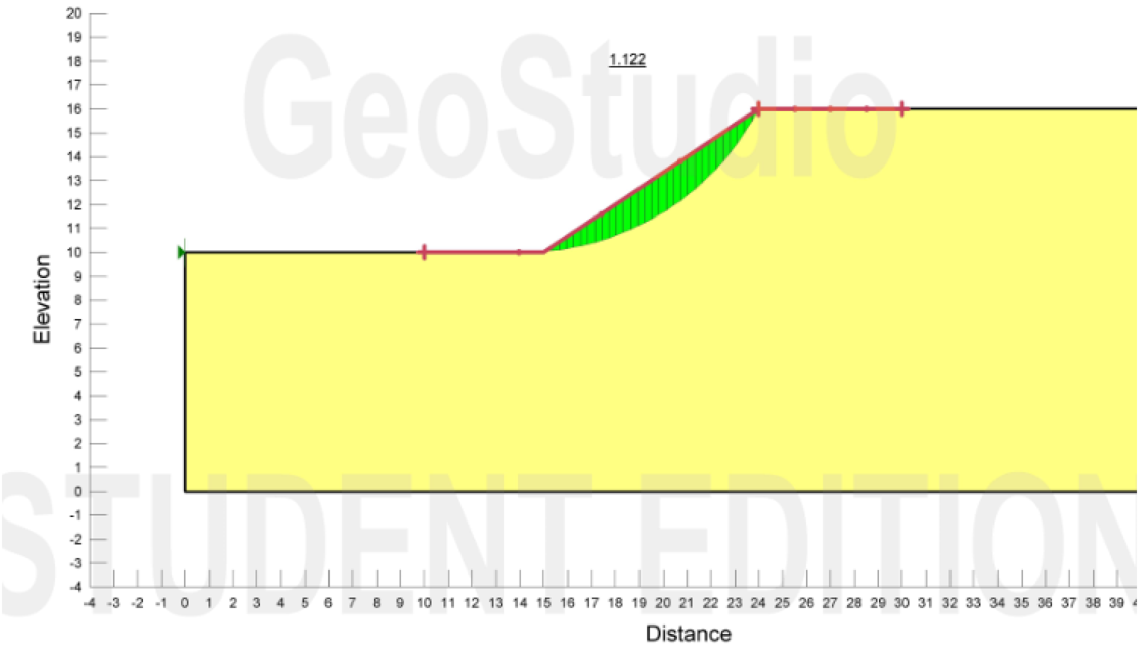


Figure 15 SLOPE/W Critical Slip Surface for Case 1 - Simple Homogeneous Soil Slope

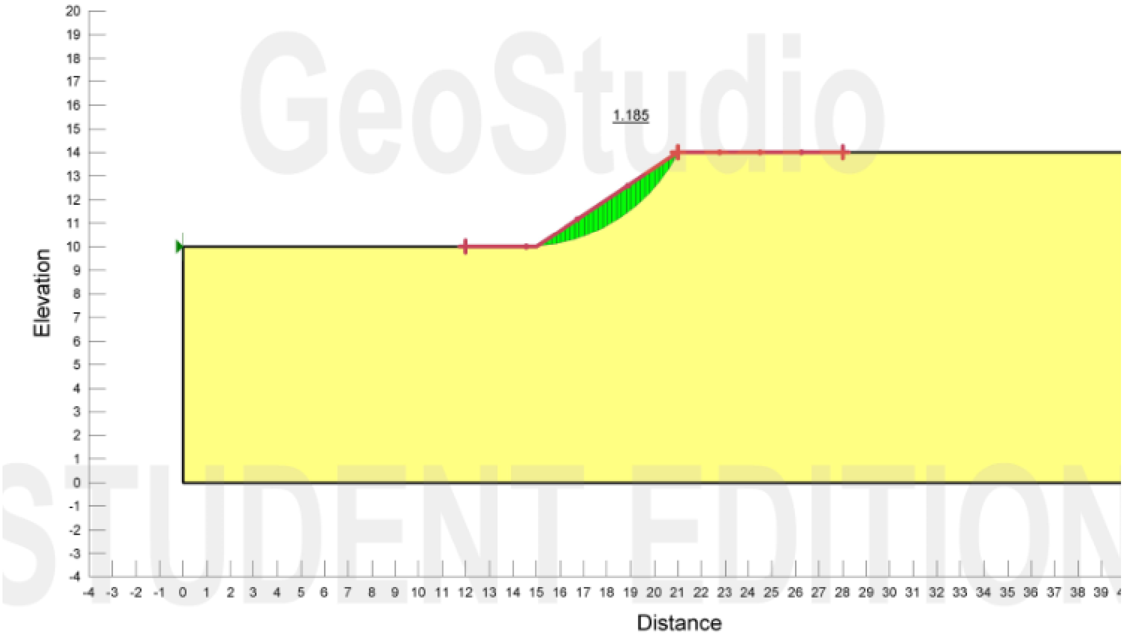


Figure 16 SLOPE/W Critical Slip Surface for Case 2 - Simple Homogeneous Soil Slope

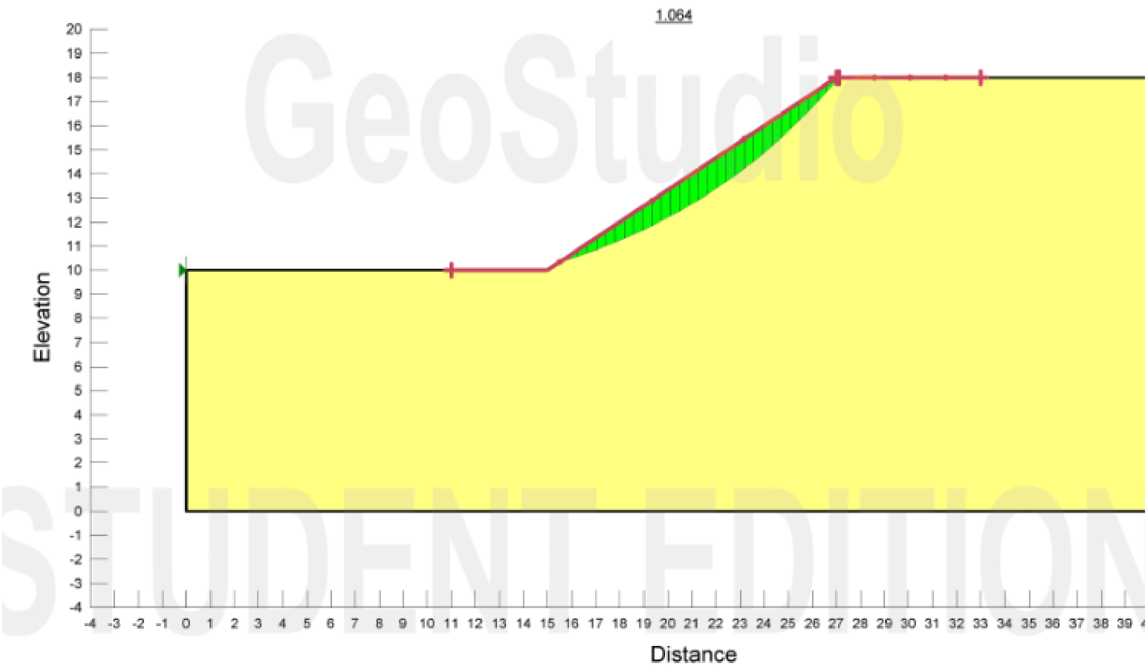


Figure 17 SLOPE/W Critical Slip Surface for Case 3 - Simple Homogeneous Soil Slope

Case	FOS
Case 1	1.185
Case 2	1.122
Case 3	1.064

Table 9 SLOPE/W FOS Results - Simple Homogeneous Soil Slope

4.4 PLAXIS Analysis

4.4.1 Methodology

i) Upon starting PLAXIS the projects title and models units and dimensions need to be set.

ii) The model is drawn using the inbuilt CAD interface.

iii) The material properties need to be created and assigned. PLAXIS requires the advanced properties of *E* and *v* of the soil as well as the standard Mohr-Coulomb.

iv) The restraints are then set as standard fixities.

v) The mesh is generated. A medium mesh is being used to help improve accuracy. The mesh for Case 1 is presented in Figure 18.

vi) In the calculation phase, the stability of the embankment needs to be simulated, Table 10 summarises each phase modelled in the PLAXIS assessment.

vii) The results are then viewed showing deformation, total displacement, FOS etc.

viii) This process is done for each case. Figure 19 to Figure 21 illustrate the critical slip surfaces for the 3 cases.

Phase	Description	Analysis Type	Loading Input	Time Period (day)
0	Set up initial ground model	Initial	-	-
1	Embankment Construction	Plastic	Staged Construction	1
2	FOS Analysis	Phi-c Reduction	Incremental Multipliers	-

Table 10 PLAXIS Finite Element Modelling Construction Stages

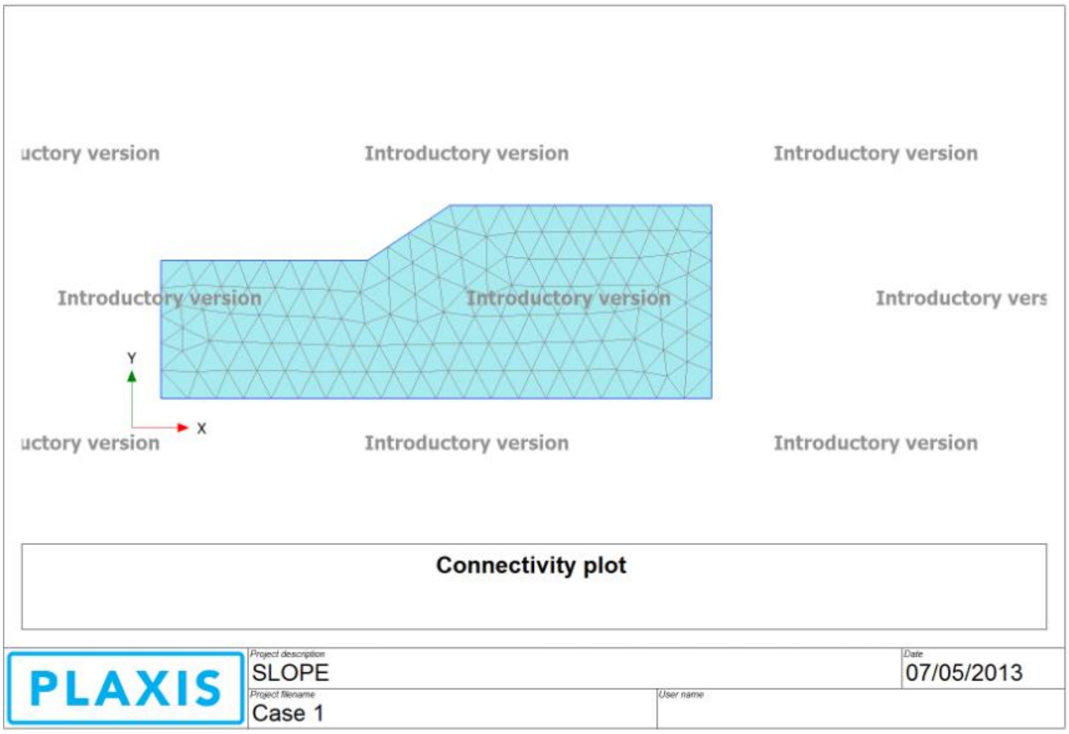
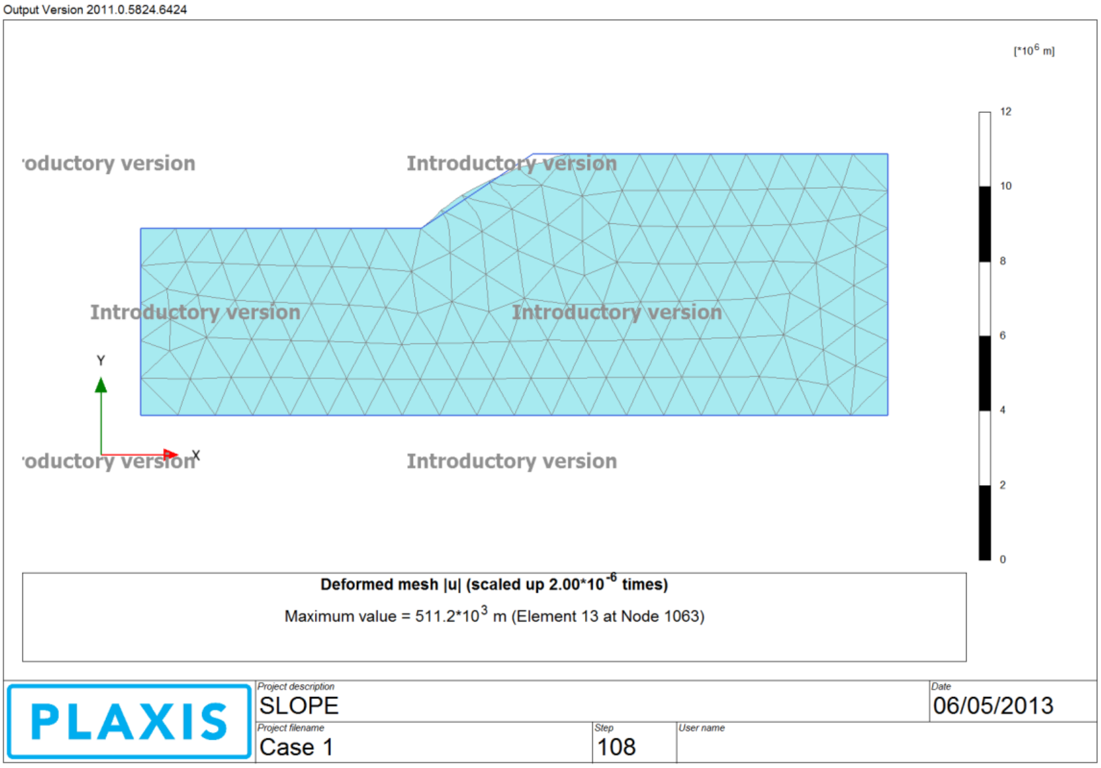


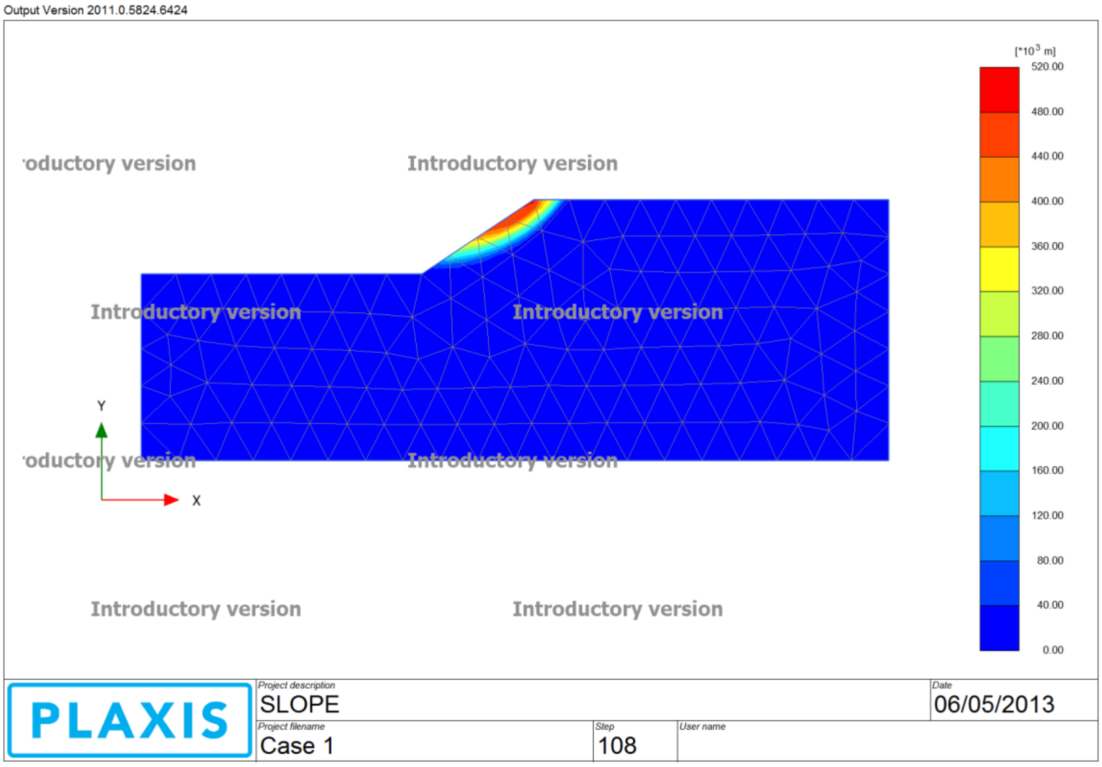
Figure 18 PLAXIS Finite Element Mesh for Case 1 - Simple Homogeneous Soil Slope

4.4.2 Results

Figure 19 to Figure 21 illustrate the critical slip surfaces for Cases 1 to 3 respectively using PLAXIS. Table 11 summarises the FOS results using PLAXIS.

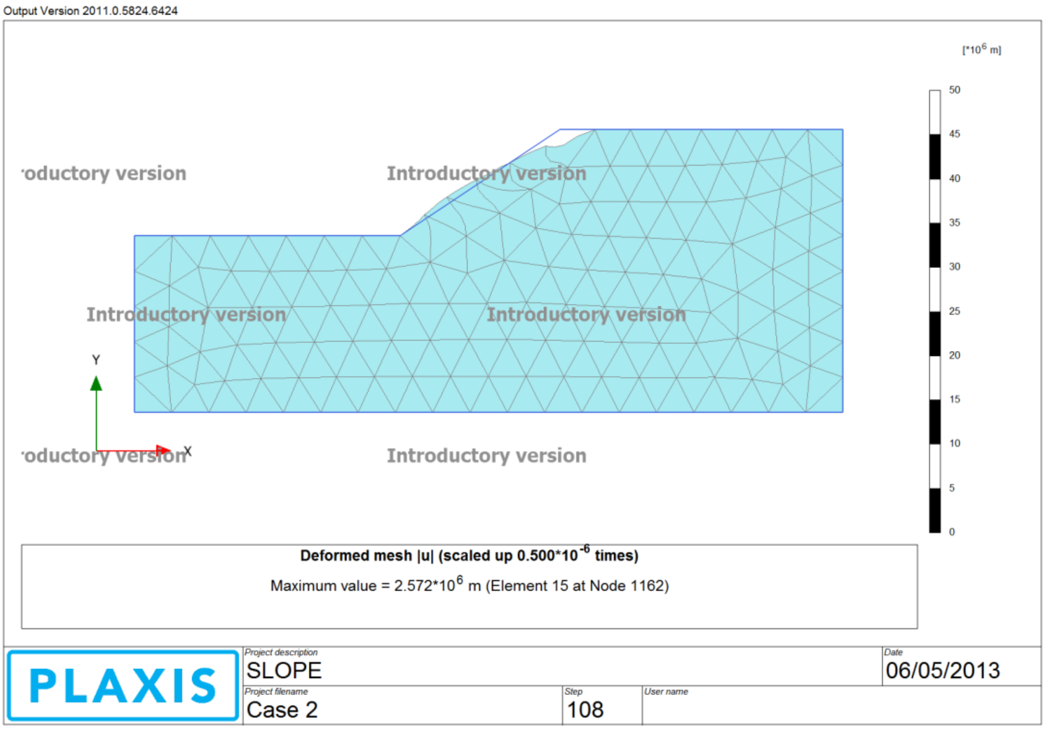


(a)

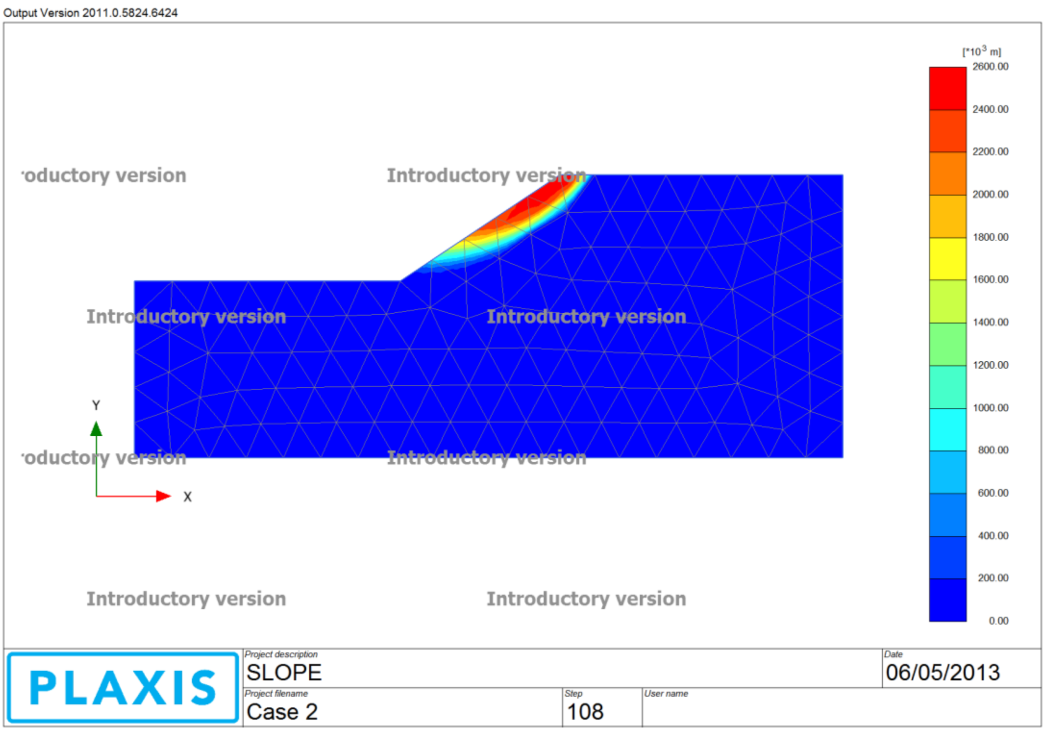


(b)

Figure 19 PLAXIS Case 1 - Simple Homogeneous Soil Slope (a) Deformation, and (b) Total Displacement

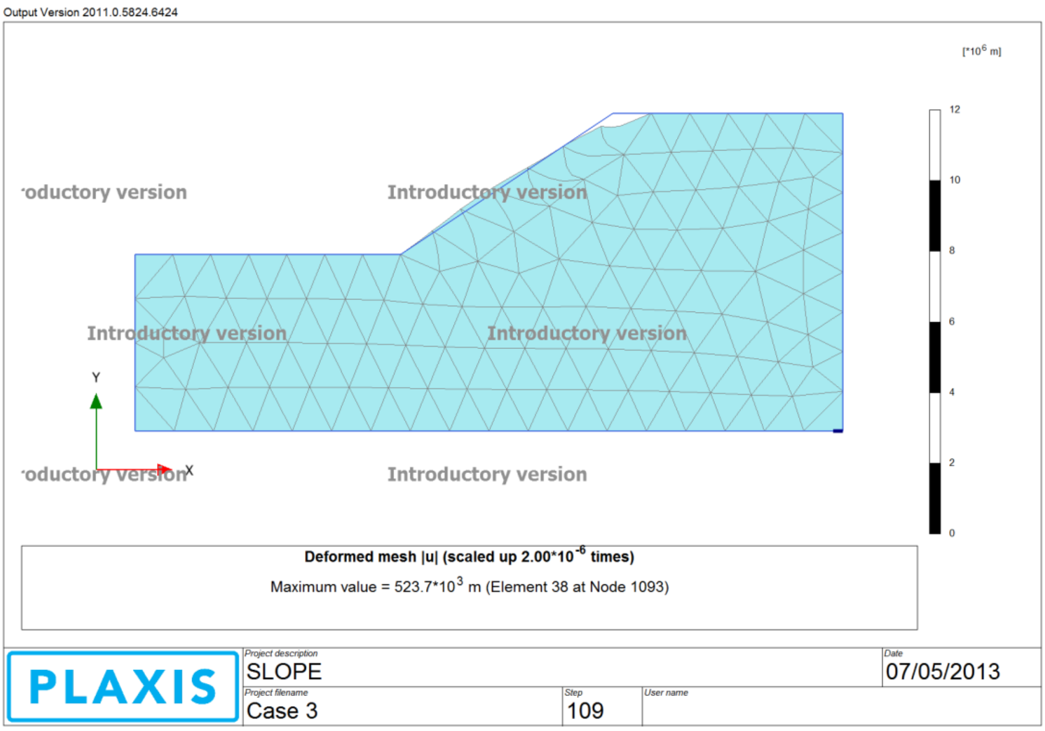


(a)

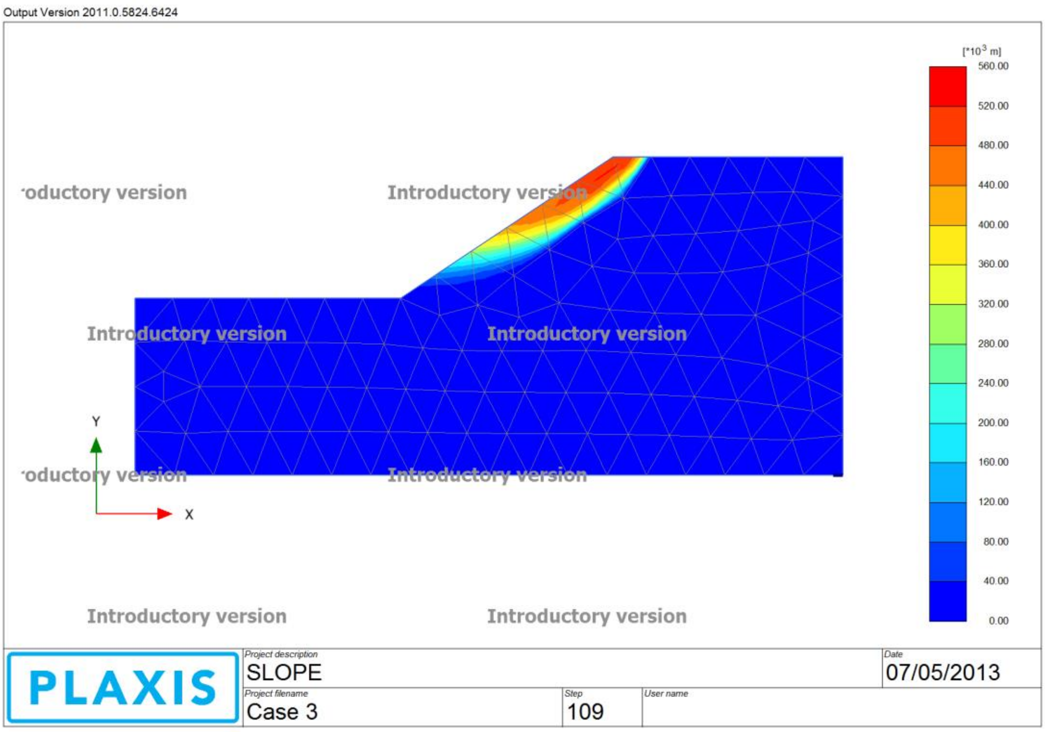


(b)

Figure 20 PLAXIS Case 2 - Simple Homogeneous Soil Slope (a) Deformation, and (b) Total Displacement



(a)



(b)

Figure 21 PLAXIS Case 3 - Simple Homogeneous Soil Slope (a) Deformation, and (b) Total Displacement

Table 11 outlines the FOS results from the PLAXIS analysis.

Case	FOS
Case 1	1.208
Case 2	1.100
Case 3	1.057

Table 11 PLAXIS FOS Results - Simple Homogeneous Soil Slope

4.5 Summary of Simple Homogeneous Soil Slope Results

The slope stability analysis has been conducted using FLAC/Slope, SLOPE/W and PLAXIS. Table 12 outlines the calculated FOS values from the proposed analysis methods. It can be seen that the SLOPE/W and PLAXIS analysis produce similar results; however the FLAC/Slope analysis results are significantly different. This is due to the coarse mesh used in the FLAC/Slope analysis producing results that can be considered not as accurate as the SLOPE/W and PLAXIS analysis.

Analysis Method	FOS		
	Case 1	**Case 2**	**Case 3**
FLAC/Slope	1.38	1.18	1.10
SLOPE/W	1.185	1.122	1.064
PLAXIS	1.208	1.100	1.057

Table 12 Summary of FOS Results - Simple Homogeneous Soil Slope

Chapter 5: Scenario 2 – Simple Reservoir Embankment with a Clayey Soil of Varying Plasticity

5.1 Geotechnical Model

The geotechnical model adopted in this analysis is illustrated in Figure 22. The soil is classified a clayey soil with varying plasticity comprising of the properties in Table 13.

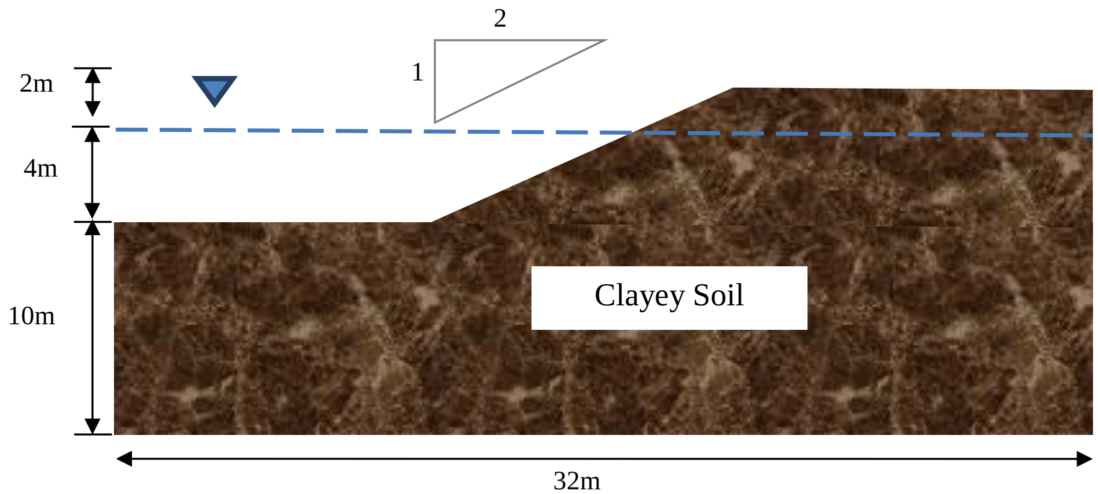


Figure 22 Simple Reservoir Embankment with a Clayey Soil

The slope considered has an embankment batter of 1:2, producing a slope angle equal to 26.6˚. The reservoir height is kept constant at 6m, with the water table for each case at 4m.

Figure 23 Image of a Reservoir Embankment (VirginiaTech 2007).

5.1.1 Material Properties

The properties of the clayey soil are presented in Table 13. All properties are kept constant except the friction angle. These properties are adequate for the Mohr-Coulomb approach.

Material	Cases	Unsaturated Unit Weight (kN/m^3)	Saturated Unit Weight (kN/m^3)	Elastic Modulus (MPa)	Poisson's Ratio	Cohesion (kPa)	Friction Angle (˚)
Clayey Soil	Case 1	16	18	3	0.15	6	24
	Case 2	16	18	3	0.15	6	20
	Case 3	16	18	3	0.15	6	17

Table 13 Clayey Soil Material Properties - Simple Reservoir Embankment

5.1.2 Units

All units used are Metric, the same as in Scenario 1. Gravity is taken as $9.18m/s^{-2}$.

5.2 FLAC/Slope Analysis

5.2.1 Methodology

i) Upon starting FLAC/Slope a model name and embankment form needs to be chosen. This model is a simple embankment.

ii) The slope parameters then need to be entered. The slope parameters are kept constant for all 3 cases, presented in Figure 24.

iii) The material properties need to be created and assigned similar to Scenario 1. All properties are kept constant for each case except the friction angle; the properties for Case 1 are presented in Figure 25. The material is then assigned to the reservoir

iv) The water table is assigned 4 meter above ground i.e. 14 meters.

v) A mesh is assigned to the reservoir. Due to the limitations of the student version of FLAC/Slope (limit on the amount of zones that can be analysed) a coarse mesh is used, presented in Figure 26. This may affect the accuracy of the results.

vi) The embankment is cloned and each Case's friction angle updated. Each case is solved giving an estimate for the FOS and a plot of the corresponding critical slip surfaces. Figure 27 to Figure 29 illustrate these critical slip surfaces.

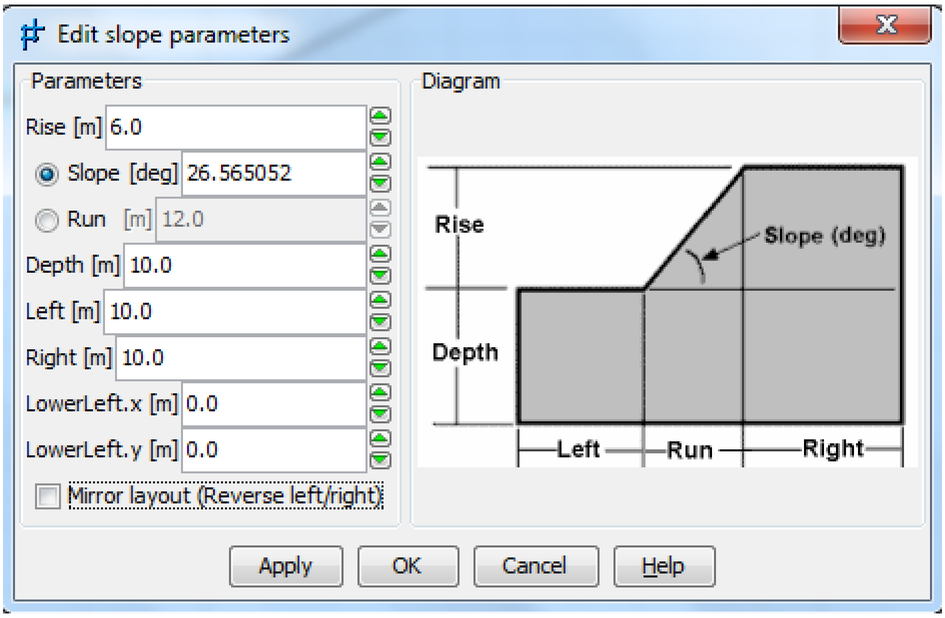


Figure 24 FLAC/Slope: Slope Parameters for all Cases - Simple Reservoir Embankment

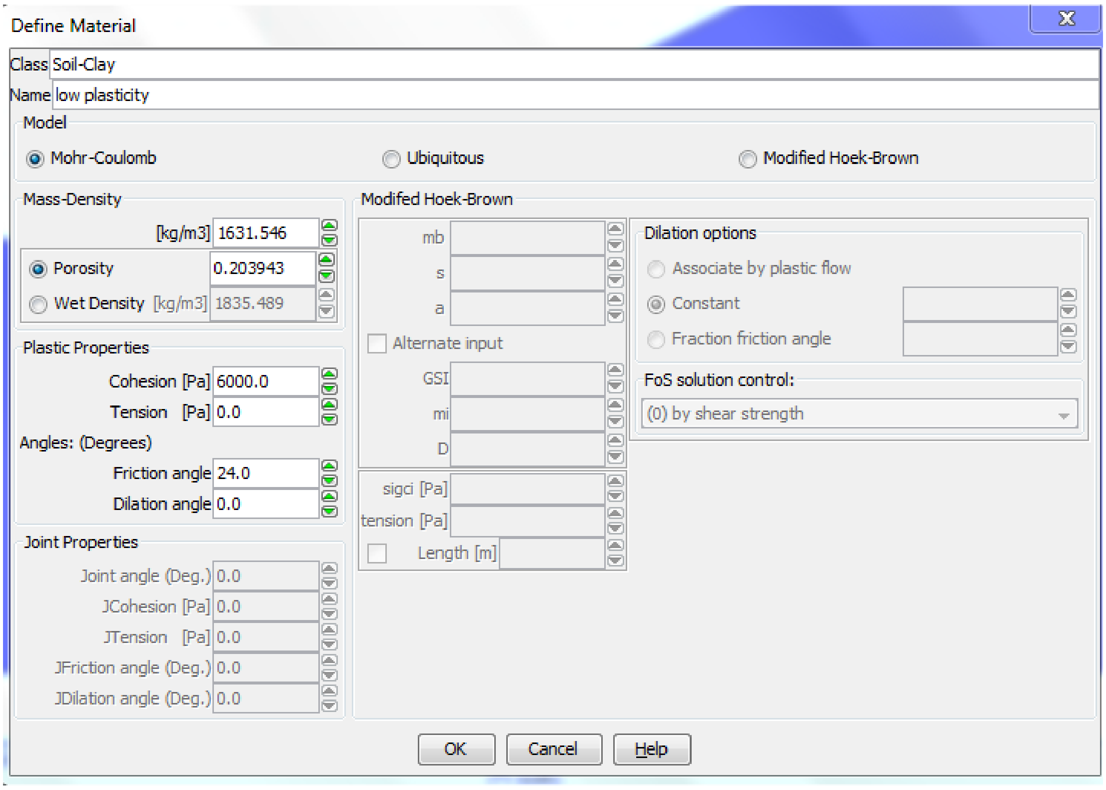


Figure 25 FLAC/Slope: Material Properties for Case 1 - Simple Reservoir Embankment

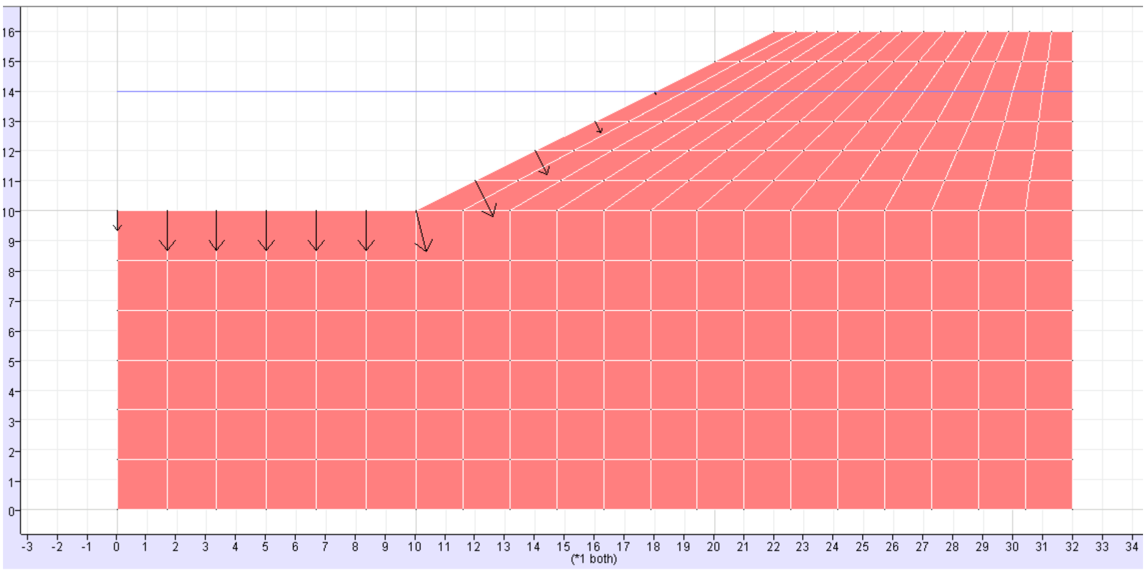


Figure 26 FLAC/Slope Finite Element Mesh - Simple Reservoir Embankment

5.2.2 Results

Figure 27 to Figure 29 illustrate the critical slip surfaces for Cases 1 to 3 respectively using FLAC/Slope. Table 14 summarises the FOS results using FLAC/Slope. Note that due to the restrictions of a coarse mesh the shear-strain contour plot is not very accurate.

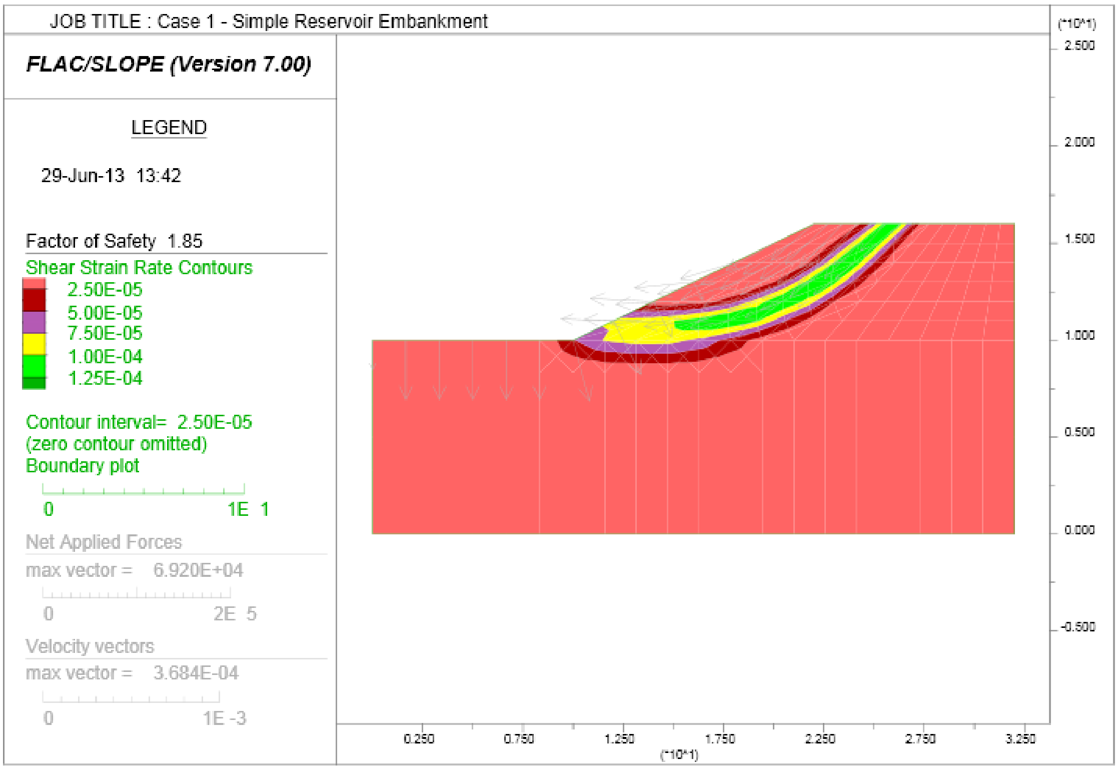


Figure 27 FLAC/Slope Critical Slip Surface for Case 1 - Simple Reservoir Embankment

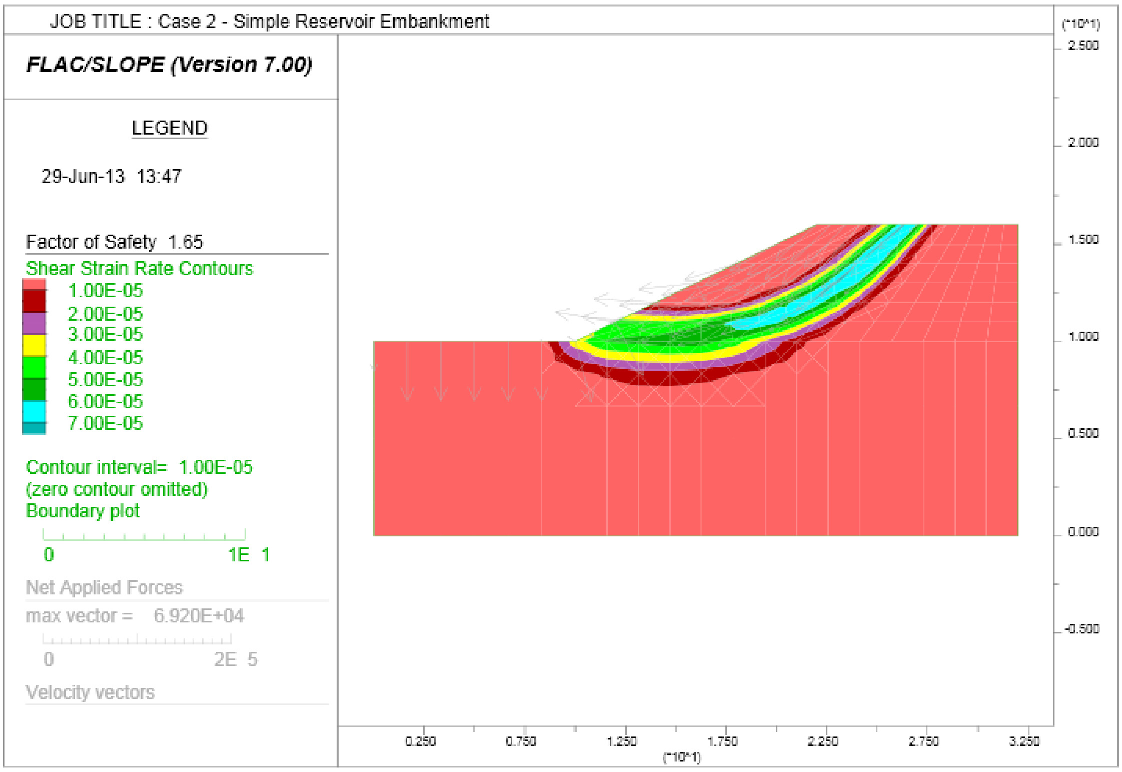


Figure 28 FLAC/Slope Critical Slip Surface for Case 2 - Simple Reservoir Embankment

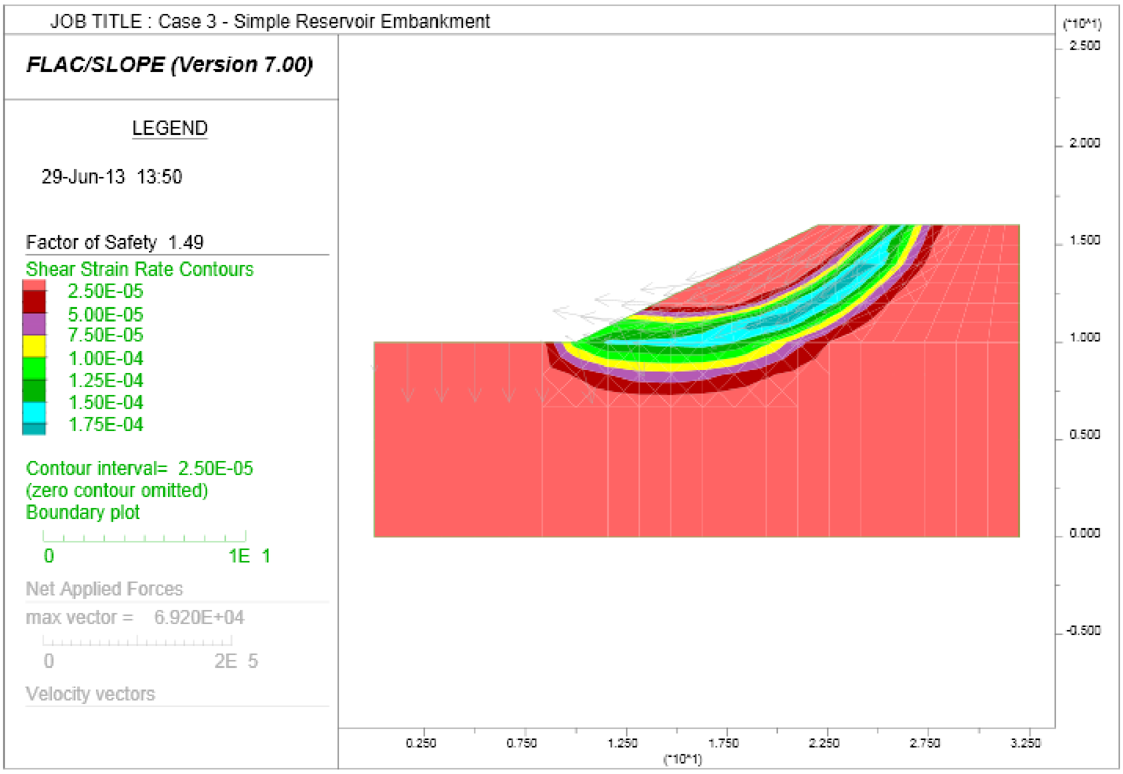


Figure 29 FLAC/Slope Critical Slip Surface for Case 3 - Simple Reservoir Embankment

Table 14 outlines the FOS results from the FLAC/Slope analysis using a coarse mesh. Note if a medium/fine mesh is chosen an error occurs as they create more zones than allowed in the student version.

Case	FOS
Case 1	1.85
Case 2	1.65
Case 3	1.49

Table 14 FLAC/Slope FOS Results - Simple Reservoir Embankment

5.3 SLOPE/W Analysis

5.3.1 Methodology

i) Upon starting SLOPE/W the first step is to set the units and scale for the model, then axes can be drawn.

ii) The model must be drawn using the inbuilt CAD interface. As this is a simple slope with one region the model can be sketched with the region function.

iii) The material properties need to be created and assigned. Figure 30 presents the material properties for Case 1. The material is then assigned to the reservoir.

iv) The water table is drawn in using the Pore-Water Pressure function.

v) The slip surface must then be selected, and the model can be solved.

vi) This process is done for each case. Figure 31 to Figure 33 illustrate the critical slip surfaces for the 3 cases.

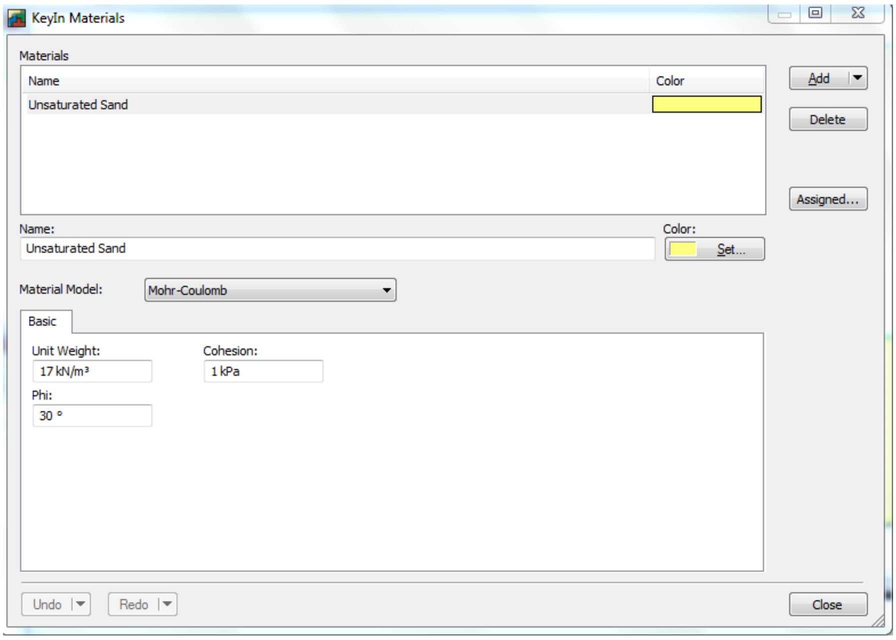


Figure 30 SLOPE/W Material Properties for case 1 - Simple Reservoir Embankment

5.3.2 Results

Figure 31 to Figure 33 illustrate the critical slip surfaces for Cases 1 to 3 respectively using SLOPE/W. Table 15 summarises the FOS results using SLOPE/W.

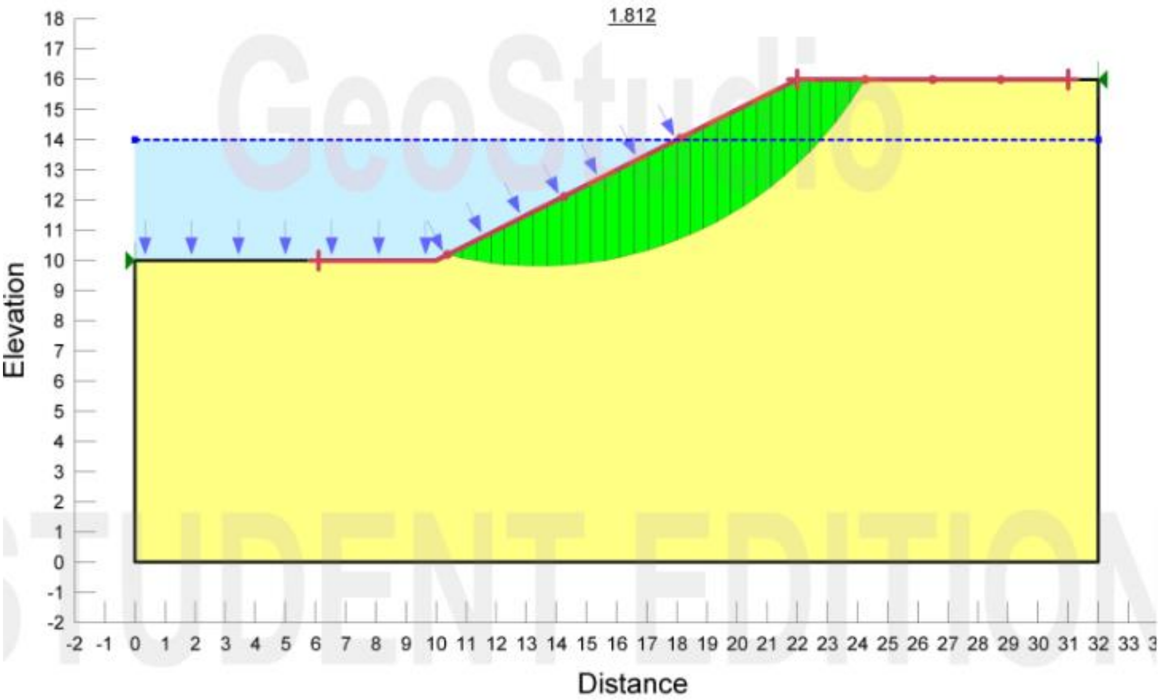


Figure 31 SLOPE/W Critical Slip Surface for Case 1 - Simple Reservoir Embankment

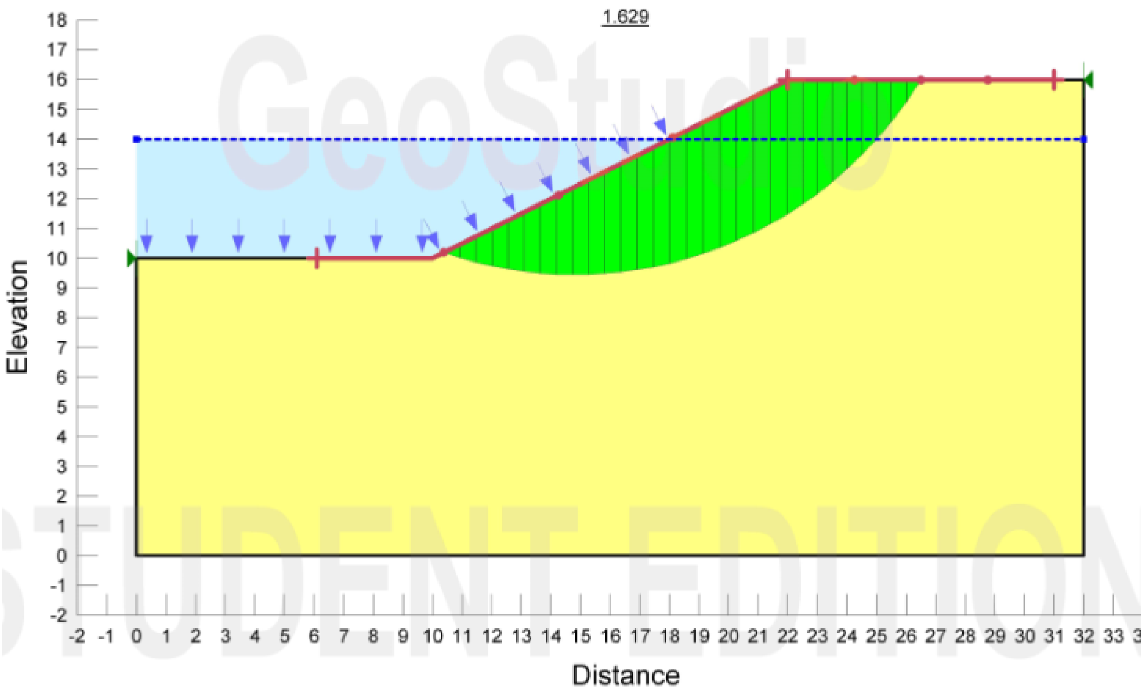


Figure 32 SLOPE/W Critical Slip Surface for Case 2 - Simple Reservoir Embankment

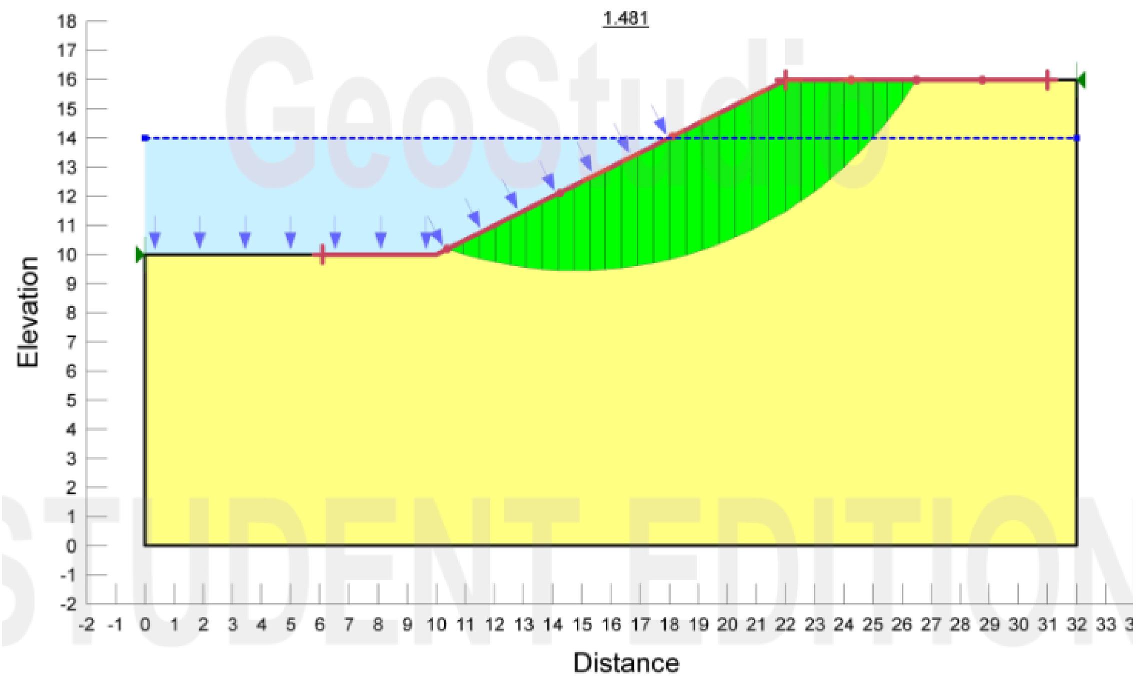


Figure 33 SLOPE/W Critical Slip Surface for Case 3 - Simple Reservoir Embankment

Table 15 outlines the FOS results from the SLOPE/W analysis.

Case	FOS
Case 1	1.812
Case 2	1.629
Case 3	1.481

Table 15 SLOPE/W FOS Results - Simple Reservoir Embankment

5.4 PLAXIS Analysis

5.4.1 Methodology

i) Upon starting PLAXIS the projects title and the models units and dimensions need to be set.

ii) The model is drawn using the inbuilt CAD interface.

iii) The material properties need to be created and assigned. PLAXIS requires the advanced properties of *E* and *v* of the soil as well as the stand Mohr-Coulomb.

iv) The restraints are set as standard fixities.

v) Then the mesh is generated. A medium mesh is being used to help improve accuracy. The mesh is presented in Figure 34.

vi) In the calculation phase, the stability of the reservoir and the water table need to be simulated, Table 16 summarises each phase modelled in the PLAXIS assessment.

vii) The results are then viewed showing the deformation, total displacement, FOS etc.

viii) This process is done for each case. Figure 35 to Figure 37 illustrate the critical slip surfaces for the 3 cases.

Phase	Description	Analysis Type	Loading Input	Time Period (day)
0	Set up initial ground model	Initial	-	-
1	Reservoir Construction	Plastic	Staged Construction	1
2	FOS Analysis	Phi-c Reduction	Incremental Multipliers	-

Table 16 PLAXIS Finite Element Modelling Construction Stages

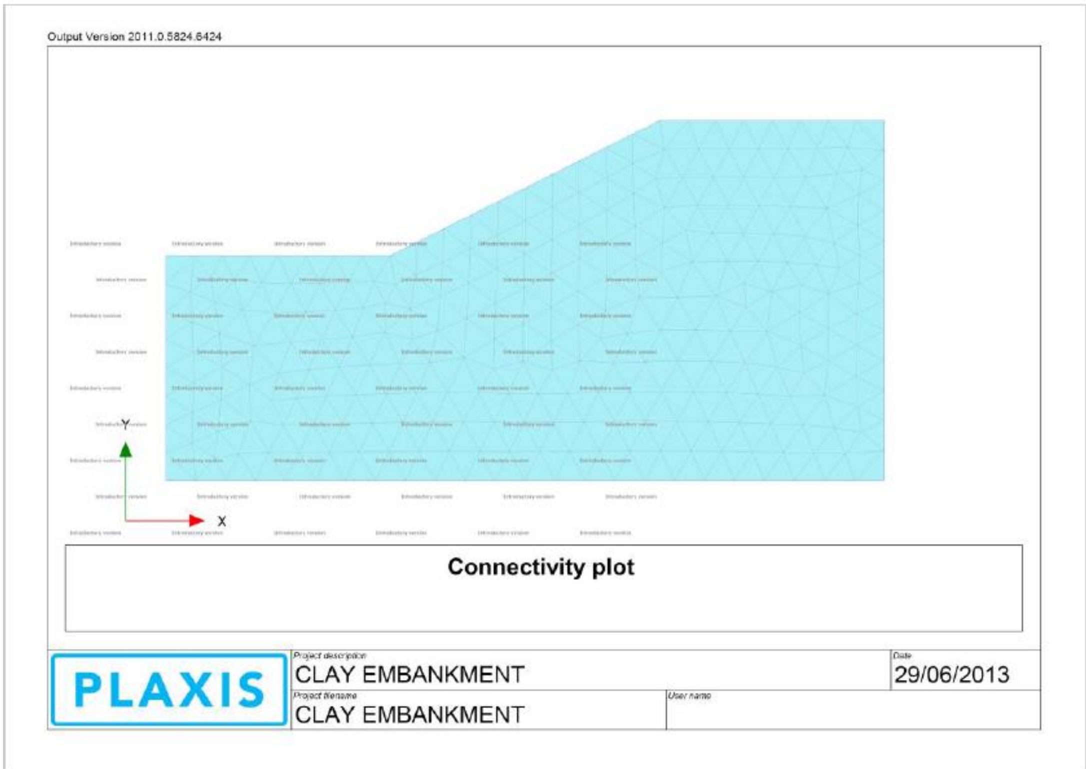
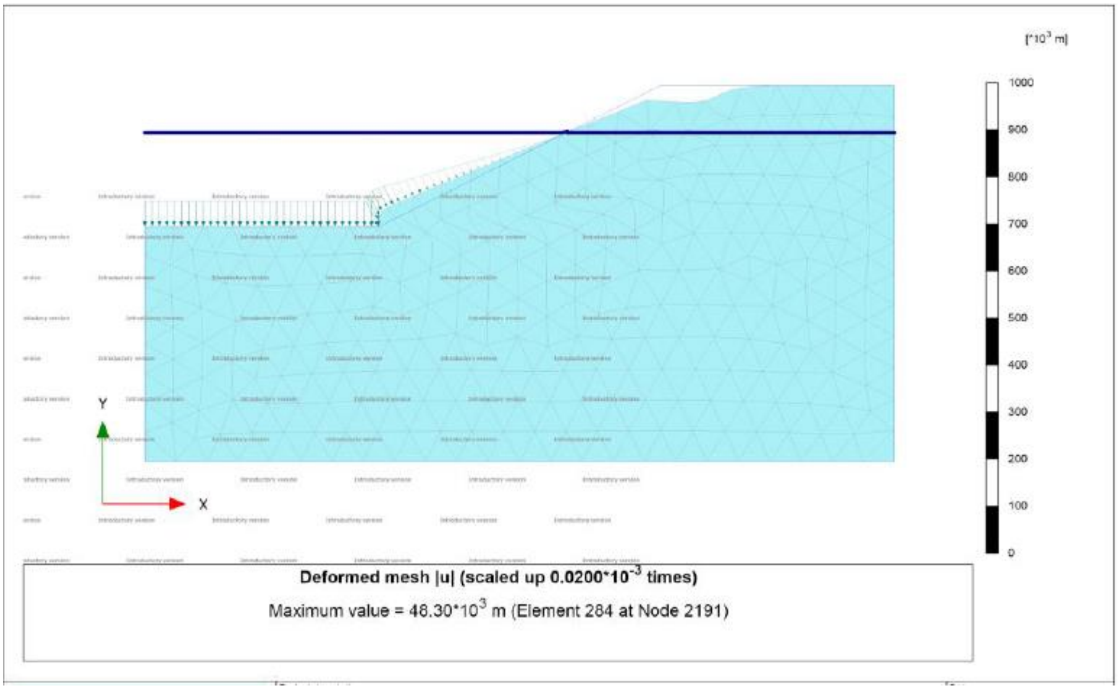


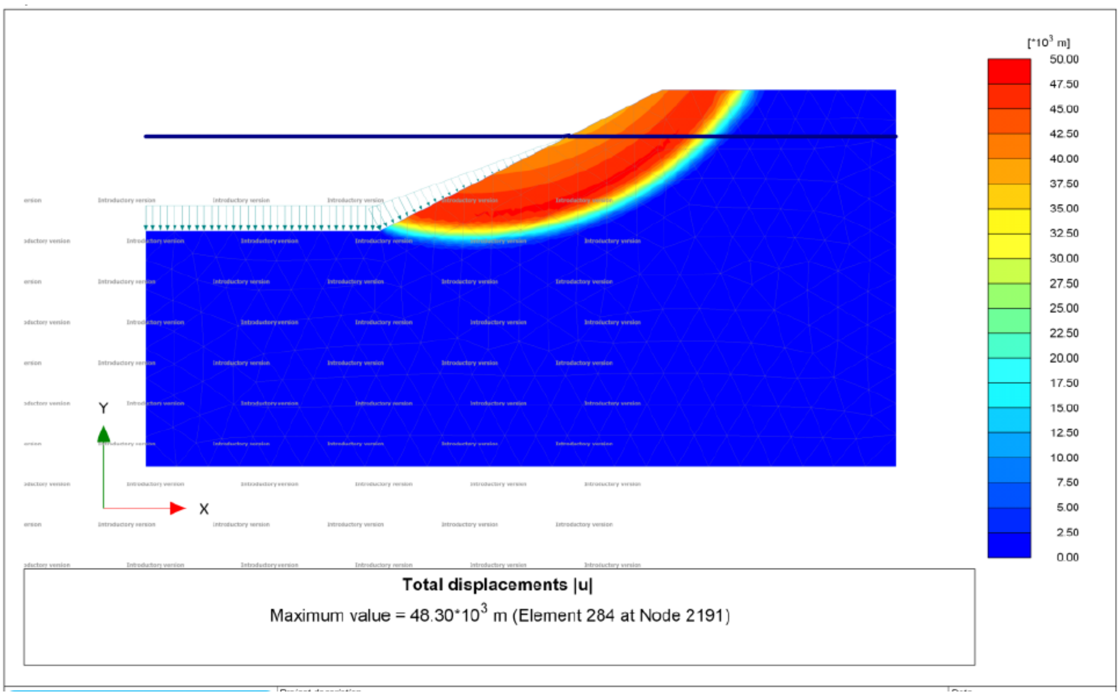
Figure 34 PLAXIS Finite Element Mesh - Simple Reservoir Embankment

3.4.2 Results

Figure 35 to Figure 37 illustrate the critical slip surfaces for Cases 1 to 3 respectively using PLAXIS. Table 17 summarises the FOS results using PLAXIS.

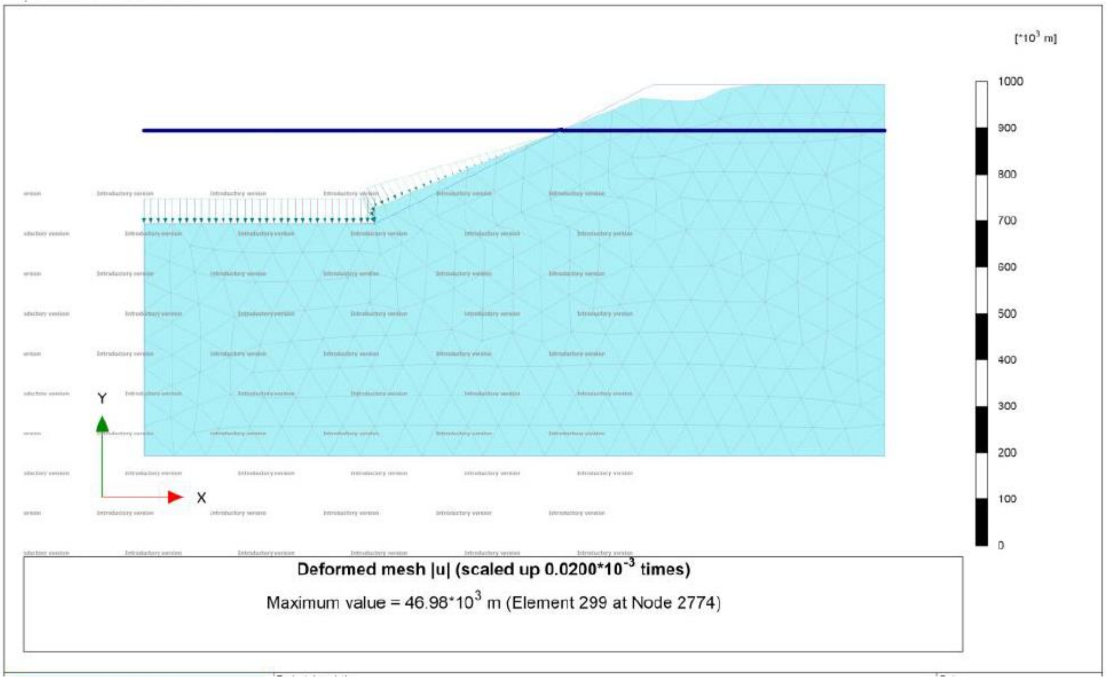


(a)

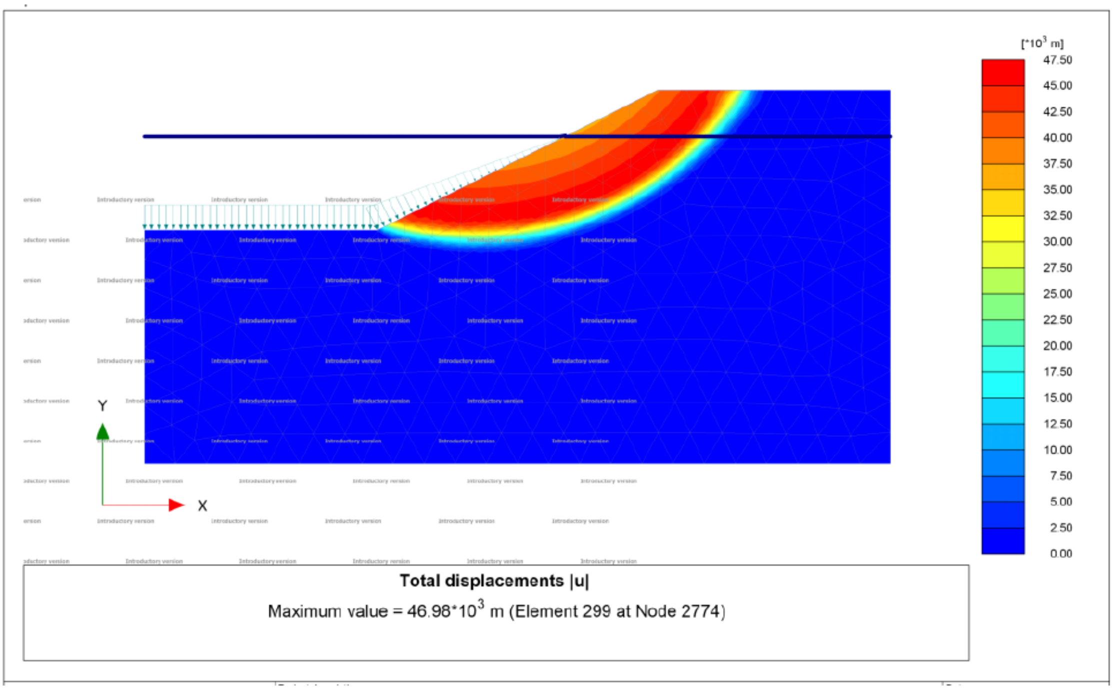


(b)

Figure 35 PLAXIS Case 1 - Simple Reservoir Embankment (a) Deformation, and (b) Total Displacement

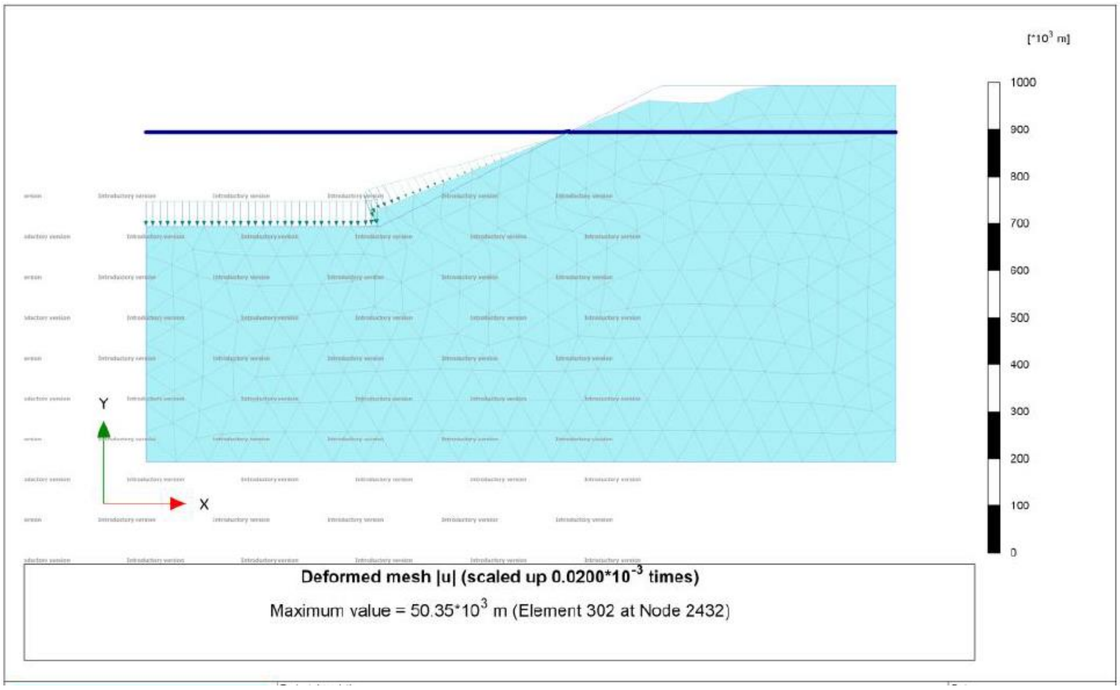


(a)

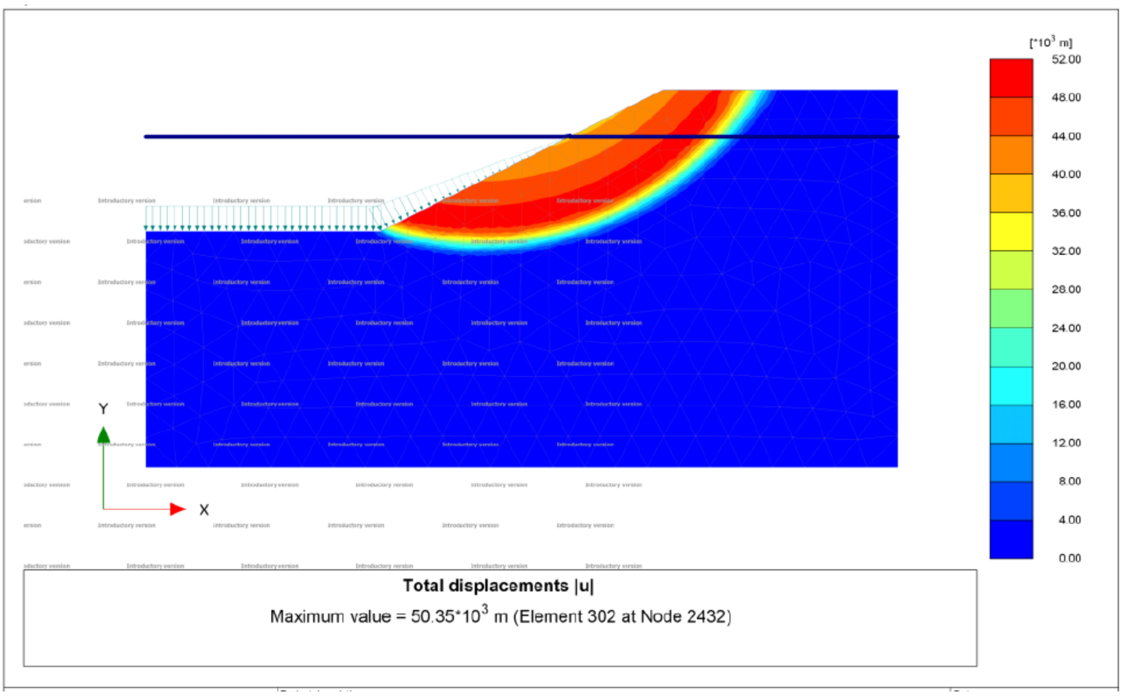


(b)

Figure 36 PLAXIS Case 2 - Simple Reservoir Embankment (a) Deformation, and (b) Total Displacement



(a)



(b)

Figure 37 PLAXIS Case 3 - Simple Reservoir Embankment (a) Deformation, and (b) Total Displacement

Table 17 outlines the FOS results from the PLAXIS analysis.

Case	FOS
Case 1	1.74
Case 2	1.548
Case 3	1.409

Table 17 PLAXIS FOS Results - Simple Reservoir Embankment

5.5 Summary of Simple Homogeneous Soil Slope Results

The slope stability analysis has been conducted using FLAC/Slope, SLOPE/W and PLAXIS. Table 18 outlines the calculated FOS values from the proposed analysis methods. It can be seen that throughout the analysis the largest and smallest FOS values are calculated using FLAC/Slope and PLAXIS respectively. This shows that the size of the mesh used in calculations has a significant impact on the results.

Analysis Method	**FOS**		
	Case 1	**Case 2**	**Case 3**
FLAC/Slope	1.85	1.65	1.49
SLOPE/W	1.812	1.629	1.481
PLAXIS	1.74	1.548	1.409

Table 18 Summary of FOS Results - Simple Reservoir Embankment

Chapter 6: Scenario 3 – Earth Dam Suffering Rapid Drawdown

6.1 Geotechnical Model

The geotechnical model adopted in this analysis is an Earth Dam suffering Rapid Drawdown, illustrated in Figure 38 and Figure 39. The soil is classified as sand and comprises of the properties in Table 19, kept constant in all analyses.

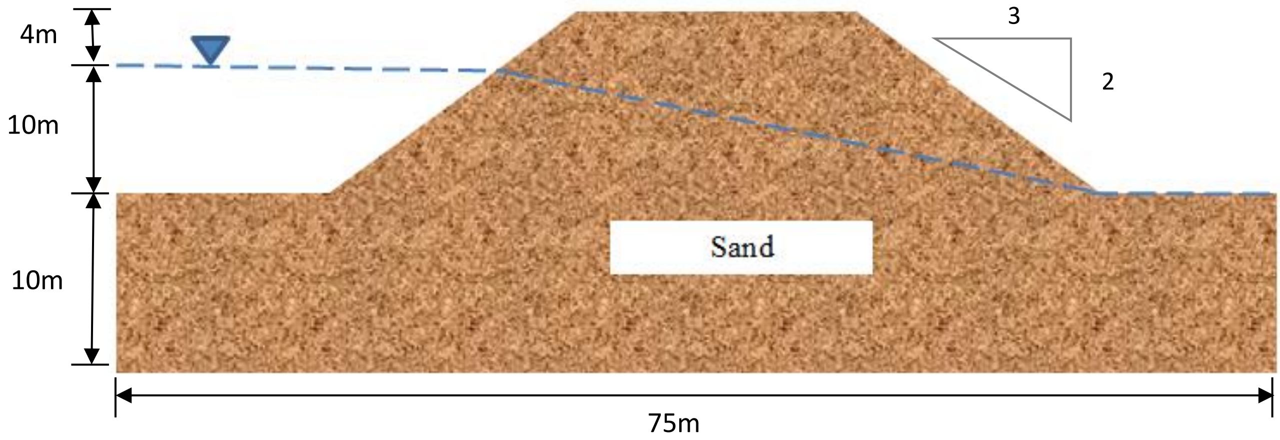


Figure 38 Earth Dam before Rapid Drawdown.

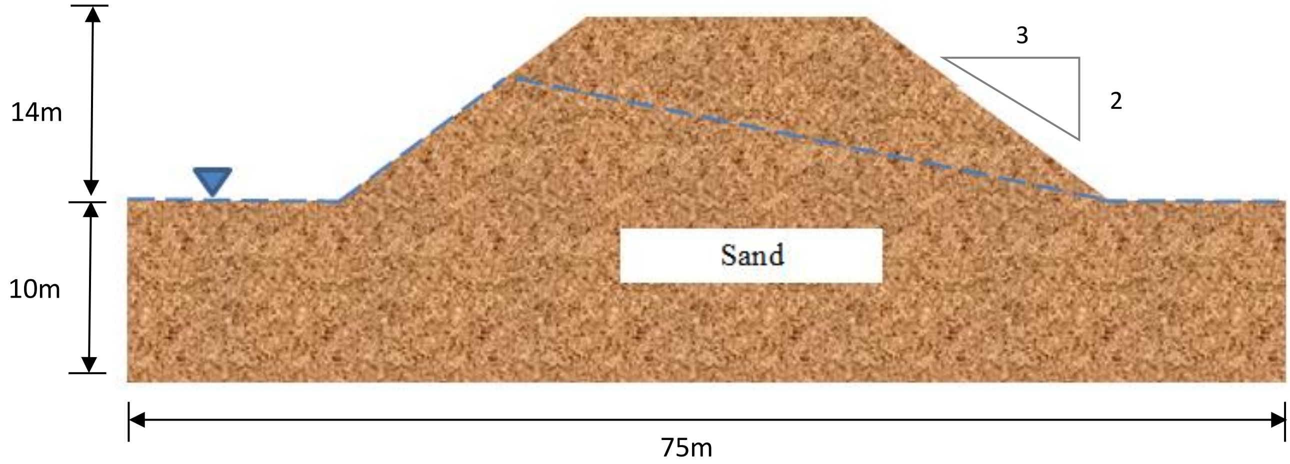


Figure 39 Earth Dam after Rapid Drawdown.

The dam considered has an embankment batter of 2:3, producing a slope angle equal to 33.7˚. The dam height is kept constant at 14m, with the water table initially at 10m on the left side of the dam and ground level on the right; then drawing down to ground level on both sides.

Figure 40 Image of an Earth Dam (U.S. Army Corps of Engineers 2013).

6.1.1 Material Properties

The properties of the sand are presented in Table 19. All properties are kept constant throughout all analyses. These properties are adequate for the Mohr-Coulomb approach.

Material	Unsaturated Unit Weight (kN/m^3)	Saturated Unit Weight (kN/m^3)	Elastic Modulus (MPa)	Poisson's Ratio	Cohesion (kPa)	Friction Angle (˚)
Unsaturated Sand	20	26	20	0.33	5	40

Table 19 Clayey Soil Material Properties - Simple Reservoir Embankment

6.1.2 Units

All units used are Metric, the same as in Scenario 1 and 2. Gravity is taken as 9.18m/s^{-2}.

6.2 FLAC/Slope Analysis

6.2.1 Methodology

i) Upon starting FLAC/Slope a model name and embankment form needs to be chosen. This model is a simple dam.

ii) The slope parameters need to be entered. The slope parameters are kept constant in both cases, presented in Figure 41.

iii) The material properties need to be created and assigned similar to in Scenario 1 and 2. All properties are kept constant for both case; these properties are presented in Figure 42. The material is then assigned to the dam.

iv) For the Earth Dam before drawdown, the water table is assigned 10 meter above ground level on the left side of the embankment and ground level on the right side.

v) A mesh is assigned to the dam. Similar limitations regarding the amount of zones occurs, however for this model a medium mesh can be used, presented in Figure 43. This may affect the accuracy of the results.

vi) The dam is cloned and the water table is relocated to replicate Figure 39 - after drawdown. Each case is solved giving an estimate for the FOS and a plot of the corresponding critical slip surfaces. Figure 44 to Figure 45 illustrate these critical slip surfaces.

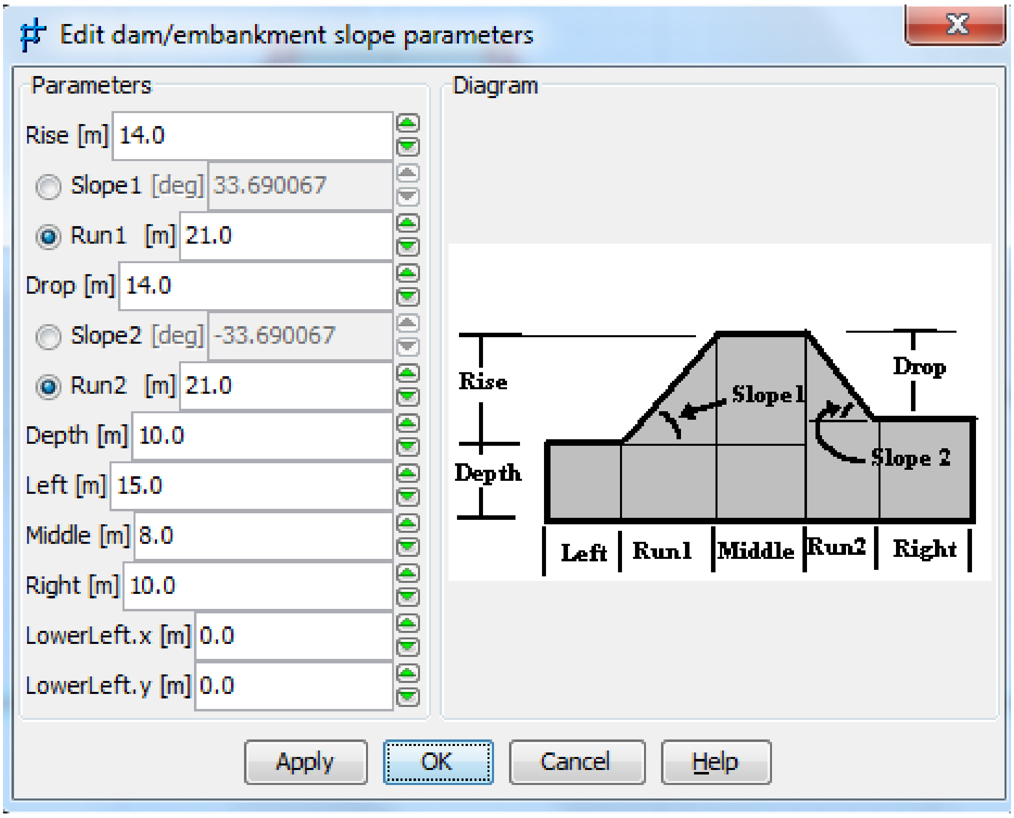


Figure 41 FLAC/Slope Slope Parameters for all Cases – Earth Dam

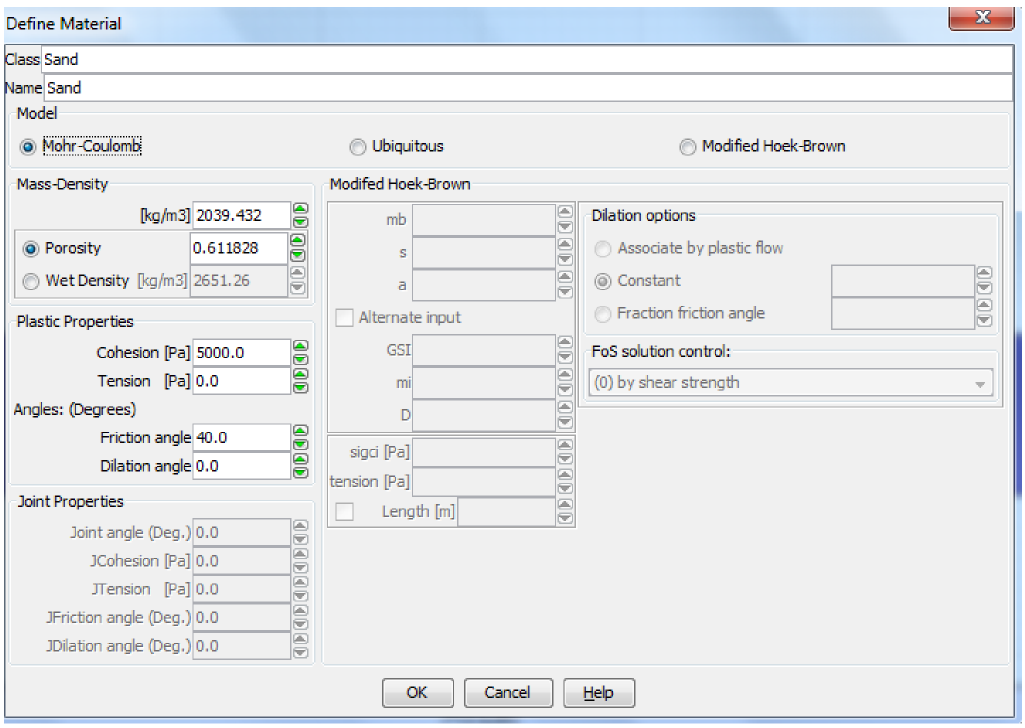


Figure 42 FLAC/Slope Material Properties – Earth Dam

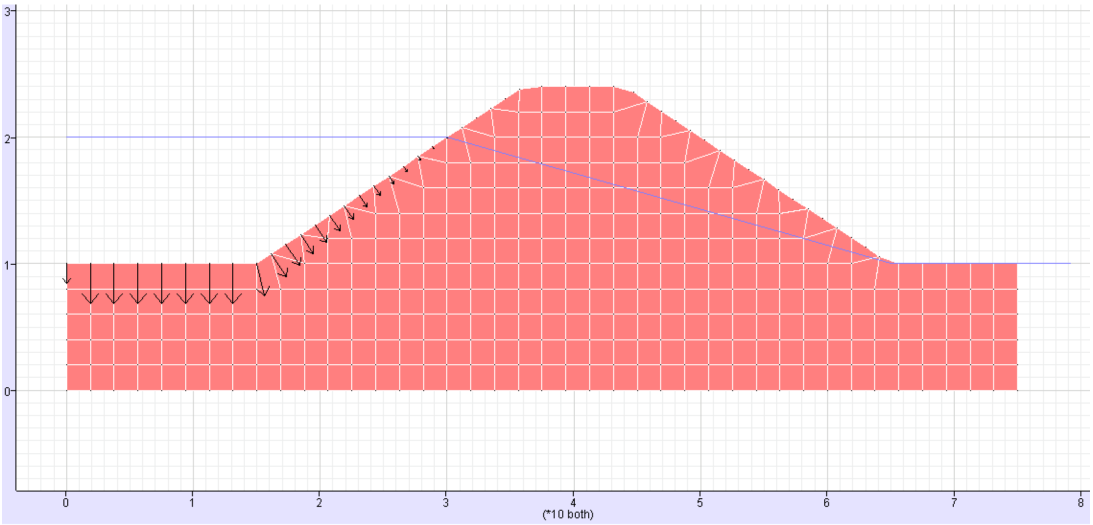


Figure 43 FLAC/Slope Finite Element Mesh for Case 1 – Earth Dam

6.2.2 Results

Figure 44 to Figure 45 illustrate the critical slip surfaces for Cases 1 to 3 respectively using FLAC/Slope. Table 20 summarises the FOS results using FLAC/Slope.

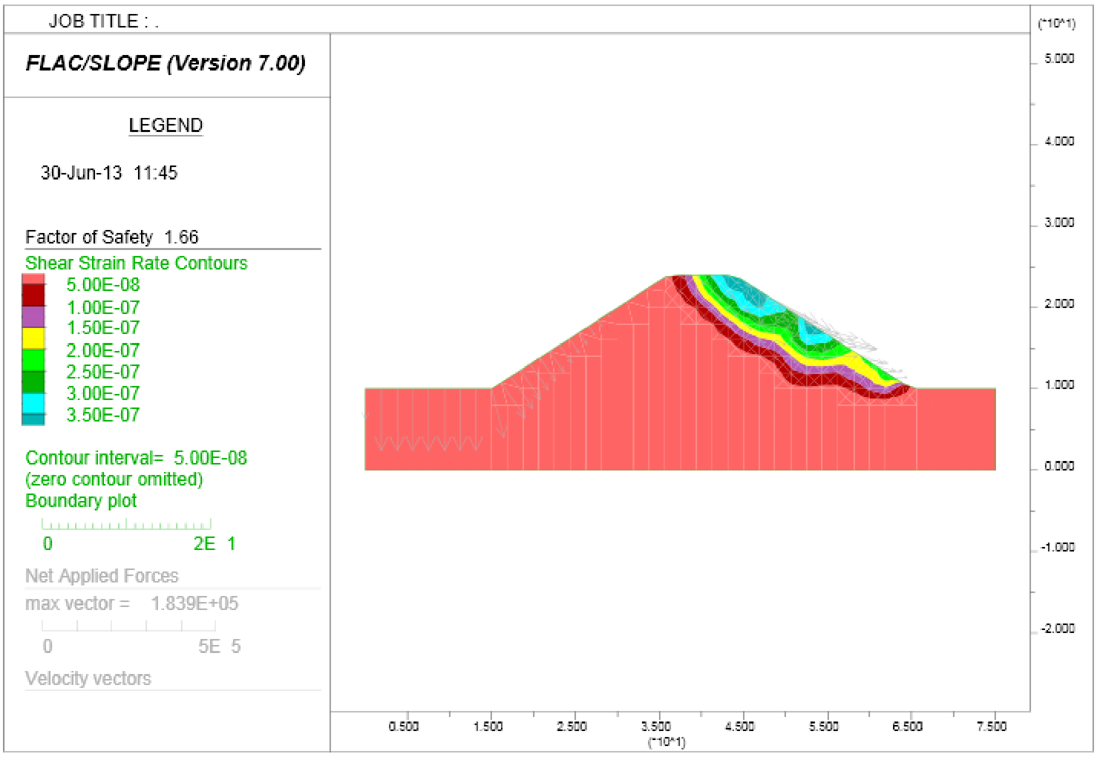


Figure 44 FLAC/Slope Critical Slip Surface before Drawdown – Earth Dam

Figure 45 FLAC/Slope Critical Slip Surface after drawdown – Earth Dam

Table 20 outlines the FOS results from the FLAC/Slope analysis using a medium mesh. Note if a fine mesh is chosen an error occurs as they create more zones than allowed in the student package.

Case	FOS
Before drawdown	1.66
After drawdown	0.99

Table 20 FLAC/Slope FOS Results – Earth Dam

6.3 SLOPE/W Analysis

6.3.1 Methodology

i) Upon starting SLOPE/W the first step is to set the units and scale for the model, then axes can be drawn.

ii) The model is then drawn using the inbuilt CAD interface. As this is a simple dam with one region the model can be sketched with the region function.

iii) The material properties need to be created and assigned. Figure 46 presents the material properties. The material is assigned to the dam.

iv) The water table is drawn in using the Pore-Water Pressure function.

v) The slip surface is selected, and then the model can be solved. It must be noted that the correct direction of the slip surface must be determined in order to achieve the correct factor of safety, presented in Figure 47.

vi) The model is re analysed with the water relocated to replicate Figure 39 - after drawdown. Figure 48 presents the critical slip Note the opposite direction of the critical slip surfaces before and after drawdown.

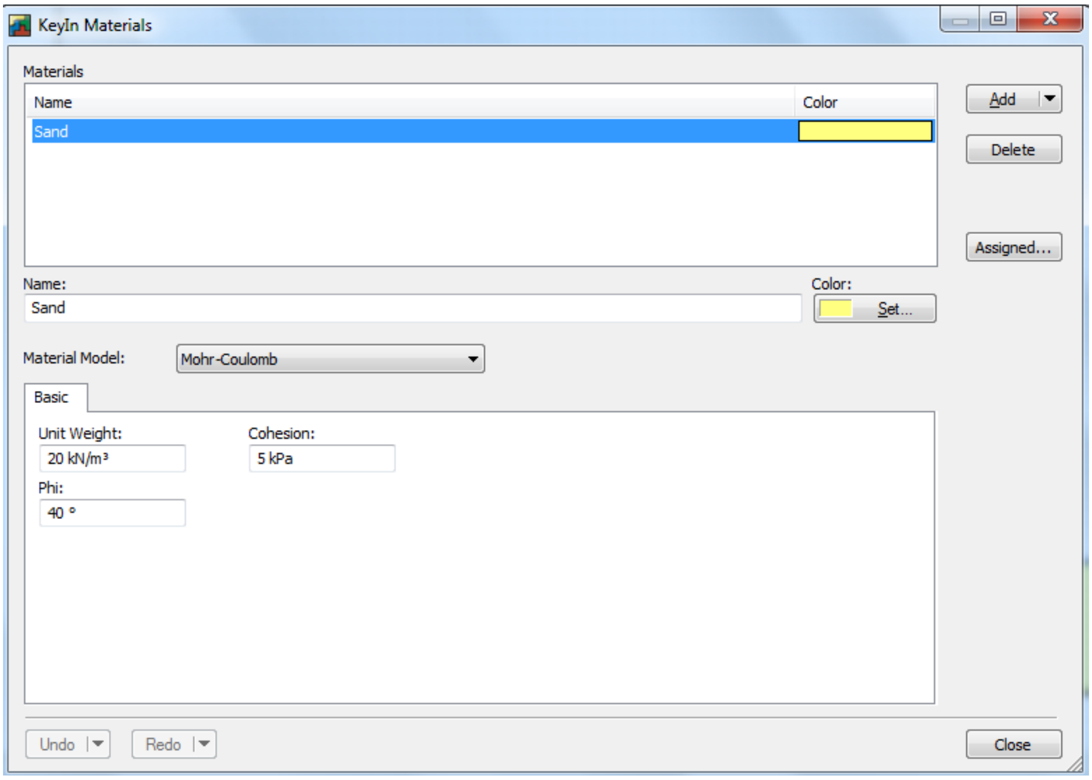


Figure 46 SLOPE/W Material Properties – Earth Dam

6.3.2 Results

Figure 47 to Figure 48 illustrate the critical slip surfaces for before and after drawdown respectively using SLOPE/W. Table 21 summarises the FOS results using SLOPE/W.

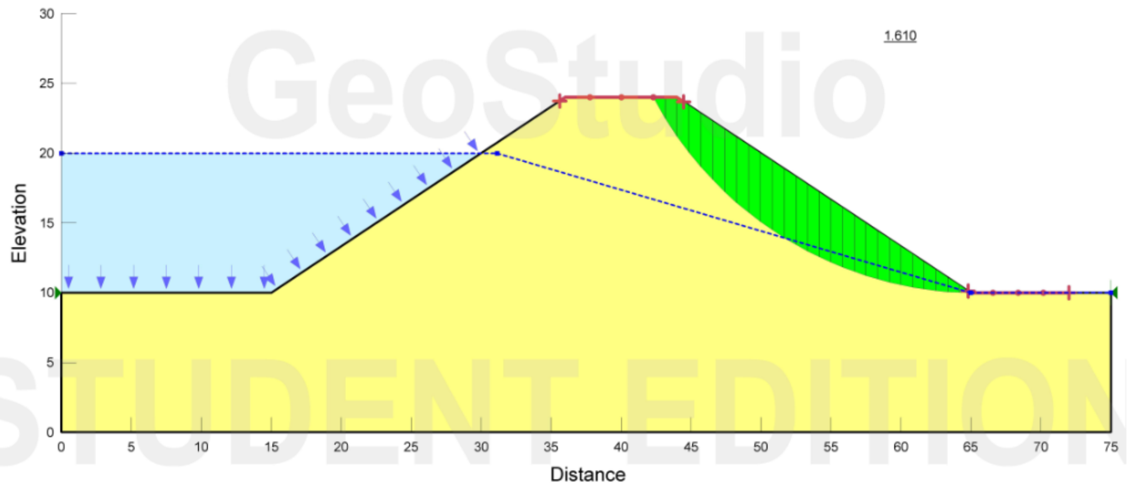


Figure 47 SLOPE/W Critical Slip Surface before drawdown – Earth Dam

Figure 48 SLOPE/W Critical Slip Surface after drawdown – Earth Dam

Table 21 outlines the FOS results from the SLOPE/W analysis.

Case	FOS
Before drawdown	1.610
After drawdown	0.862

Table 21 SLOPE/W FOS Results – Earth Dam

6.4 PLAXIS Analysis

6.4.1 Methodology

i) Upon starting PLAXIS the projects title and models units and dimensions need to be set.

ii) The model is drawn using the inbuilt CAD interface.

iii) The material properties need to be created and assigned. PLAXIS requires the advanced properties of *E* and *v* of the soil as well as the stand Mohr-Coulomb.

iv) The restraints are set as standard fixities.

v) The mesh is generated. A fine mesh is being used to help improve accuracy. The mesh is presented in Figure 49

vi) In the calculation phase, the stability of the dam and the water table before drawdown needs to simulated, the FOS is calculated for this stage. The stability of the dam and the water table after drawdown is simulated and the corresponding FOS is calculated. Table 22 summarises each phase modelled in the PLAXIS assessment.

vii) The results are then viewed showing deformation, total displacement, FOS etc. Note that after drawdown the dam soil fails, PLAXIS does not continue calculations of the FOS value once the model fails.

viii) Figure 50 and Figure 51 illustrate the critical slip surfaces for the Earth Dam before and after drawdown.

Phase	Description	Analysis Type	Loading Input	Time Period (day)
0	Set up initial ground model	Initial	-	-
1	Dam Construction before drawdown	Plastic	Staged Construction	1
2	FOS Analysis	Phi-c Reduction	Incremental Multipliers	-
3	Dam Construction after drawdown	Plastic	Staged Construction	1
4	FOS Analysis	Phi-c Reduction	Incremental Multipliers	-

Table 22 PLAXIS Finite Element Modelling Construction Stages

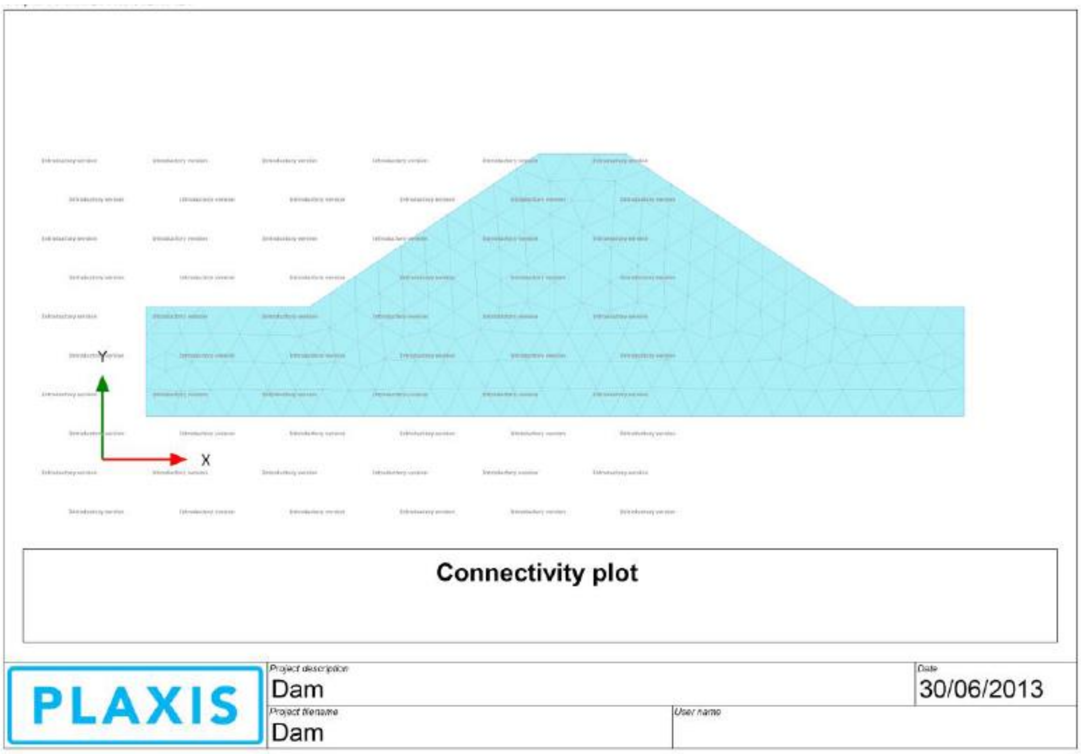
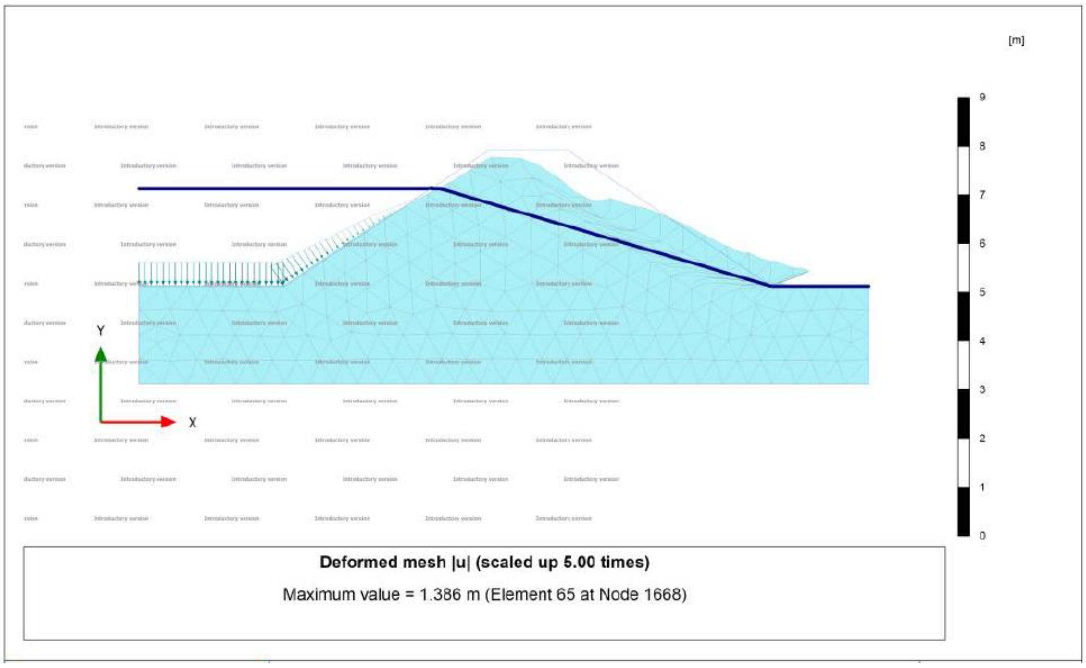


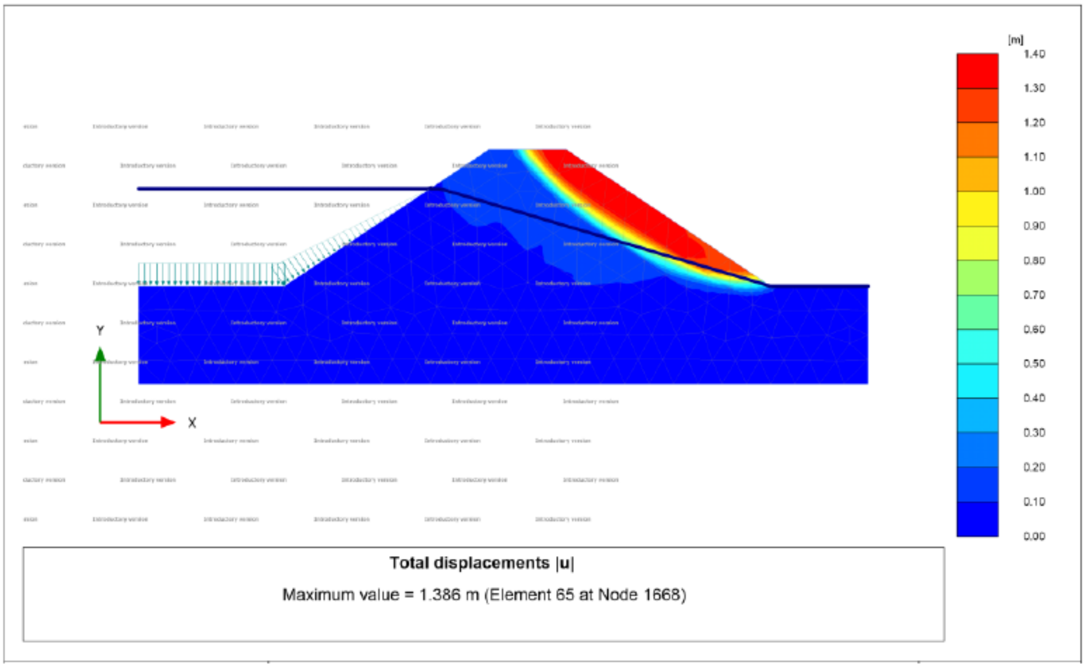
Figure 49 PLAXIS Finite Element Mesh - Earth Dam

6.4.2 Results

Figure 50 and Figure 51 illustrate the critical slip surfaces for the Earth Dam before and after drawdown using PLAXIS. Table 23 summarises the FOS results using PLAXIS.

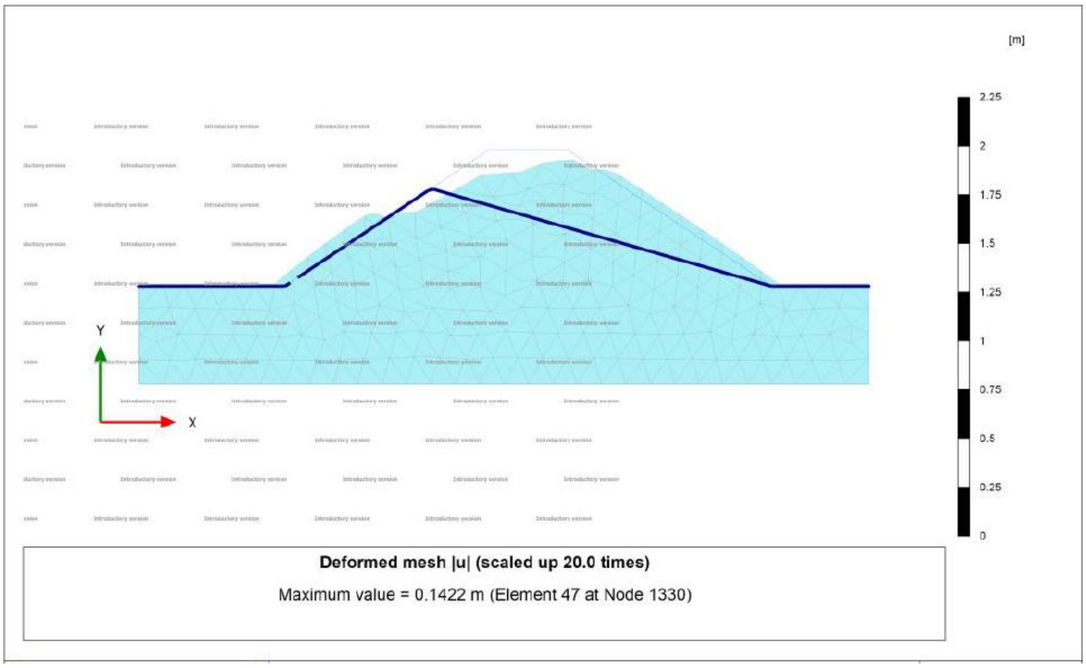


(a)

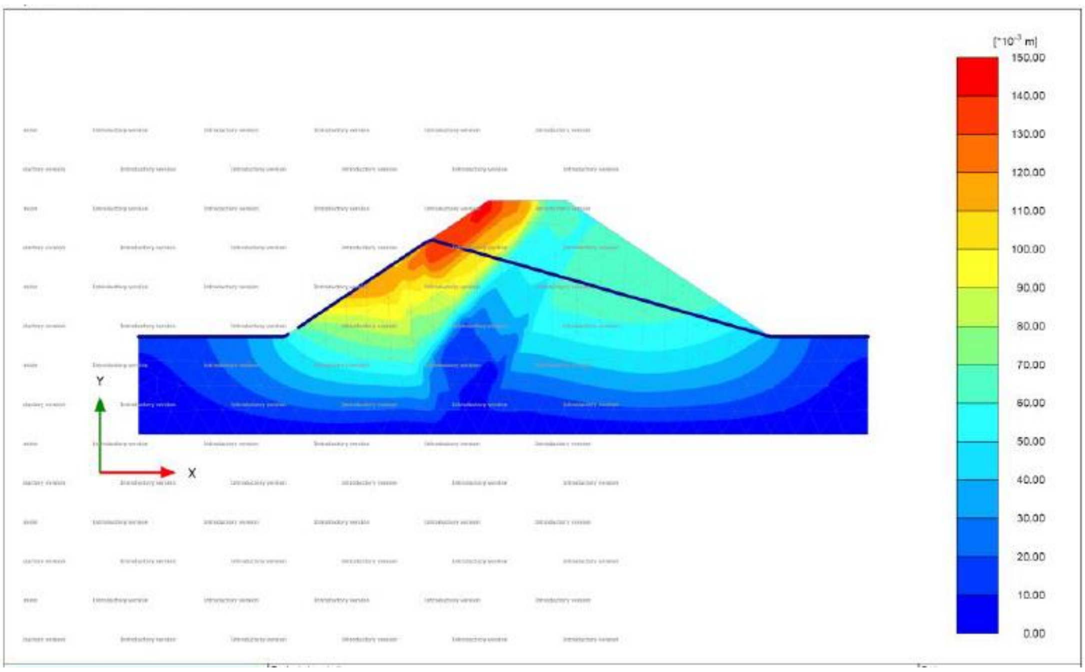


(b)

Figure 50 PLAXIS - Earth Dam before drawdown (a) Deformation, and (b) Total Displacement



(a)



(b)

Figure 51 PLAXIS - Earth Dam after drawdown (a) Deformation, and (b) Total Displacement

Table 23 outlines the FOS results from the PLAXIS analysis.

Case	FOS
Before drawdown	1.642
After drawdown	Value not calculated. Soil body collapsed

Table 23 PLAXIS FOS Results – Earth Dam

6.5 Summary of Earth Dam Results

The slope stability analysis has been conducted using FLAC/Slope, SLOPE/W and PLAXIS. Table 24 outlines the calculated FOS values from the proposed analysis methods. It can be seen that failure occurs after drawdown in all three software packages. PLAXIS is unable to calculate the FOS value once failure occurs.

Analysis Method	**FOS**	
	Before drawdown	**After drawdown**
FLAC/Slope	1.66	0.99
SLOPE/W	1.610	0.862
PLAXIS	1.642	Value not calculated. Soil body collapsed

Table 24 Summary of FOS Results – Earth Dam

Chapter 7: Results and Discussion

7.1 Results

7.1.1. Simple Homogeneous Soil Slope at Varying Heights

For Scenario 1 the FOS results generated by FLAC/Slope are higher than those generated using PLAXIS and SLOPE/W. Table 25 presents the average percentage difference between the corresponding software packages. It can be seen that on average FLAC/Slope generates an FOS value that is 8.33% higher than the other two packages. Statistically this is a significant difference and can result in-appropriate design and possible instability (failure) of the design.

FOS Difference (%)	FLAC/Slope	SLOPE/W	PLAXIS
FLAC/Slope	-	7.90%	8.77%
SLOPE/W	7.90%	-	0.18%
PLAXIS	8.77%	0.18%	-

Table 25 FOS Differences (%) - Simple Homogeneous Soil Slope

Figure 52 presents a graphical representation of the comparison between each software packages FOS results for Scenario 1. It can be seen for Case 1 FLAC/Slope calculates an FOS value of 1.38 which is on average 13.30% higher than the other two packages compared to Case 3 where FLAC/Slope calculates an FOS value on average 3.60% higher than the other two packages. This shows that the embankment height has an effect on the range of FOS values, where for a higher embankment the difference between computed FOS values reduces dramatically.

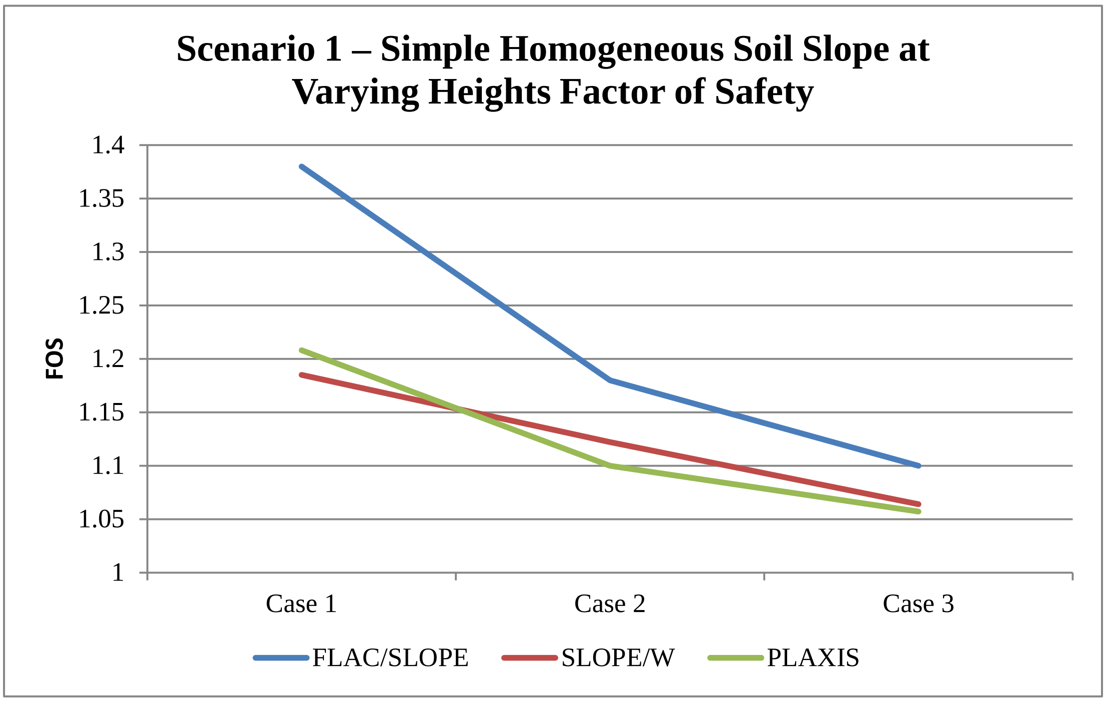


Figure 52 Results Comparison - Simple Homogeneous Soil Slope

From the results of Scenario 1 it can be concluded that an increase in height of an embankment decreases the calculated FOS value and consequently its stability. The limitation of the student version of FLAC/Slope only allowing the use of a coarse mesh in analysis has a significant impact on the FOS value that can result in in-accurate design. However this impact seems to reduce with the increase in embankment height. The advanced properties of Elastic Modulus (E) and Poisson's Ratio (ν) shows no evidence of impacting on the FOS value with FOS values calculated through PLAXIS analysis and SLOPE/W analysis being similar.

7.1.2. Simple Reservoir Embankment with a Clayey Soil of Varying Plasticity Factor of Safety

The FOS results generated by PLAXIS are lower than those generated by FLAC/Slope and SLOPE/W. Table 26 presents the average percentage difference between the corresponding software packages. In contrast to Scenario 1, PLAXIS generates an FOS value that is on average 5.40% less than the other two packages. Statistically this is a significant difference and may result in a more conservative and consequently more expensive slope stabilisation methods may be unnecessarily utilised due to the smaller calculated FOS value.

FOS Difference (%)	FLAC/Slope	SLOPE/W	PLAXIS
FLAC/Slope	-	1.36%	6.24%
SLOPE/W	1.36%	-	4.57%
PLAXIS	6.24%	4.57%	-

Table 26 FOS Differences (%) - Simple Reservoir Embankment

Figure 53 presents a graphical representation of the comparison between each software packages FOS results for Scenario 2. In contrast to Scenario 1 where there was a significant change in the difference between the FOS values for the various cases; in Scenario 2 for all 3 cases the calculated FOS values are reasonably consistent throughout. For Case 1 the FOS value achieved with PLAXIS is 6.3% and 4.1% smaller than the FOS values achieved with FLAC/Slope and SLOPE/W respectively. Compared to Case 3 where the difference in the FOS value achieved with PLAXIS being 5.7% and 5.1% smaller than FOS results from FLAC/Slope and SLOPE/W respectively.

From the results of Scenario 2 it can be concluded that decreasing the friction angle and consequently increasing the plasticity of the material increases the calculated FOS value resulting in a less stable material. Throughout Scenario 2 the FOS values calculated with PLAXIS where significantly less than those calculated by the other two packages. A result of using more conservative FOS values is the use of more expensive slope stabilisation methods that may be unnecessary. SLOPE/W analysis achieved FOS values in between both PLAXIS and FLAC/Slope consistently throughout all three cases.

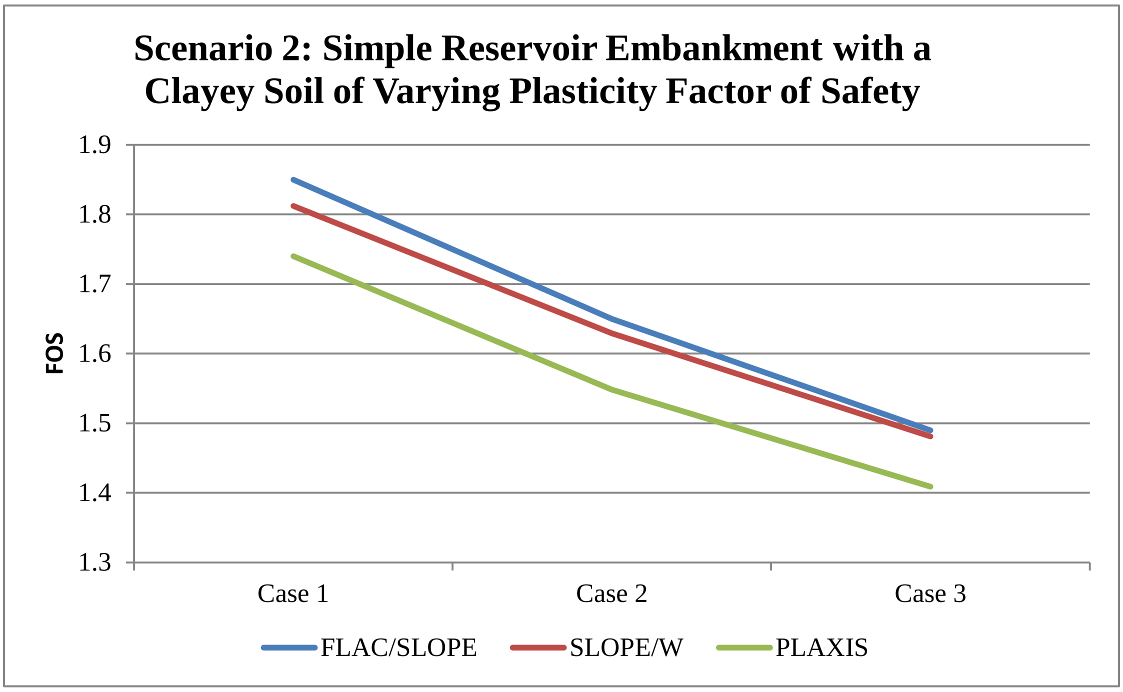


Figure 53 Results Comparison - Simple Reservoir Embankment

7.1.3. Earth Dam Suffering Rapid Drawdown

In contrast to Scenario 1 & 2 the FOS results generated for Scenario 3 by all three packages before rapid drawdown occurs are reasonably similar. The percentage difference between the corresponding software packages before rapid drawdown is presented in Table 27, it can be seen that there is no statistically significant difference between the packages. Table 28 presents the difference in FOS values once rapid drawdown takes place and failure occurs. There is a significant difference between the FOS values calculated by FLAC/Slope and SLOPE/W of 14.85%; note that once failure occurs PLAXIS terminates its calculations and does not determine a final FOS value.

FOS Difference (%)	FLAC/Slope	SLOPE/W	PLAXIS
FLAC/Slope	-	3.01%	1.10%
SLOPE/W	3.01%	-	1.99%
PLAXIS	1.10%	1.99%	-

Table 27 FOS Differences (%) before Rapid Drawdown – Earth Dam

FOS Difference (%)	FLAC/Slope	SLOPE/W	PLAXIS
FLAC/Slope	-	14.85%	Value not Determined
SLOPE/W	14.85%	-	Value not Determined
PLAXIS	Value not Determined	Value not Determined	Value not Determined

Table 28 FOS Differences (%) after Rapid Drawdown – Earth Dam

From the results of Scenario 3 it can be seen that stable pore water pressure has no significant effect on the FOS values calculated by each software package. There is a significant difference in FOS values by each package once rapid drawdown occurs; showing that generating a pressure imbalance within the soil does have an effect on the FOS values calculated between the software packages.

For Scenario 3; the difference in FOS values between the packages after rapid drawdown occurs is not a significant issue as it has resulted after failure of the design in all three packages therefore slope stabilisation methods would be utilised regardless of which package was used for the analysis. PLAXIS not calculated a final FOS value can be seen as a limitation on a theoretical level; however in practice when failure occurs the design requires changes regardless of the FOS value. In contrast to both Scenario 1 & 2 there is no significant difference in the FOS values calculated before rapid drawdown occurs.

7.2 FLAC

7.2.1 Student Version Specific Limitations

The limitations placed by ITASCA Consulting Group on the student (demonstration) version of FLAC and FLAC/Slope limits the amount of zones (mesh) that can be utilised in analysis to no more than 600 zones. All other functions within the packages can be used i.e. multiple materials, applying surcharges etc.

For the 3 scenarios analysed in this report; FLAC/Slope was used due to it being a specific package within FLAC to analyse stability scenarios.

7.2.2 Modelling

The modelling capability in the student version of FLAC/Slope is limited to the models presented in Figure 54. FLAC/Slope has a relatively primitive interface regarding drawing capabilities and for more complex scenarios it can be considered less user friendly compared to PLAXIS and SLOPE/W. The student version does not allow the importing of CAD drawings files.

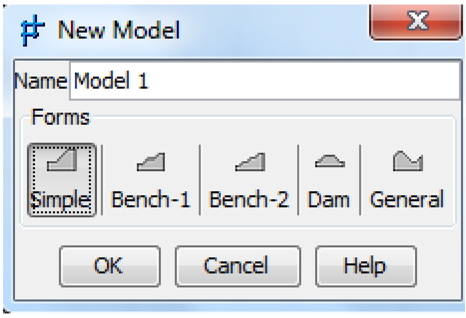


Figure 54 FLAC/Slope allowed models.

7.2.3 Materials

The student versions of FLAC and FLAC/Slope do not limit the materials properties and number of materials used within the analysis. This is a benefit over the student versions of both PLAXIS and SLOPE/W as they limit analysis to 1 and 3 materials respectively.

Compared to both PLAXIS and SLOPE/W; FLAC uses the density of the material (kg/m^3) instead of Unit Weight (kN/m^3) this requires gravity to be defined, for this report gravity has been taken as 9.81ms^{-2}. The units for Cohesion in FLAC are Pascals compared to the other packages where Cohesion's units are KiloPascals. A comparison of the parameters is presented in Table 29.

Property	Symbol	Units PLAXIS & SLOPE/W	Units FLAC/Slope
Unit Weight / Density	γ	kN/m^3	kg/m^3
Cohesion	*c*	kPa	Pa
Friction angle	ϕ	°	°
Elastic Modulus	*E*	MPa = 10^3 kN/m^2	-
Poisson's Ratio	*v*	-	-

Table 29 Parameters for Analysis

7.2.4 Solving Process

In order to calculate the FOS; FLAC requires the creation of a mesh. Due to the student version only allowing a maximum of 600 zones a coarse mesh was used for Scenario 1 and 2 and a medium mesh was utilised for Scenario 3. This resulted in a less extensive analysis of the model and consequently a less accurate FOS calculated. This can be seen in the results for both Scenario 1 and 2 where the analysis by FLAC/Slope using a coarse mesh resulted in higher FOS values compared to SLOPE/W and PLAXIS which could lead to under designing.

The limit of the amount of zones allowed can also result in the distortion of the model. Figure 55 presents a coarse mesh for an open cut mine pit wall where the shape has been distorted due to the use of a coarse mesh.

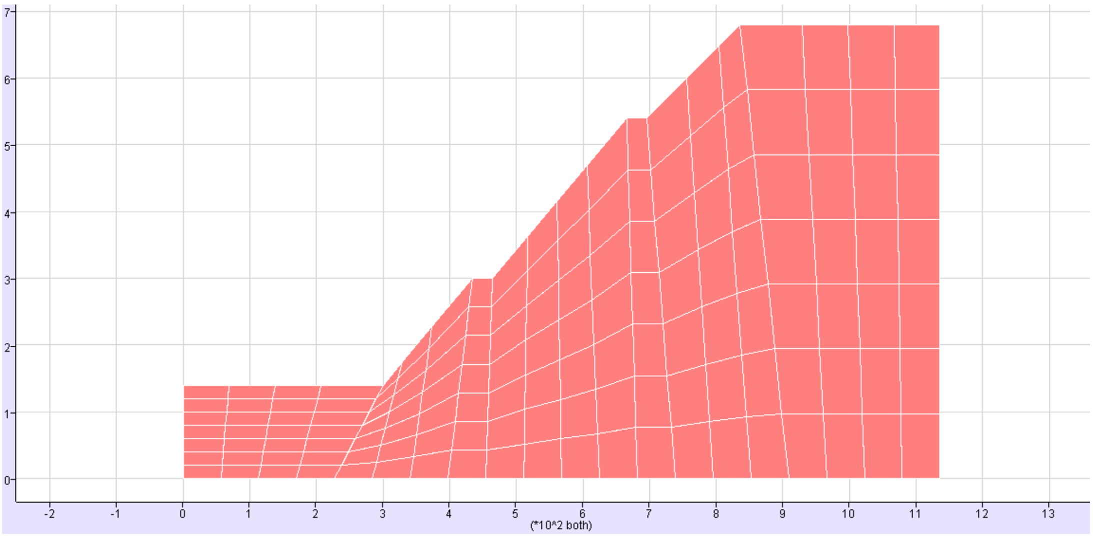


Figure 55 FLAC coarse mesh of an Open Cut Mine Pit Wall.

7.2.5 Results

FLAC/Slope results are displayed in a relatively simple screenshot. The FOS is displayed in the top left hand corner with the legend of the shear-strain contours. The model is plotted showing the failure surface and indicates the shear-strain rate of the surrounding elements. As FLAC uses an FD method in its analysis, the slip direction does not need to be pre-determined by the user (ITASCA Consulting Group 2011b). Due to the use of a coarse mesh for Scenario 1 & 2 the shear strain contours are not very accurate.

7.2.6 Discussion

FLAC and in particular FLAC/Slope are relatively user friendly software packages used to analysis geotechnical stability scenarios with the student version not limiting the type of analysis taking place. However the student version does not lend itself to the modelling and analysis of more complex scenarios due to the primitive drawing interface and limited use of mainly a coarse mesh. Due to the limit in the amount of zones allowed and consequently a less accurate FOS calculated it is recommended that for detailed analysis the full licensed version of FLAC or a different software package be used.

7.3 SLOPE/W

7.3.1 Student Version Specific Limitations

The student version of SLOPE/W has the following limitations:

- Number of multiple/staged analyses - 2
- Number of regions - 10
- Number of materials - 3
- Finite Element Integration – 500 elements

7.3.2 Modelling

SLOPE/W's drawing interface can be considered user friendly. Before the model can be defined the units, scale and axes need to be defined. Unlike FLAC/Slope, the drawing interface of SLOPE/W does allow itself to more complex models; however the model is limited to 10 regions. The student version does not allow the import of CAD drawings files.

7.3.3 Materials

The student version of SLOPE/W only allows analysis of materials with the Mohr-Coulomb properties

- Unit Weight (kN/m^3);
- Cohesion (kPa);
- Friction Angle (˚).

The student version limits the analysis to 3 materials only.

7.3.4 Solving Process

For this report the *'Entry & Exit'* approach was utilised in the solving process of SLOPE/W. Before the solving process can commence consideration must be made to the direction of the slip surface; this requires the user to have an understanding of the geotechnical and slope stability principals involved within the analysis. If the chosen slip surface analysed does not contain the *critical slip surface* the resulting FOS will be incorrect and could lead to catastrophic ramifications, this is illustrated in the analyses of Scenario 3. The correct direction of the slip surface before drawdown occurs, presented in Figure 47 generates an FOS value of 1.61; in contrast taking the incorrect direction of the slip surface before drawdown occurs, presented in Figure 56 generates an FOS value of 1.719. This shows that the direction of the slip surface assumed is extremely important and that assuming the incorrect direction can result in a difference FOS values which can lead to incorrect slope stabilisation methods used and in the case of the earth dam possible reinforcement of the wrong embankment.

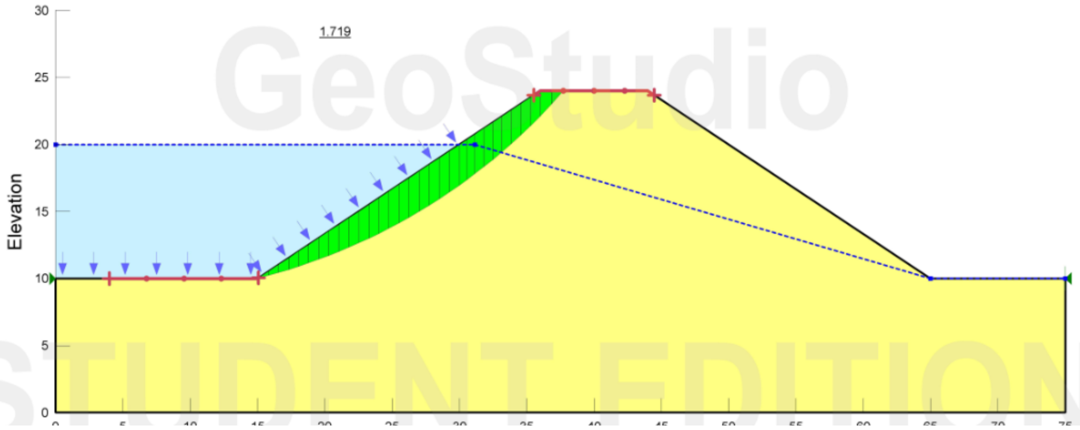


Figure 56 SLOPE/W Critical Slip Surface before drawdown (incorrect direction) – Earth Dam

The student version of SLOPE/W utilises the same process involved in the full licensed version. Therefore the results obtained can be considered more accurate than the FE and FD results obtained using a coarse mesh.

7.3.5 Results

SLOPE/W utilises the LE approach and as a result the output is relatively simple. The model is plotted showing the failure surface, location of the critical slip surface, the corresponding vertical slices and the critical FOS calculated is displayed. No indication is made to the stresses or the deformation experienced by other elements within the model.

For typical analysis of simple models such as highway slopes and embankments an FOS value is all that is required.

7.3.6 Discussion

SLOPE/W is a relatively simple and user friendly software package used to analyse geotechnical stability scenarios. The student version does limit the type of models that can be analysed; particularly only allowing 3 materials to be within the model and not allowing surcharges to be applied. A significant benefit in using the student version of SLOPE/W compared to FLAC or PLAXIS is it using a LE approach and not requiring a mesh to be generated, consequently the calculated FOS value is the same as that if it was calculated using the full licensed version. Therefore it can be considered that the calculated FOS by SLOPE/W is more accurate than FOS values calculated using a coarse mesh though FLAC or PLAXIS.

7.4 PLAXIS

7.4.1 Student Version Specific Limitations

The student version of PLAXIS has the following limitations:

- Number of multiple/staged analyses - 5
- Number of materials - 1
- Material models - 3

7.4.2 Modelling

PLAXIS uses a very intuitive drawing interface that allows for more custom and complex models to be defined. The student version of PLAXIS does not allow importing CAD drawings.

7.4.3 Materials

In addition to requiring the basic Mohr-Coulomb properties, the same as SLOPE/W; PLAXIS requires the advanced properties of the Elastic Modulus (E) and Poisson's Ratio (ν).

From the results obtained for Scenario 1, 2 & 3 no evidence was established that the advanced properties have a bearing on the results using a homogeneous material; however they do add an additional complexity to the scenarios.

The student version of PLAXIS only allows the analysis of 1 material within the scenario and 3 material models to be defined. In contrast the full licensed version of PLAXIS allows unlimited materials and material models; it also allows the additional function of sharing materials between different projects.

7.4.4 Solving Process

PLAXIS utilises the staged construction approach in the solving process. This approach simulates construction and utilises time steps throughout the analysis. The student version of PLAXIS only allows 5 stages which limits the ability to analyse scenarios involving multiple regions. The solving process used in PLAXIS is more complex compared to both FLAC and SLOPE/W requiring more time to input the necessary parameters and using the correct procedure to perform the analysis.

7.4.5 Results

As PLAXIS uses an FE approach in its analysis it is able produce more detailed results of the model. PLAXIS is able to model the deformation, shows the corresponding displacements and stresses up to and including the FOS. To obtain the FOS the total displacement (|u|) needs to be graphed against $\sum Msf$.

PLAXIS is able to produce more detailed results of the model compared to both FLAC and SLOPE/W.

7.4.6 Discussion

PLAXIS can be considered the most complex of the three software packages. The student version does limit the type of models that can be analysed; particularly only allowing 1 material to be within the model and not allowing surcharges to be applied. For a simple slope under assessment the complexity of PLAXIS could be considered unnecessary, requiring advanced material properties and an increased amount of time to input the parameters and conduct the correct procedure (staged construction) to produce the results.

For more complex scenarios with advanced parameters, particularly those that require a time step; PLAXIS can be considered the most suitable software package for analysis. However the student version of PLAXIS does not allow the capabilities to analyse complex scenarios.

Chapter 8: Conclusions

8.1 Conclusions

The purpose of this report is to gain a better understanding of the factors that cause slope instability and compare the student versions of FLAC, PLAXIS and SLOPE/W; three software packages developed for geotechnical stability analysis and their respective analysis methods.

From the three scenarios analysed it can be seen that increasing the height of an embankment, increasing the plasticity of the material or the creation of a pressure imbalance within the design can have a negative impact on the calculated FOS value and consequently the designs stability. With regards to the advanced properties of the Elastic Modulus (E) and Poisson's Ratio (ν); it could not be concluded that they have a significant effect on the predicted FOS results or not; this was also seen in validating the three packages (Appendix B). Further work is required in order to determine the significance of these advanced properties.

Other studies have suggested that the FE and FD methods provide greater benefits than the LE method and for more complex scenarios with advanced parameters, particularly those that require a time step; the FE and FD methods can be considered more suitable for the analysis. However, the LE method is a much simpler method, requiring minimal data and consequently less time and is highly regarded throughout the industry. The simplicity of the LE method can be considered to outweigh the complexity of the FE and FD methods as they require an increased amount of time to input the necessary parameters and in using the correct procedures to perform similar calculations (RocScience 2004b).

From this report it can be concluded that for software packages using the FE or FD method the type of 'mesh' generated and utilised in calculating the FOS value has a significant effect on accuracy of the results. Due to the limit in the amount of zones allowed within the FLAC student version and in general only allowing a coarse mesh analysis it can be considered that the FOS values calculated are less accurate compared to the student versions of PLAXIS and SLOPE/W.

Each package has its own benefits and limitations and it is recommended that the users choose the package that best suits the models requirements and its complexity. The student versions should be used as an indication only and any detailed analysis requires the use of a full licensed version of the chosen software package.

8.2 Further Work

The next stage in gaining a better understanding of FLAC, SLOPE/W and PLAXIS and their use in geotechnical stability analysis is to compare the full licensed versions of each software package.

Comparing the full licensed versions will remove the limitations of the student versions and allow the user to utilise all functions within each package. More complex scenarios such as multiple materials, surcharges etc. should be analysed so the user can make a more detailed judgement into which package best suits their needs and the possible effects of the advanced soil properties.

Figure 57 Image of the Kalgoorlie 'Super Pit' (The Super Pit 2009)

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Appendix A: Project Specification

University of Southern Queensland
Faculty of Engineering and Surveying

ENG 4111/4112 Research Project
PROJECT SPECIFICATIONS

FOR: **MICHAEL PETER SERRA**

TOPIC: GEOTECHNICAL STABILITY ANALYSIS USING STUDENT VERSIONS OF FLAC, PLAXIS AND SLOPE/W

SUPERVISOR: Dr Jim Shiau

ENROLMENT: ENG 4111 – S1, D, 2013
ENG 4112 – S2, D, 2013

PROJECT AIM: This project aims to compare the student versions of FLAC, PLAXIS and SLOPE/W. Three "real life scenario" problems will be analysed using FLAC, PLAXIS and SLOPE/W and a discussion will be carried out about each packages benefits and limitations.

PROGRAMME: **Issue A, 8th March 2013**

1. Background into the reasoning behind the development of these geotechnical software packages and their use in engineering practice.
2. Research into the analysis methodology (mainly Limit Equilibrium Method and Finite Element Method) behind the geotechnical software packages.
3. Discussion of the processes, requirements and steps used in each of the packages.
4. Analyses of three "real life scenario" geotechnical problems using the student versions of FLAC, PLAXIS and SLOPE/W.
5. Evaluate and compare the results achieved by each package. Identify possible techniques that could improve these results.
6. Discuss the benefits and limitations of each package.
7. Evaluate my own personal experiences and preferences in the packages.

AGREED: ______________________ (Student) ______________________ (Supervisor)

Date: / / 2013 Date: / / 2013

Appendix B: Software Validation

SOFTWARE VALIDATION

1.1 Geotechnical Model

To validate each of the software packages there calculated FOS results will be compared with hand calculations using the ordinary method of slices. The geotechnical model adopted for this validation test is illustrated in Figure 1. The soil comprises of the properties in Table 1. This scenario has been taken from Das 2010 p.573; Problem 15.20b

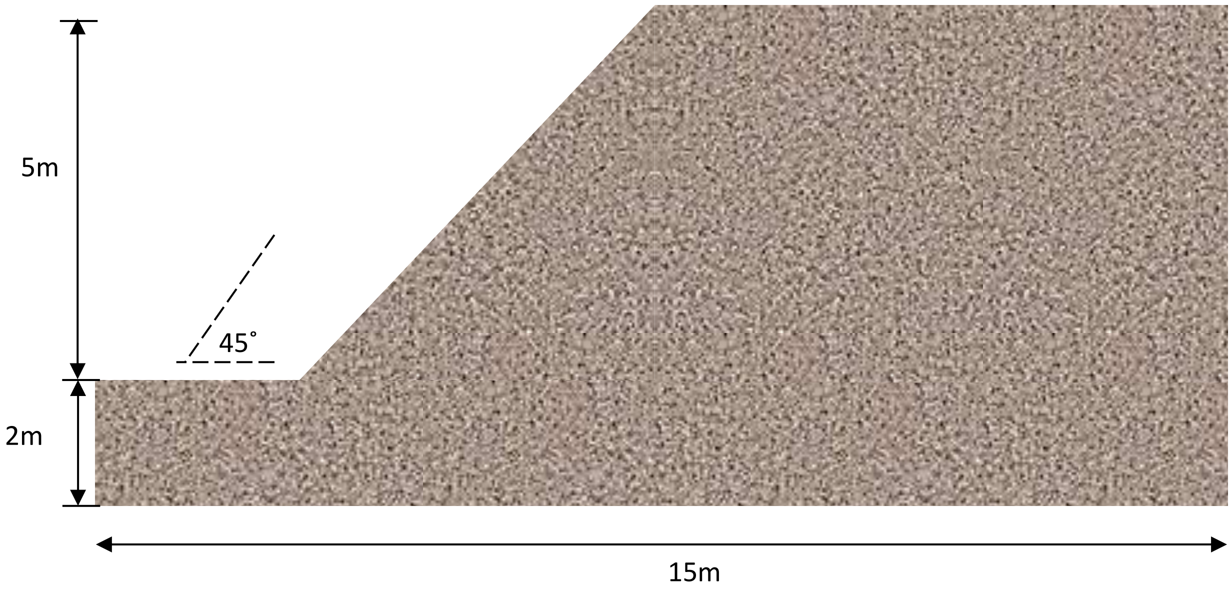

Figure 1 Simple Soil Slope adopted from Das 2010 p.573; Problem 15.20b

A slope of 45˚; the embankment height is kept constant at 5m. No water table has been considered.

1.1.1 Soil Properties

The properties of the soil are presented in Table 1.

Material	Unit Weight (kN/m^3)	Cohesion (kPa)	Friction Angle (°)
Soil	17.1	18	15

Table 1 Soil Properties - Simple Soil Slope

1.1.2 Units

PLAXIS, FLAC/Slope and SLOPE/W are all capable of using Metric units. However, FLAC/Slope uses different units to PLAXIS and SLOPE/W. The basic parameters and their units required in the analysis are outlined in Table 2. Gravity is taken as $9.81m/s^{-2}$.

Property	Symbol	Units PLAXIS & SLOPE/W	Units FLAC/Slope
Unit Weight / Density	γ / *p*	kN/m^3	kg/m^3
Cohesion	*c*	kPa	Pa
Friction angle	ϕ	°	°
Elastic Modulus	*E*	MPa = 10^3 kN/m^2	-
Poisson's Ratio	*v*	-	-

Table 2 Parameters for Analysis

1.2 Hand Calculations – Ordinary Method of Slices

The hand calculations will be done using the ordinary method of slice. This will utilise the additional parameters and the assumed slip surface presented in Figure 2.

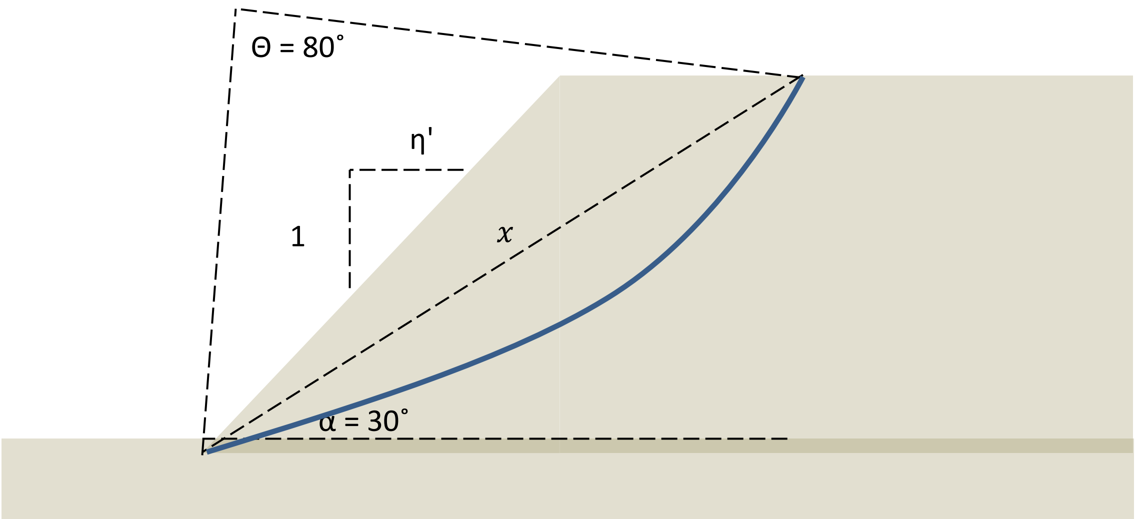

Figure 2 Additional parameters required for ordinary method of slices (Das 2010 p.573)

4 slices (θ is divided equally) are then assumed through the slip surface (more can be used to increase the accuracy). To determine the radius of the circle:

$$\frac{H\ (5m)}{x} = \sin(45^{\circ})$$

$$x = 10m$$

$$\frac{10}{\sin(80)} = \frac{R}{\sin(\frac{100}{2})}$$

$$R = 7.78\ meters$$

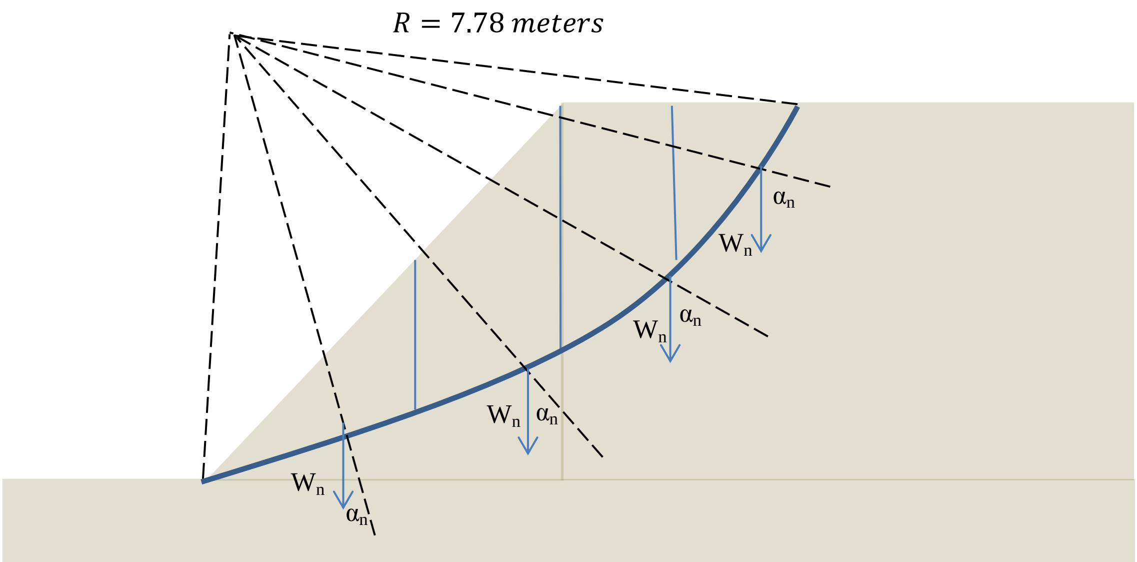

Figure 3 Assumed slices through the mass

1.2.1 Calculations

The Calculations are presented in Table 2.

Slice no.	Areas of the slices (m2)	Weight of Slice W_n= Axϒ (kN/m)	α_n	$W_n\cos(\alpha_n)$	$W_n\sin(\alpha_n)$
1	1.95	33.345	54	19.5997	26.97667
2	6.8	116.28	38	91.62989	71.58912
3	7	119.7	20	112.4812	40.93981
4	4.2	71.82	6	71.42656	7.507234
				$\sum$ 295.1374	$\sum$ 147.0128

Table 3 Calculations for the ordinary method of slices

From the values presented in Table 1 and calculated in Table 3 the FOS can be calculated using the following equation:

$$\text{FOS} = \frac{\sum[R\theta c' + \text{Wncos}(\alpha_n)\times\tan(\phi)]}{\sum \text{Wnsin}(\alpha_n)} \qquad \text{(Das 2010, p.546)}$$

$$\text{FOS} = \frac{\left[7.78 \times 18 \times \left(\frac{80\pi}{180}\right)\right] + (295.1374) \times (\tan(15))}{147.0128}$$

$$= 1.867963 \approx 1.87$$

1.3 FLAC/Slope Analysis

The FOS analysis is then done using FLAC/Slope. In order to complete the analysis Unit Weight must be converted to Density; Due to the limitations of the student version a coarse mesh has been used. Figure 4 illustrates the Critical Slip Surface calculated by FLAC/Slope.

Calculated FOS = 1.82

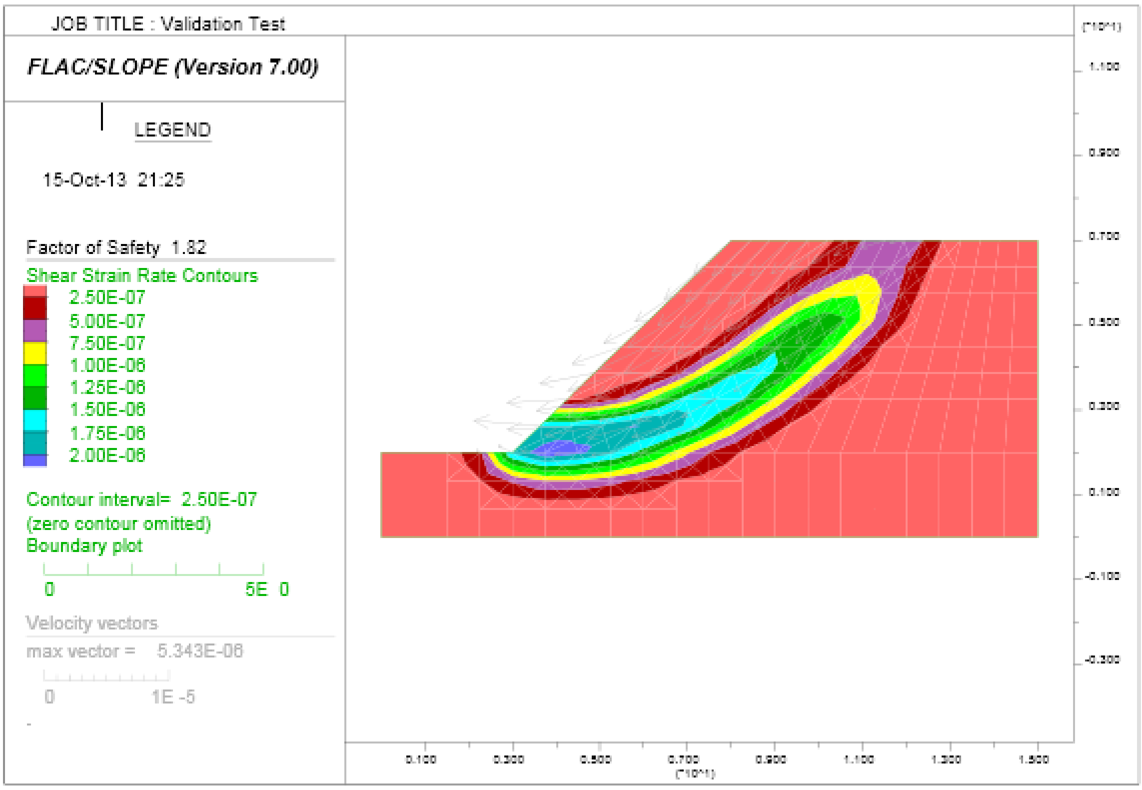

Figure 4 FLAC/Slope Critical Slip Surface – Validation Test

1.4 SLOPE/W Analysis

The FOS analysis is then done using SLOPE/W. Figure 5 illustrates the Critical Slip Surface calculated by SLOPE/W.

Calculated FOS = 1.81

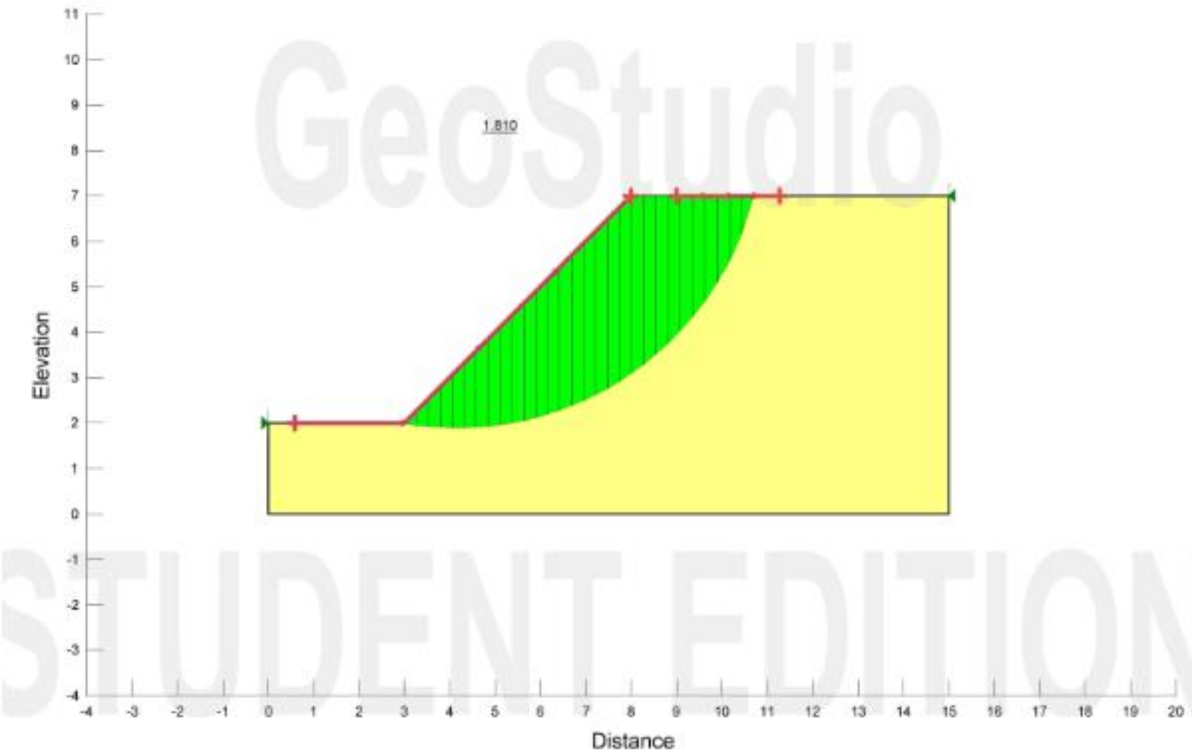

Figure 5 SLOPE/W Critical Slip Surface – Validation Test

1.5 PLAXIS Analysis

The FOS analysis is then done using PLAXIS. Figure 6 and 7 illustrate the Critical Slip Surface calculated by PLAXIS. As PLAXIS requires the advanced properties of *E* and *v'*; these values have been assumed the same as Scenario 2 – Simple Reservoir Embankment with a Clayey Soil, that is:

E = 3 MPa

v' = 0.15

Calculated FOS = 1.738

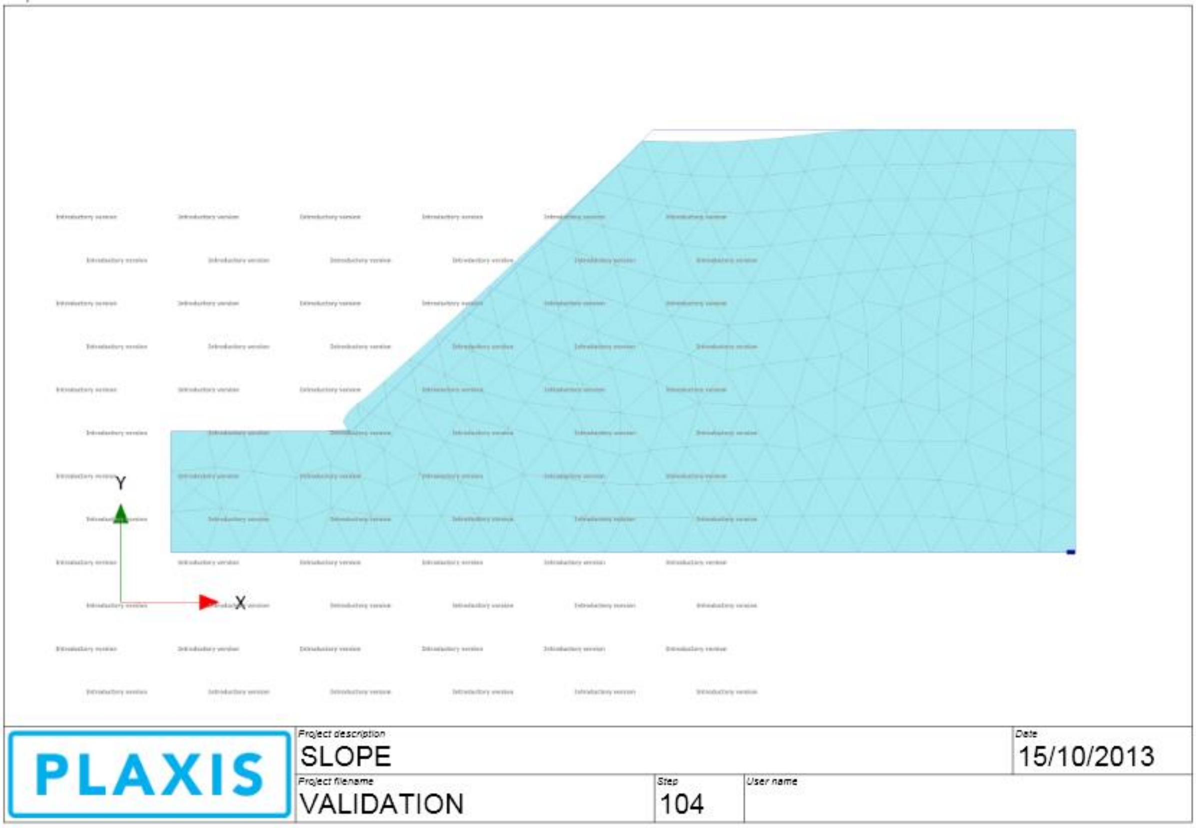

Figure 6 PLAXIS deformation – Validation Test

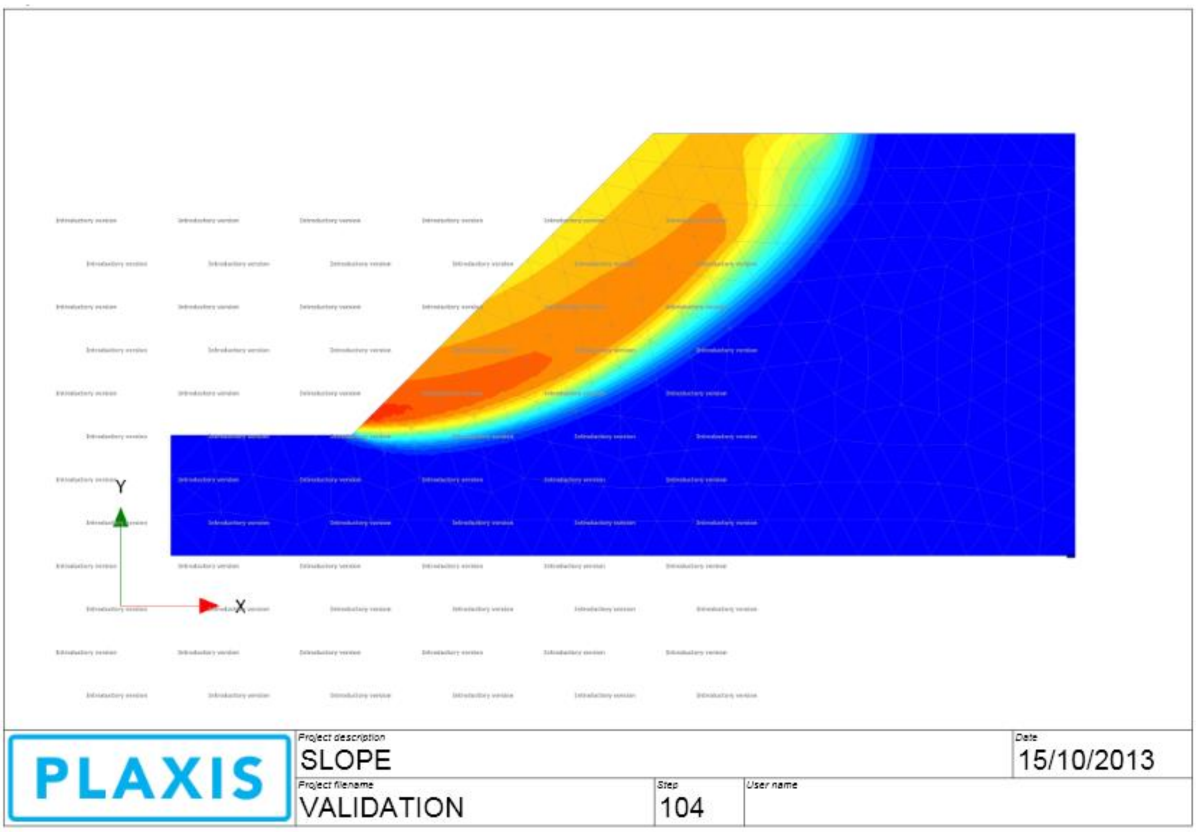

Figure 7 PLAXIS Total Displacement – Validation Test

1.6 Results and Discussion

The slope stability analysis has been conducted by hand calculations and using FLAC/Slope, SLOPE/W and PLAXIS. Table 4 compares the calculated FOS values from the proposed analysis methods. Both FLAC/Slope and SLOPE/W produce results within 5% of the hand calculations therefore can be considered validated. However the result generated by PLAXIS has a difference greater than 5% of the hand calculations (possibly due to the use of advanced soil properties); however within the hand calculations only 4 slices where assumed and more accurate results could be produced with more slices assumed. Therefore consideration must be given regarding the validity of results obtained using PLAXIS.

HAND CALCULATION: FOS = 1.87		
Analysis Method	**FOS**	**% Difference from Hand Calculations**
FLAC/Slope	1.85	1.07%
SLOPE/W	1.812	3.10%
PLAXIS	1.74	6.95%

Table 4 Comparison of Results – Validation Test

1.7 References

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Appendix C: Simple Homogeneous Soil Slope with Applied Surcharge (Attempt)

SIMPLE HOMOGENEOUS SOIL SLOPE WITH APPLIED SURCHARGE (Attempt)

1.1 Geotechnical Model

The geotechnical model adopted in this analysis is illustrated in figure 1. The soil is classified as unsaturated sand and comprises of the properties in table 1, kept constant in all analyses.

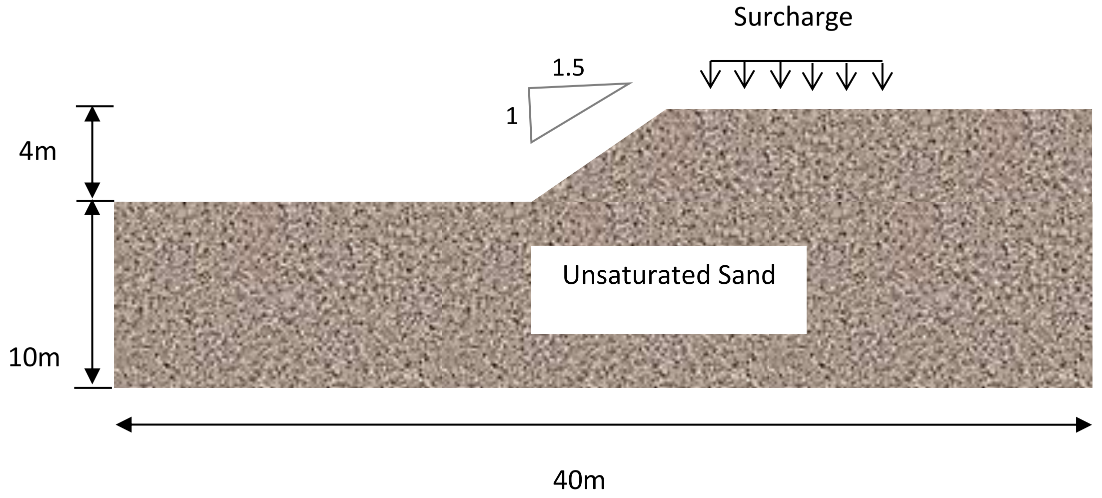

Figure 1 Simple Homogeneous Soil Slope with applied surcharge

The slope considered has an embankment batter of 1:1.5, producing a slope angle equal to 33.7˚. The embankment height is kept constant at 4m and a surcharge of 20kPa is applied over 9 meters on the top of the embankment. No water table has been considered.

1.2 Properties

The properties of the unsaturated sand material and the surcharge pressure being applied are presented in Table 1. These properties are adequate for the Mohr-Coulomb approach.

Material	**Unit Weight (kN/m^3)**	**Elastic Modulus (MPa)**	**Poisson's Ratio**	**Cohesion (kPa)**	**Friction Angle (°)**	**Surcharge (kPa)**
Unsaturated Sand	17	13	0.3	1	30	20

Table 1 Unsaturated Sand Material Properties - Simple Homogeneous Soil Slope

1.3 Units

PLAXIS, FLAC/SLOPE and SLOPE/W are all capable of using Metric units. However, FLAC/SLOPE uses different units to PLAXIS and SLOPE/W. The basic parameters and their units required in the analysis are outlined in Table 3.

Property	**Symbol**	**Units PLAXIS & SLOPE/W**	**Units FLAC/SLOPE**
Unit Weight / Density	γ	kN/m^3	kg/m^3
Cohesion	c	kPa	Pa
Friction angle	ϕ	°	°
Elastic Modulus	E	MPa = 10^3 kN/m^2	-
Poisson's Ratio	v	-	-

Table 3 Parameters for Analysis

1.4 FLAC/Slope Analysis

The scenario is modelled using FLAC/Slope similar to that presented in Scenario 1 with a surcharge load applied of 20,000Pa. Due to the limitations of the student version of FLAC a coarse mesh has been adopted for FOS analysis.

Figure 2 presents the critical slip surface. The calculated FOS is:

FOS = 1.29

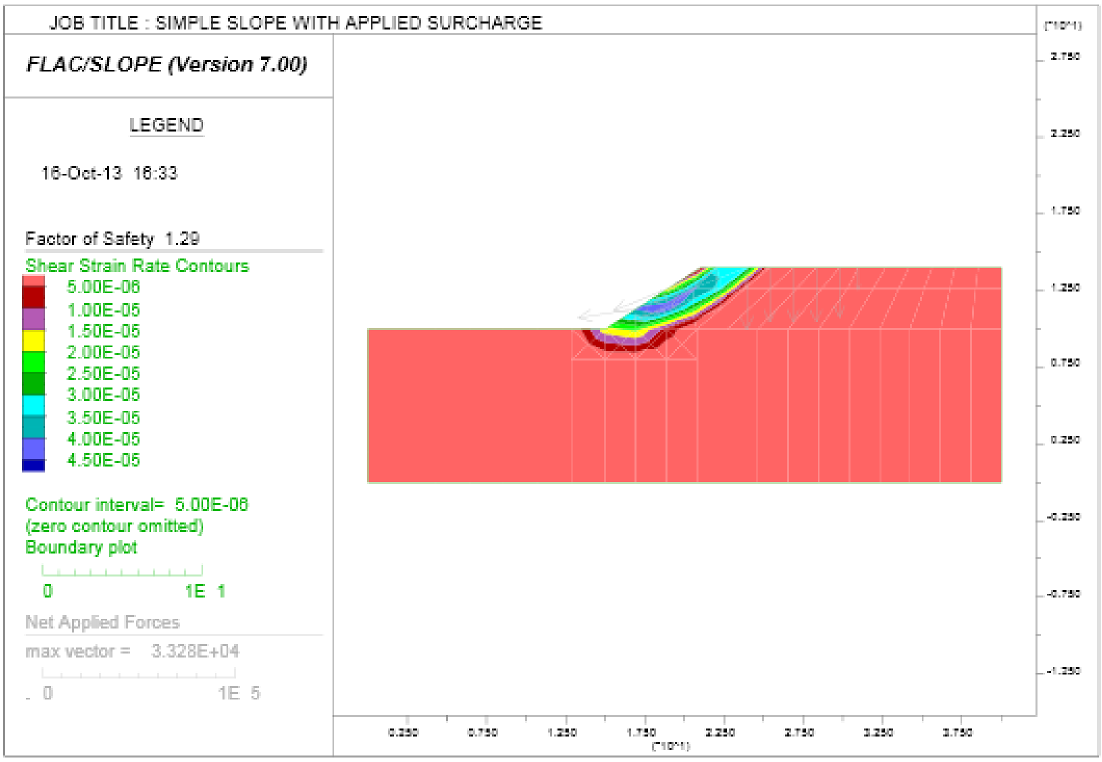

Figure 2 FLAC/Slope Critical Slip Surface – Simple Slope with Applied Surcharge

1.5 SLOPE/W Analysis

The student version of SLOPE/W does not allow the application of external loads. Therefore this scenario cannot be correctly analysed using the student version of SLOPE/W. A possible way to bypass this limitation would be to add an additional layer of soil 1m in height that's unit weight is equal to the surcharge. That is:

$$\text{Unit Weight} = 20\text{kN/m}^3$$

$$\text{Friction Angle} = 90^\circ$$

Note an unrealistic friction angle is assumed so that the failure does not occur through this additional soil layer.

The analysis is then done to calculate the FOS. Figure 3 presents the critical slip surface for this scenario. The calculated FOS is:

$$\text{FOS} = 1.29$$

It must be noted that this method is highly unorthodox and is purely a theoretical exercise to calculate FOS. The result obtained cannot be validated and therefore is irrelevant.

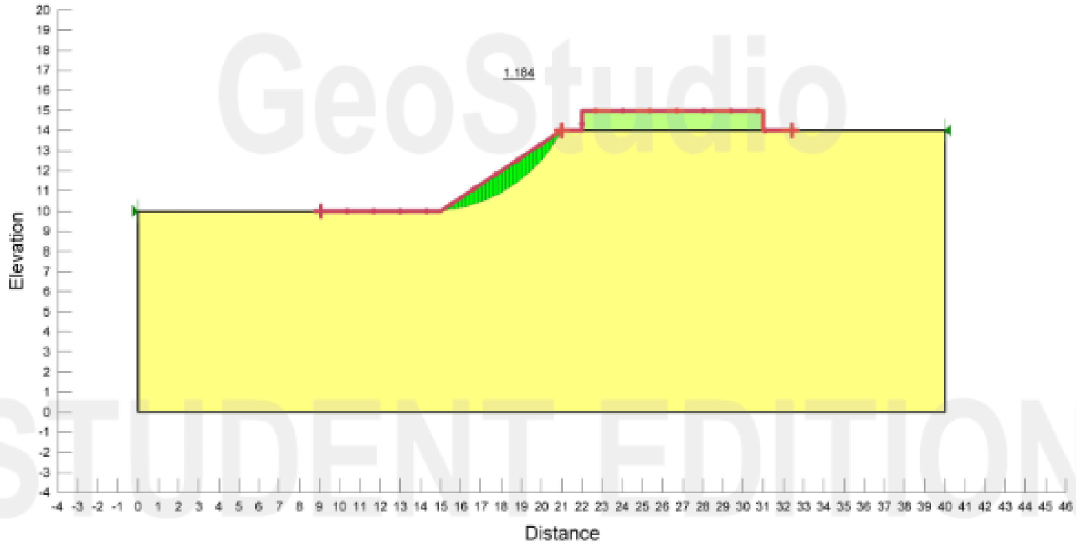

Figure 3 SLOPE/W Critical Slip Surface – Simple Slope with Applied Surcharge

1.6 PLAXIS Analysis

Similar to SLOPE/W the student version of PLAXIS does not allow the application of an external force. The student version of PLAXIS also limits the amount of materials to only one; therefore the unorthodox methodology used to in 1.5 cannot be used here.

The student version of PLAXIS is unable to determine a result for any slope with an external force applied.

1.7 Discussion

FLAC/Slope is the only software package that's student version allows slope stability analysis of scenarios where an external force is applied to the slope. Both the student versions of SLOPE/W and PLAXIS are unable to analyse scenarios with an external force applied.