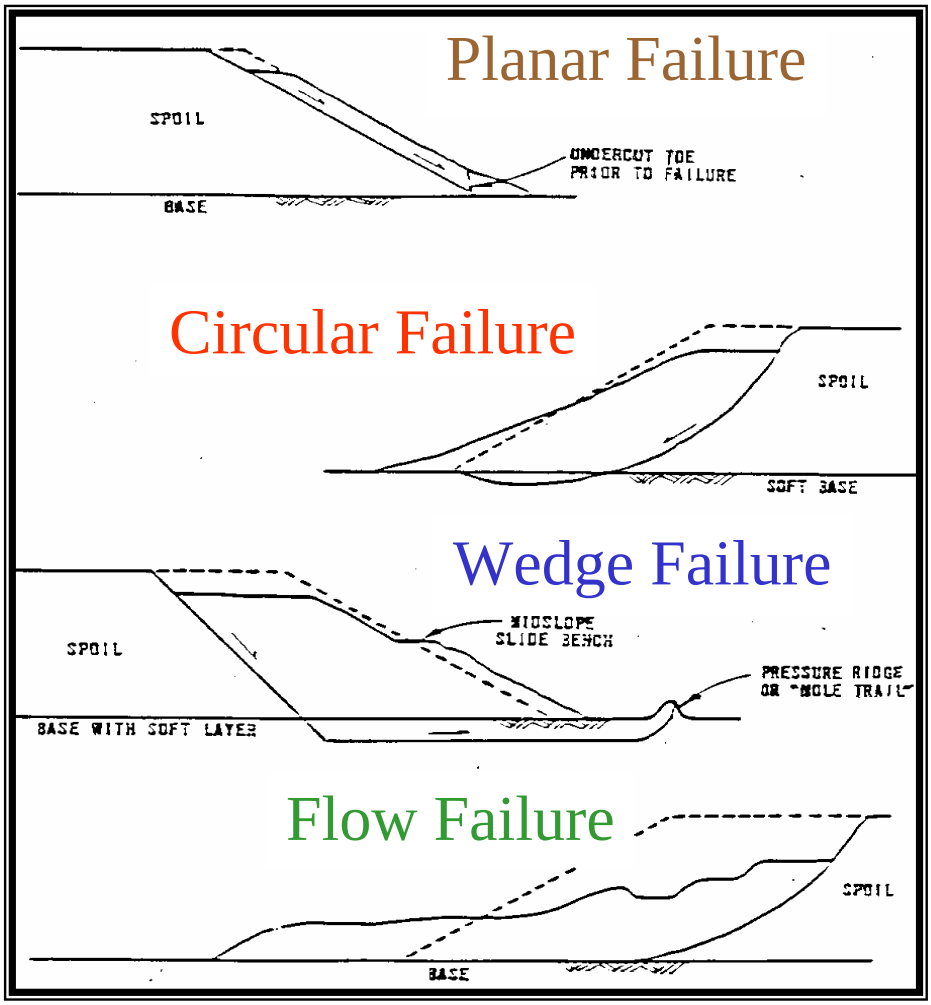
Slope Stability Analysis

Clover Technology (Clover Associates Pty Limited)
Robertson, NSW Australia

V. 3.1

Office of Surface Mining, TIPS Training Course

Student Notes



Galena Class

Agenda

Day One

8:00 – 8:15	Introduction and Logistics
8:15 – 9:00	Slope Stability Analysis Theory & Bishop Method
9:00 – 9:15	Break
9:15 – 9:40	Spencer’s Method
9:40 – 10:00	Sarma Method
10:00 – 10:15	Break
10:15 – 10:40	Soil Testing Methods
10:40 – 11:30	Introduction to Data Entry
11:30 – 12:30	Lunch
12:30 - 1:10	Class Data Entry in Galena
2:10 - 2:55	Embankment Analysis by Bishop's Method
2:55 - 3:45	Embankment Analysis by Spencer's Method
3:45 - 4:00	Questions and Daily Wrap-Up

Day Two

8:00 - 8:50	Analysis by Sarma
8:50 - 9:00	Break
9:00 - 9:45	Analysis Options
9:45 - 9:50	Break
9:50 - 10:40	Slope Stability Problem Solving
10:40 - 11:30	Hints and Error Messages
11:30 - Noon	Questions and Class Wrap-up

Student Notes
Galena Slope Stability

1. Introduction

a. Objectives
   i. Provide students with a working knowledge of the Galena software. How to enter data and obtain accurate results.
   ii. Demonstrate the options available in the Galena software and how to use them.
   iii. Discuss the difference between analytical methods and which is most appropriate for different slope stability cases.

b. Requirements
   i. This course is intended for students with an engineering background or understanding. Students must be familiar with basic engineering principles and calculus.

2. Slope Stability Analysis Theory

Four basic factors determine the stability of a slope:

1)

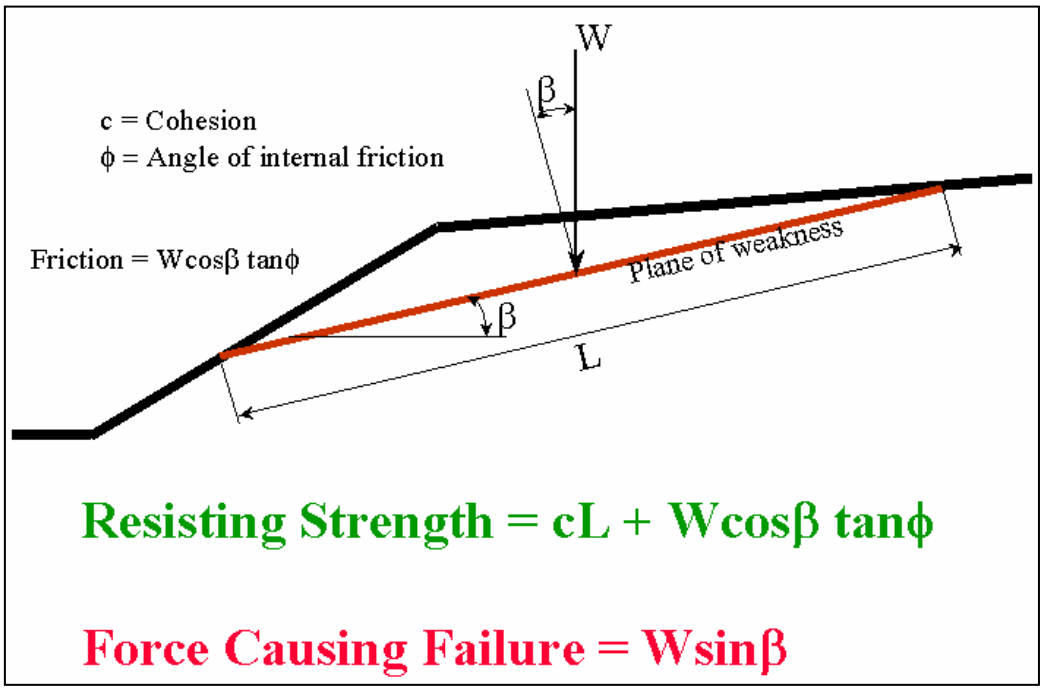
2)

3)

4)

Angle of Internal Friction -- Measures the amount of friction that keeps a block from moving when a shear force is applied.

With these four elements you can calculate a block's tendency to move or resist movement along an inclined slope.



Around 1920, the Swedish Geotechnical Commission presented their findings that slope failures tend to occur along a curved surface in soils and unconsolidated material.

3. Bishop Method

a. On Tuesday morning, September 21, 1954; Dr. Alan W. Bishop presented his paper on "The Use of the Slip Circle in the Stability Analysis of Slopes."
b. Bishop method divides the slip circle into slices.

Bishop Analysis is Performed by:

- Dividing the cross-section with failure surface into slices.
- Resolving forces on each slice to calculate the Factor of Safety.
- Summing all slice results over the entire slope and obtaining an overall Factor of Safety.

c. Factor of Safety – The factor of safety is a ratio of the resisting strength to the forces causing failure:

i. Bishop definition of Factor of Safety:

Simplified Bishop Method

- Defines the "Factor of Safety" as the ratio of the available shear strength of the soil to that required to maintain equilibrium

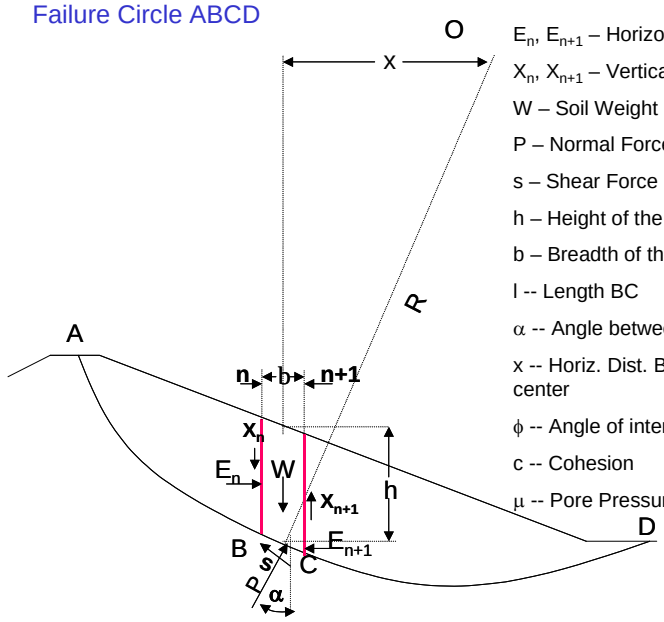
$$s = \frac{1}{F}\left\{c + \left(\sigma_n - \mu\right)\tan\phi\right\}$$

Where c = Cohesion; ϕ=Angle of Internal Friction

σ_n=Total Normal Stress; μ=Pore Pressure

s=Shear Strength; F= Factor of Safety

Failure Circle ABCD



E_n, E_{n+1} – Horizontal forces

X_n, X_{n+1} – Vertical shear forces

W – Soil Weight

P – Normal Force

s – Shear Force at the base

h – Height of the slice

b – Breadth of the slice

l -- Length BC

α -- Angle between BC and horizontal

x -- Horiz. Dist. Between slice & circle center

ϕ -- Angle of internal friction

c -- Cohesion

μ -- Pore Pressure

Resulting in the following Bishop equation for Factor of Safety:

$$F = \frac{1}{\sum W \sin\alpha} \sum \left[cl + \tan\phi \left(W \cos\alpha - \mu l \right) \right]$$

d. Values of factors of safety

(1) Values commonly used in engineering practice are:

1.5 for permanent or sustained loading conditions.
2.0 for foundations for a structure.
1.25 to 1.3 for temporary loads.
1.15 to 1.2 for seismic loading.

(2) Factors of safety from the surface mining regulations (these may vary from state to state).

Situation	Factors of Safety		
	Static	Seismic	CFR Reference
MSHA size dams	___	___	
Non-MSHA size dams	___		
Excess spoil fills	___		
Durable rock fills	___	___	
Pre-existing benches	___		
Coal mine waste	___		
Coal waste dams	___		
Graded spoil	___		
Road embankments	___		

(3) Factors of safety compensate for the uncertainties of an engineering analysis. The lower the factor of safety, the greater the risk involved and/or the lower the engineering confidence in the analysis.

e. Conditions change and factors of safety may not remain valid.

(1) Changes in pore water pressure.

(2) Weathering of spoil or coal waste.

(3) Departure from the assumed conditions of the analysis during field construction.

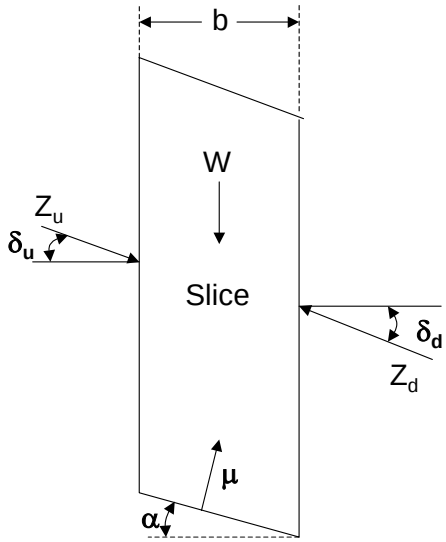
(4) Conditions can change overnight. It is difficult to assign realistic properties to an analysis.

f. Factors of safety can be manipulated. A 1.5 factor of safety can be achieved for many conditions by changing the input parameters, cross-sectional geometry, or engineering model used.

4. Spencer Method

Spencer Analysis

- Limiting equilibrium technique which balances vertical force, horizontal force, and moment equilibrium.
- Contrasts with Bishop which satisfies only vertical force and moment equilibrium.
- Used in both circular failures and non-circular failure cases.



Where:

Zu = Interslice force on the upslope side

Zd = Interslice force on the downslope side

Mn = Net system moment

μ = Pore Pressure at the center of the slice base

α = Angle of the slice base

ϕ = Angle of internal friction

c = Cohesion

F = Factor of Safety

b = Width of the slice

W = Weight of the slice

i = The slice number starting with the toe slice as number 1

The uphill and downhill interslice forces on each slice are calculated with the following equations:

Spencer Force Equation

$$Z_u = \frac{\left(c/F\right) b \sec\alpha - W\sin\alpha + \left(\tan\phi/F\right)\left(W\cos\alpha - \mu b\sec\alpha\right)}{\cos\left(\alpha-\delta_u\right)\left[1+\left(\tan\phi/F\right)\tan\left(\alpha-\delta_u\right)\right]}$$

$$Z_d = \frac{\cos\left(\alpha-\delta_d\right)\left[1+\left(\tan\phi/F\right)\tan\left(\alpha-\delta_d\right)\right]}{\cos\left(\alpha-\delta_u\right)\left[1+\left(\tan\phi/F\right)\tan\left(\alpha-\delta_u\right)\right]}$$

The net system moment equation is resolved as follows:

Spencer Moment Equation

$$M_n = \sum \left\{ 0.5 Z_d \left[\sin \delta_d \left(b_i + b_j \right) - \cos \delta_d \left(b_i \tan a_i + b_j \tan \alpha_j \right) \right] \right\}$$

Spencer's Theta

Since the values for the angle of interslice force may vary between slices, it is represented as a function:

$$\tan \delta_i = k_i \tan \theta$$

Where: δ_i is the angle of interslice force on the upslope side of the slice.

k_i is a coefficient that adjusts δ_i over the last 20% of slices.

θ is a constant angle known as Spencer's theta.

Side Force Function

In Spencer's Theta, the k_i coefficient adjusts the interslice forces as they near the head of the failure surface.

k=1 in all slices except the last 20% where k is linearly reduced to zero.

Spencer Solution

The solution is the value of the Factor of Safety and the value of Spencer's Theta for which Z_n and M_n are zero.

Z_n is the upslope side interslice force on the last slice.

M_n is the resultant moment.

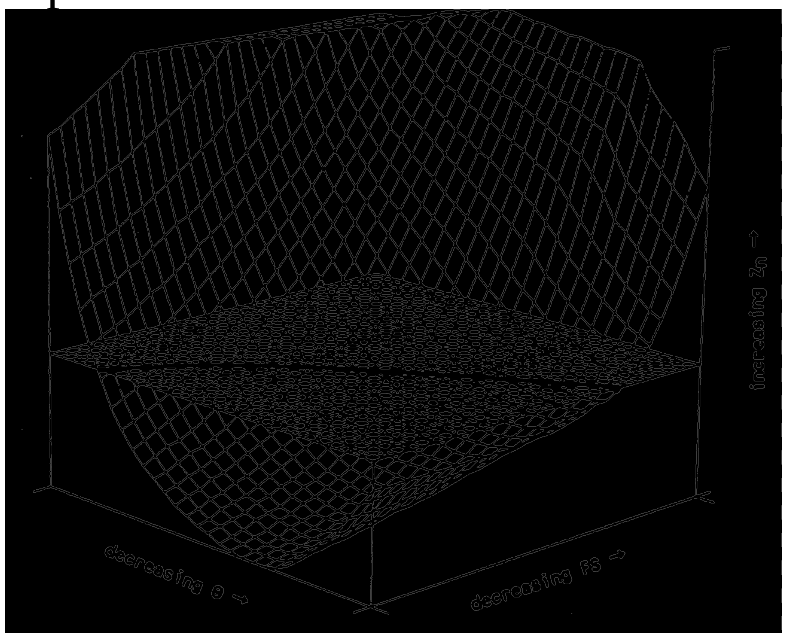
a. To reach a solution with the Spencer method, the program uses a procedure to minimize the Interslice Force and Moment equations for like values of Spencer's Theta and Factor of Safety. In other words, the program works by varying the Factor of Safety and Spencer's Theta such that the upslope side interslice force on the last slice AND the resultant moment approach ZERO.

Solution Process

To reach the solution Galena uses a procedure to minimize the Z_n and M_n equations for like values of FS (Factor of Safety) and θ.

This concept can be demonstrated graphically in the following slides:

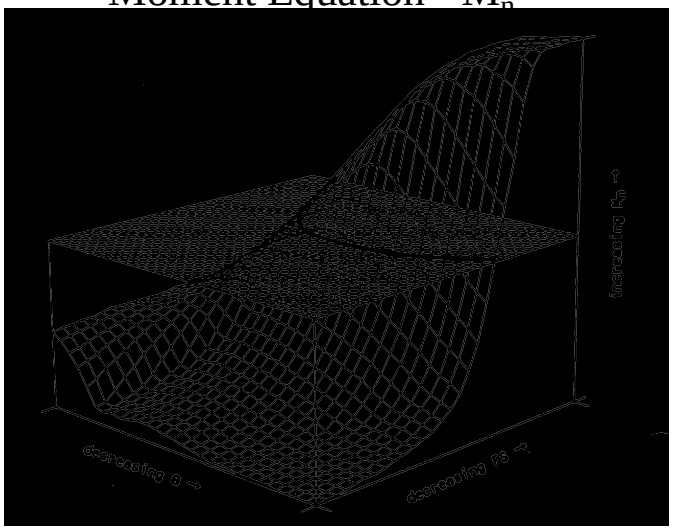
Upslope Interslice Force on the Last Slice



The intersection of the solution surface with the zero plane defines values for factor of safety and Spencer's theta that satisfy the force equation for $Z_n(FS,\theta) = 0$.

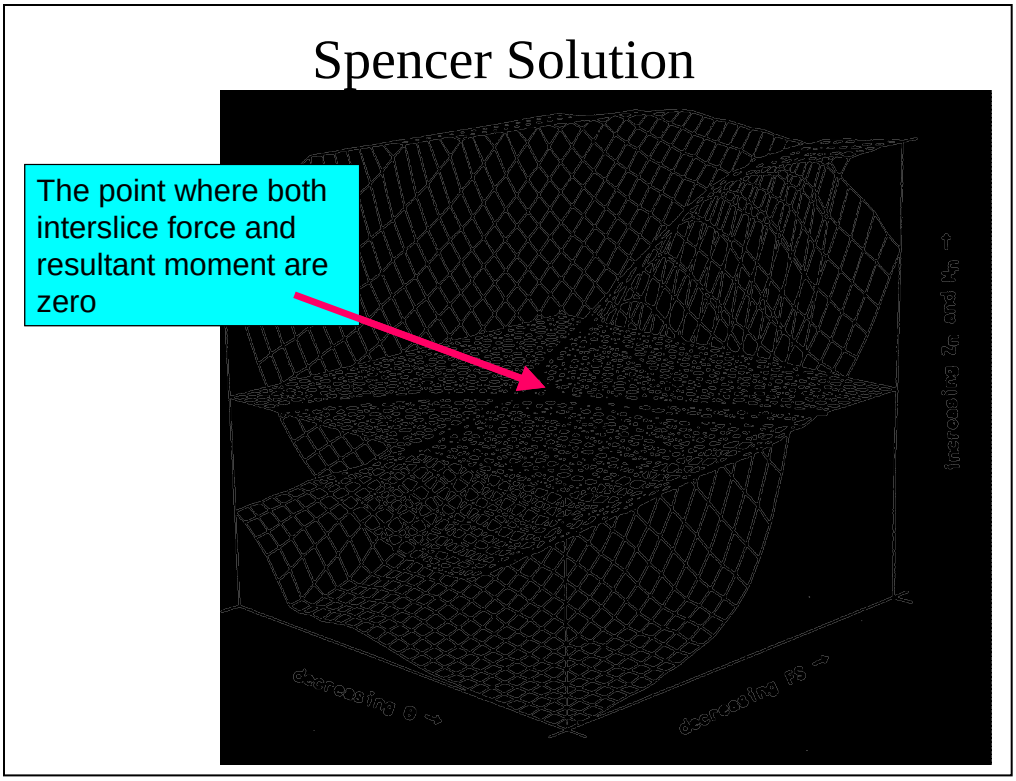
Similarly, an example of the solutions for the moment equation, M_n, for varying values of factor of safety and Spencer's theta are shown graphically in the next slide:

Moment Equation - M_n



The intersection of the solution surface with the zero-plane defines values of factor of safety and Spencer's theta that satisfy the moment equation for $M_n(FS, \theta) = 0$.

By merging the two previous illustrations the final solution, that satisfies both the moment equation and the force equation is shown in the next slide:



The value of FS and θ that makes both $Z_n(FS,\theta) = 0$ and $M_n(FS, \theta) = 0$ is the solution, and is the point where the three surfaces intersect.

5. Sarma Method

a. **Background and Description**:

i. The Sarma method is a different approach to determining the safety factor for a slope. Both the Bishop and Spencer methods use the ratio of the resisting forces to the driving forces at the failure surface to calculate the safety factor. Through iterations, a series of failure surfaces are tested and the failure surface with the minimum ratio is the accepted safety factor for the slope and materials specified.

ii. The Sarma method determines slope stability by applying a horizontal acceleration (as a fraction of the gravitational constant) to the material above the failure surface and calculating the safety factor the soil mass has to the applied force.

iii. This method was developed by Sarma as part of research done for the Corps of Engineers to predict deformation of earthen dams due to seismic loading. Sarma extended the research to calculating safety factors since he reasoned that as a mass of soil moves from no movement to failure during a seismic event, the mass must pass through acceleration where the safety factor is 1.0, that is, the point where the mass is at limiting equilibrium. He called this acceleration value the critical acceleration and labeled it $\mathbf{K_c}$.

iv. Using the Sarma method, the factor of safety is defined as the factor by which the strength of the material must be reduced to produce a state of limiting equilibrium. That is, the strength where the driving forces equal the resisting forces. This factor is derived by a series of trial and error reductions of the engineering properties to reach a K_c value of 0.0 representing a safety factor of 1.0.

Sarma Method

This method can be adapted to find a static factor of safety by reducing the soil strength parameters until a zero horizontal acceleration is required for failure.

This means the factor of safety has the value of just **1.0**.

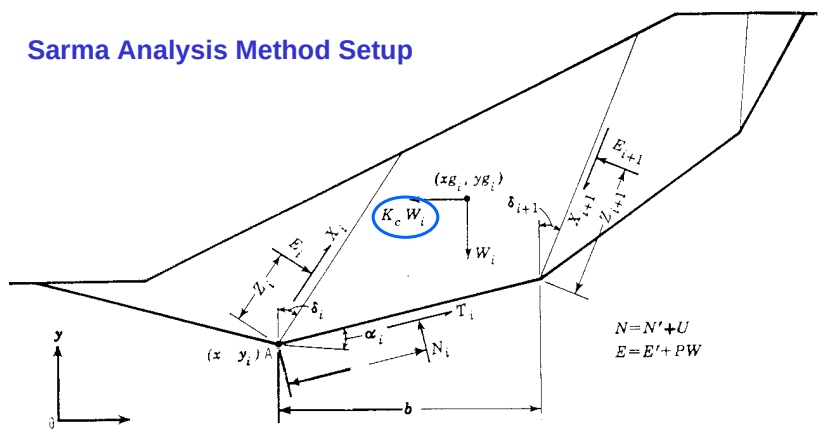
b. **Differences between Sarma and other methods of slices (Bishop, Spencer, Morganstern-Price, Janbu, etc**)

i. In Sarma the driving force is the K factor (0.0 – 1.0) that is needed to place the soil mass into limiting equilibrium. Whereas, the other methods compute the ratio of the total resisting force to the total driving force for the soil mass being evaluated.

ii. In Sarma the K factor is determined explicitly by solving the equations for equilibrium for each of the constraints specified by the user. In the other methods, the safety factor is determined for each failure configuration by varying the geometry of the failure surface by changing the left and right ending points and the radius of the failure surface. This requires a hunting algorithm for the other methods to vary the geometry, compute the safety factor, keep track of minimum safety factor within the confines of the constraints placed on the search area.

iii. The Sarma methods allows for non-vertical non-parallel boundaries between slices where the other methods encourage but do not require vertical slices. The non-vertical slices make the arithmetic more difficult especially for calculating moments. Since Sarma does not use moments in the solution, the use of non-vertical slice boundaries is avoided.

Sarma Analysis Method Setup

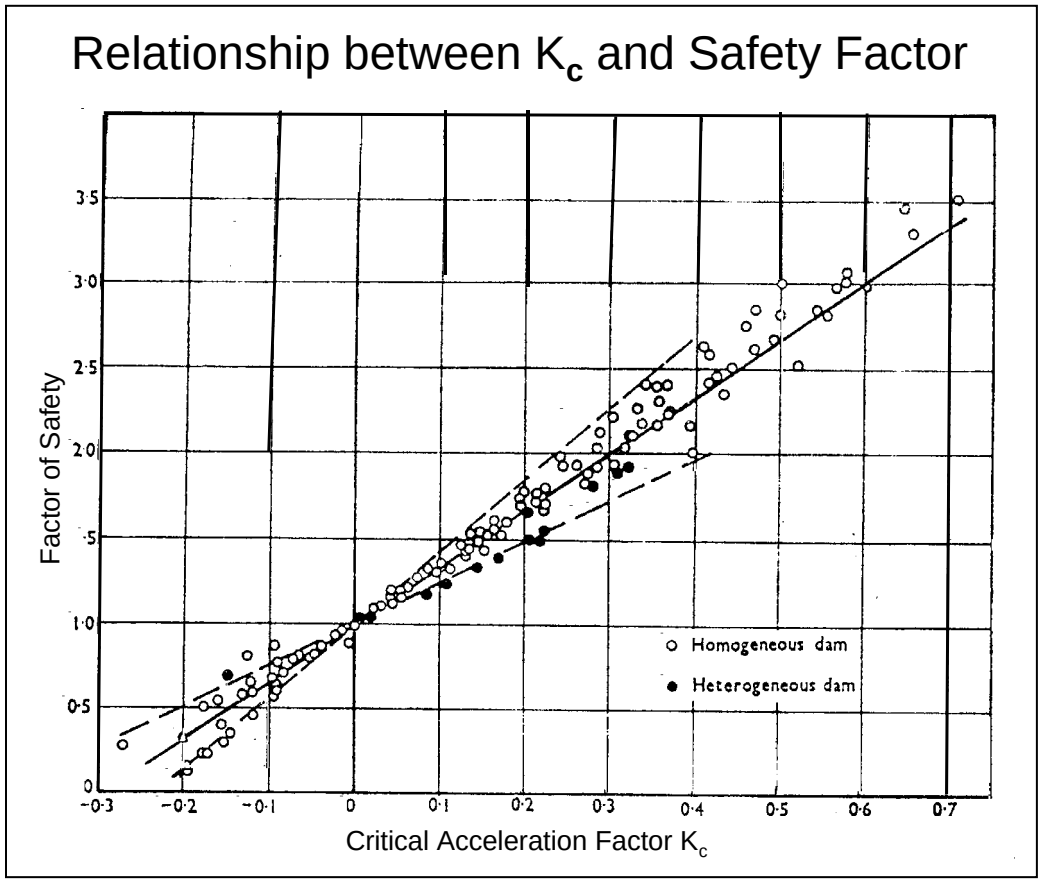


E_i, E_{i+1} – Horizontal forces	T_i – Shear Force at the base	μ -- Pore Pressure
Zi, Zi+1 – Application pt. of interslice force	b – Breadth of the slice	
X_i, X_{i+1} – Vertical shear forces	l -- Length BC	
W_i – Soil Weight	α -- Angle between element bottom and horizontal	
K_c – Critical Acceleration Factor	ϕ -- Angle of internal friction	
N_i – Normal Force	c -- Cohesion	

c. Determination of safety factor from critical acceleration factor (K_c)

Sarma found through analysis that a linear relationship exists between the critical acceleration and the factor of safety. This relationship was calculated by plotting the safety factor using the Bishop and Spencer-Wright methods against the calculated acceleration factor calculated using the Sarma method.

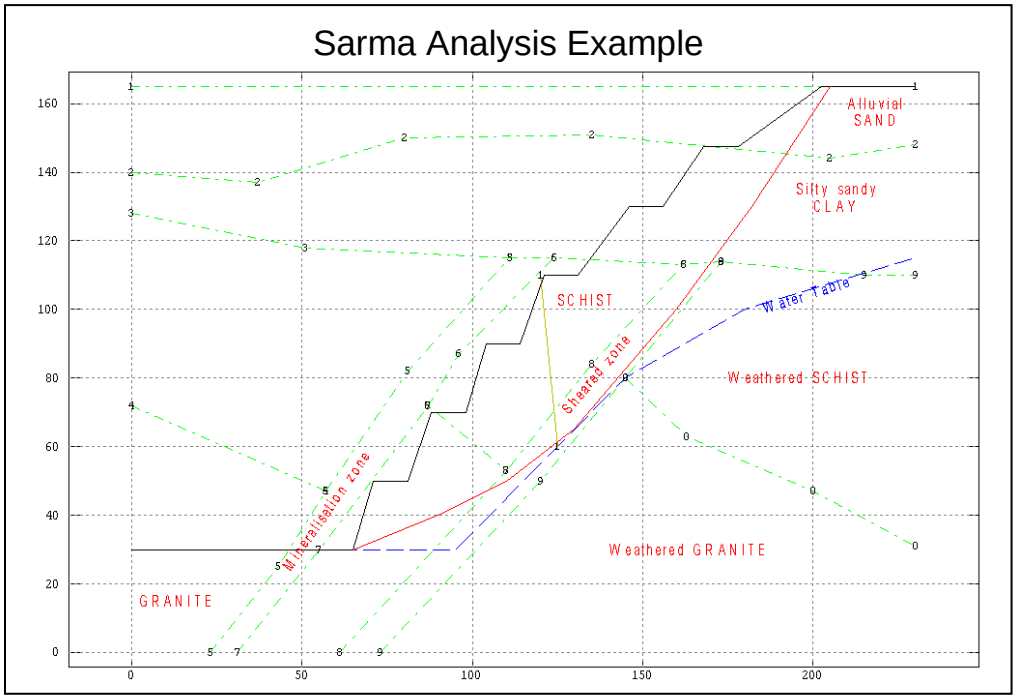
Sarma developed a curve to translate or convert a given critical acceleration factor to a safety factor. The relationship between the safety factor and critical acceleration was found to be linear over a wide range of typical values.



d) Situations for using Sarma over other methods

The Sarma method can be used on any slope where the other methods are used.

So then when does Sarma need to be used? Sarma's method has the best applicability on slopes where thin zones of soils are present and when you need to model fracture zones in an embankment cut such as highwalls. These structures are difficult to model in other methods. More so using Bishop with the required circular failure mode than with the Spencer method, but still placing the failure surface directly on the weakest zone is difficult to achieve. Sarma easily models these zones because moment equations don't enter into the analysis.



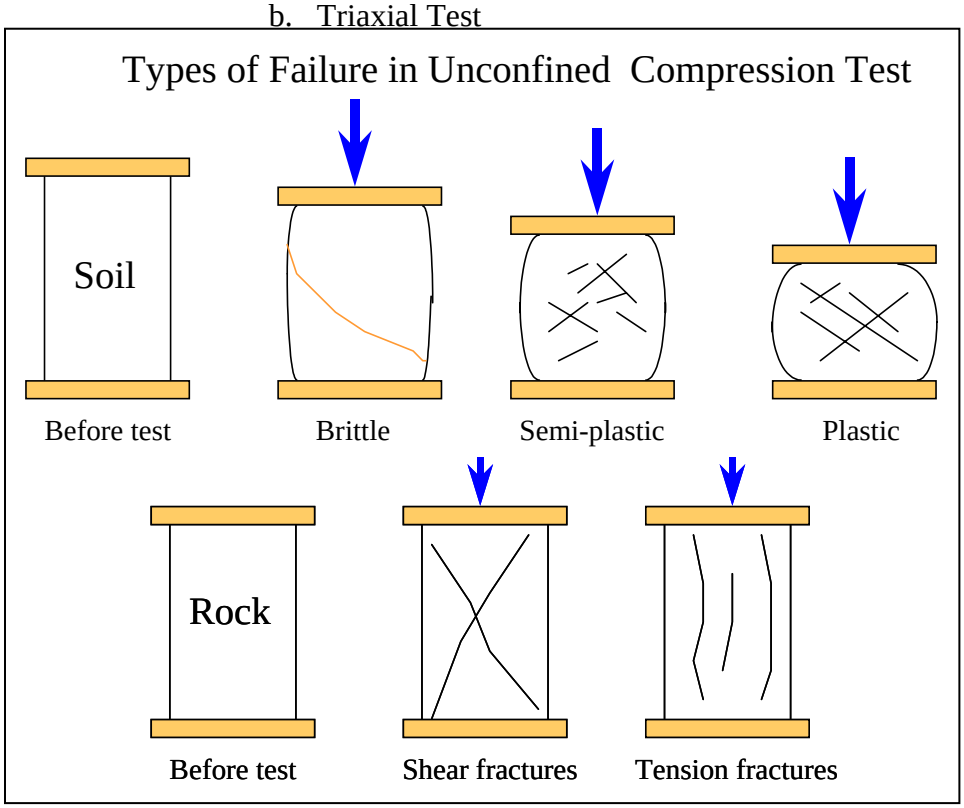
This example from the Galena manual (file EXAMPLE05.GMF) shows a situation where SARMA is well suited. The sheared zone in the highwall of this mining operation would be difficult to model using another method due to the difficulty of ensuring the failure surface includes the shear zone during the determination of the safety factor. Using Sarma, the initial failure surface is placed in the shear zone ensuring inclusion of the shear zone in the analysis.

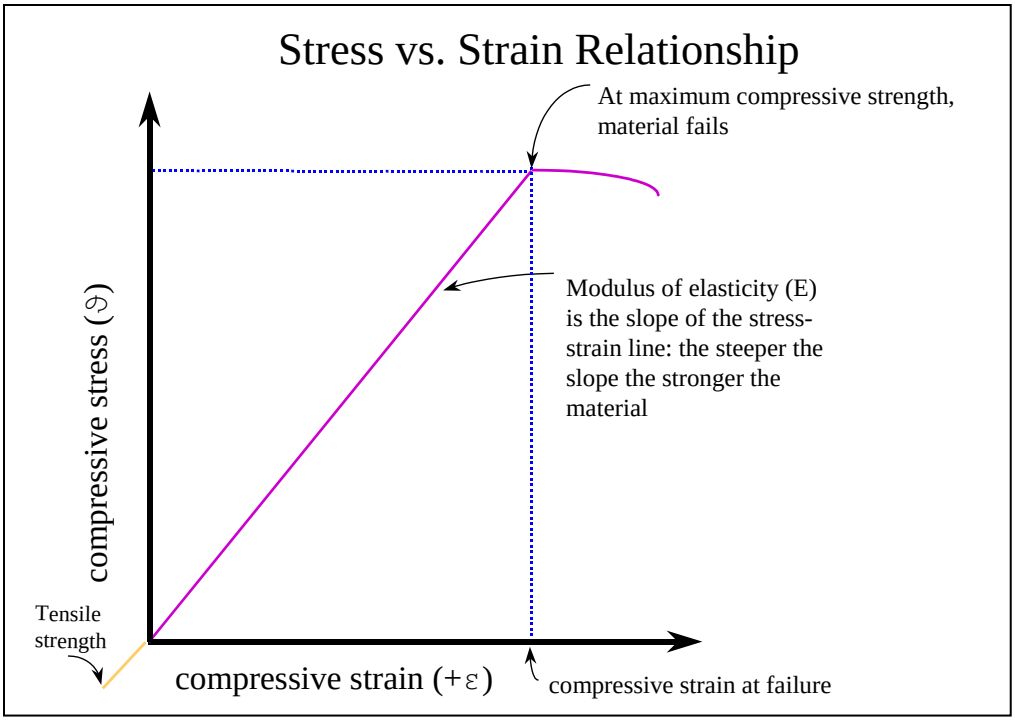
6. Soil Testing

a. The program is a tool for assembling an "educated guess" of the stability of the modeled slope. The "guess" is made "educated" by the power of the computer model. The quality of that guess depends on the quality of the data that goes into the program – "Garbage in, garbage out."

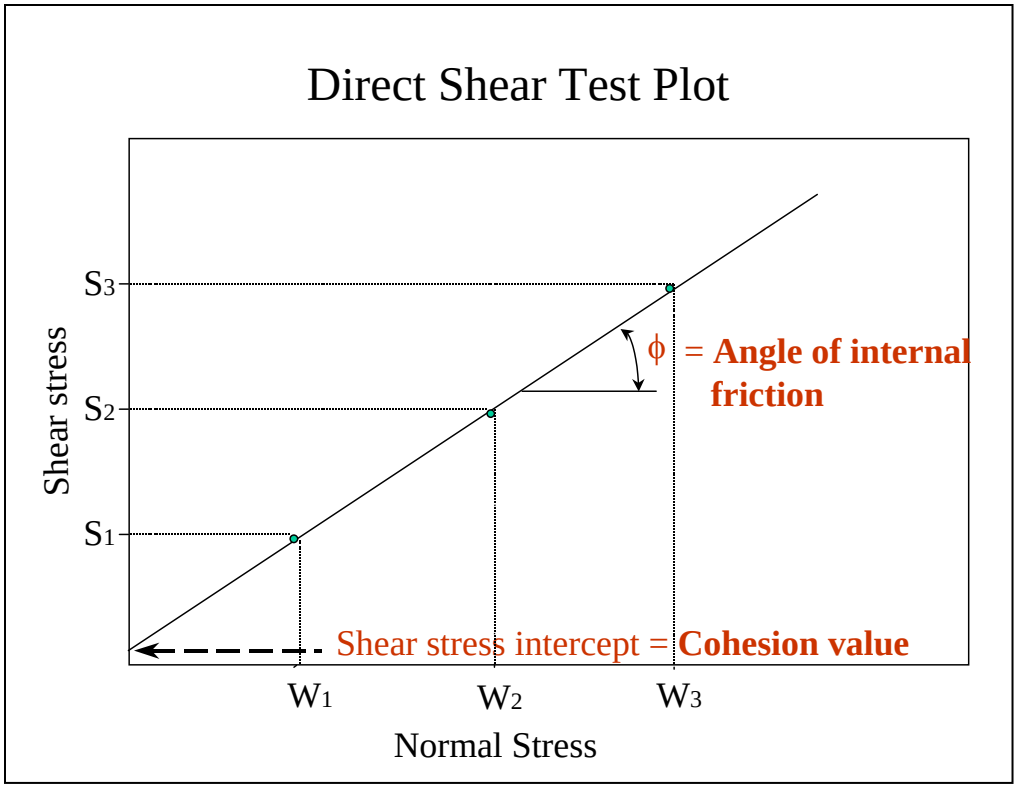
b. The data is composed of two components:
   i. Slope cross-section
   ii. Soil data

c. Soil Data
   i. Usually part of the permit application. This relies upon quality sampling by the applicant.
   ii. Field sampling methods.
      1) Drilling
      2) Electronic
      3) Trenching
      4) Pit
   iii. Ideally you want the sample as "undisturbed" as possible.
   iv. Laboratory Testing
      1) Compression Test
         a. Shear Test – Unconfined
         b. Triaxial Test





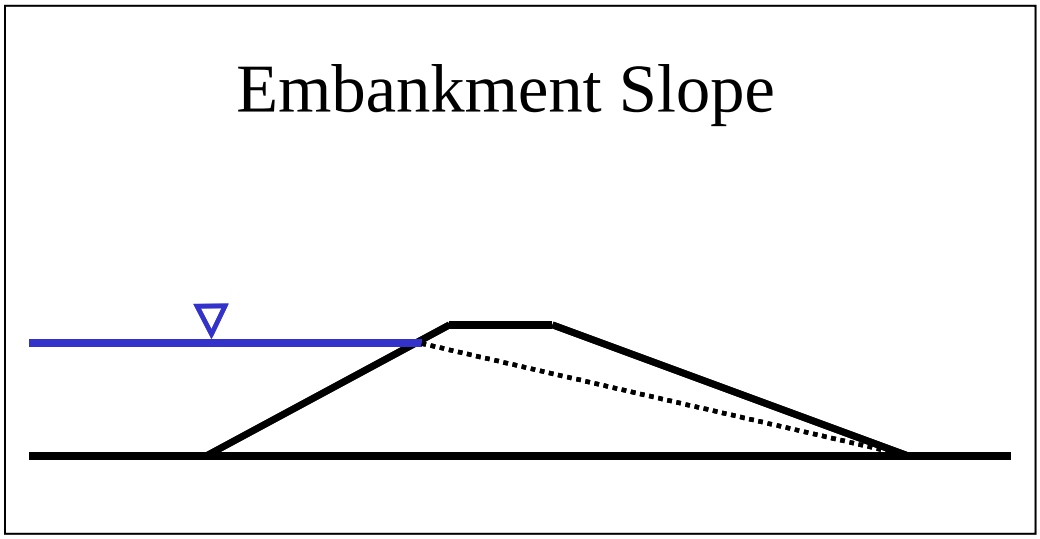
The soil values essential to Galena data input are derived from these tests. The slide below shows how the Direct Shear Test results provide values for cohesion and angle of internal friction.



v. See Appendix C, *ASTM Standards*.
vi. Video – "Engineering Slope Stability." Run time, 7 minutes.

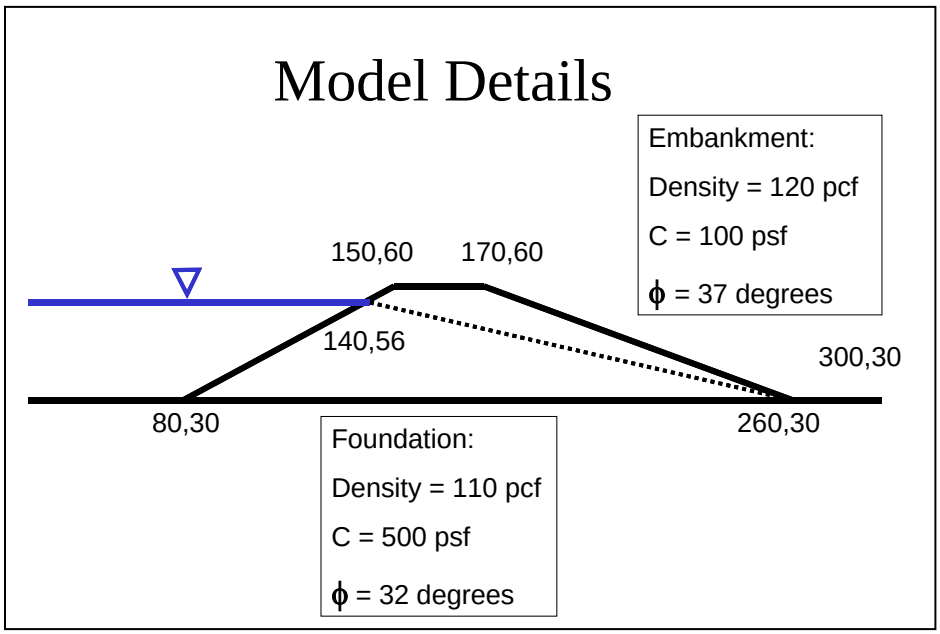
7. Using Galena

a. Class example – Embankment



b. Example details

i. Data is entered in X, Y format.



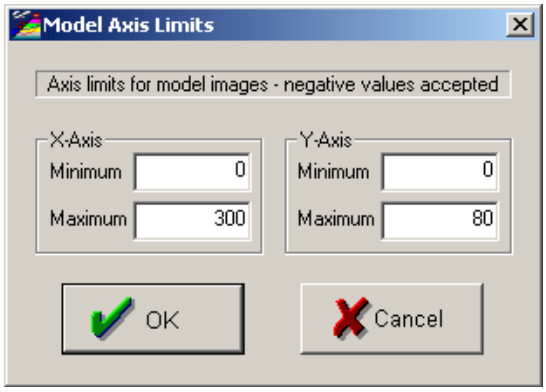
c. Start the program. Go to the "Data Definition Toolbar."

Start Galena

Begin with the Data Definition Toolbar

Then, work down the toolbar

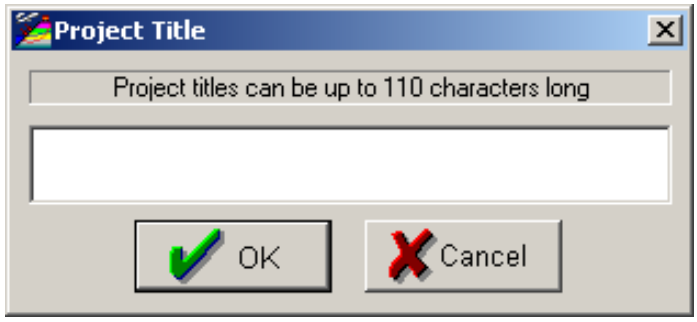
First is the "Axis Limits"



d. The **Axis limits** for this example embankment are as marked above. The program uses X and Y values to make a cross-section in the model units.

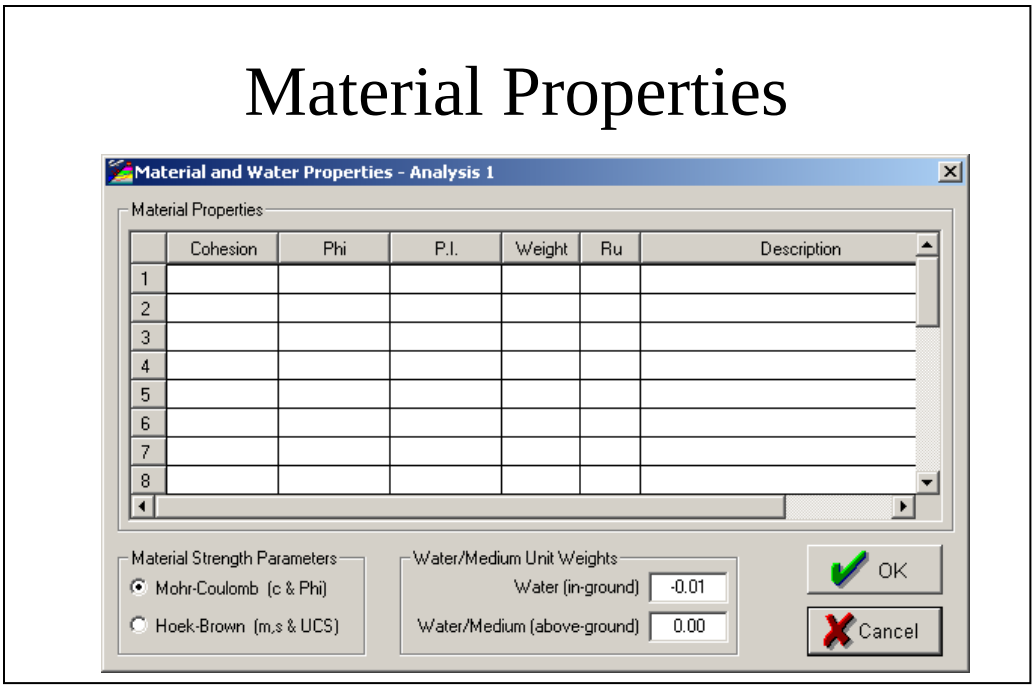
e. Working down the menu bar, the next button after Axis Limits is "**Project Title**." This title will be displayed within the Galena main window title bar, and on all printed results and images for identification. Only one Project Title can be defined for each model.

Project Title



f. Skip the "**Analysis Title**" at this point. This is an option users can use later if they wish

g. **Material Properties** – This is where the soil data is entered for each soil or rock type in the cross-section.



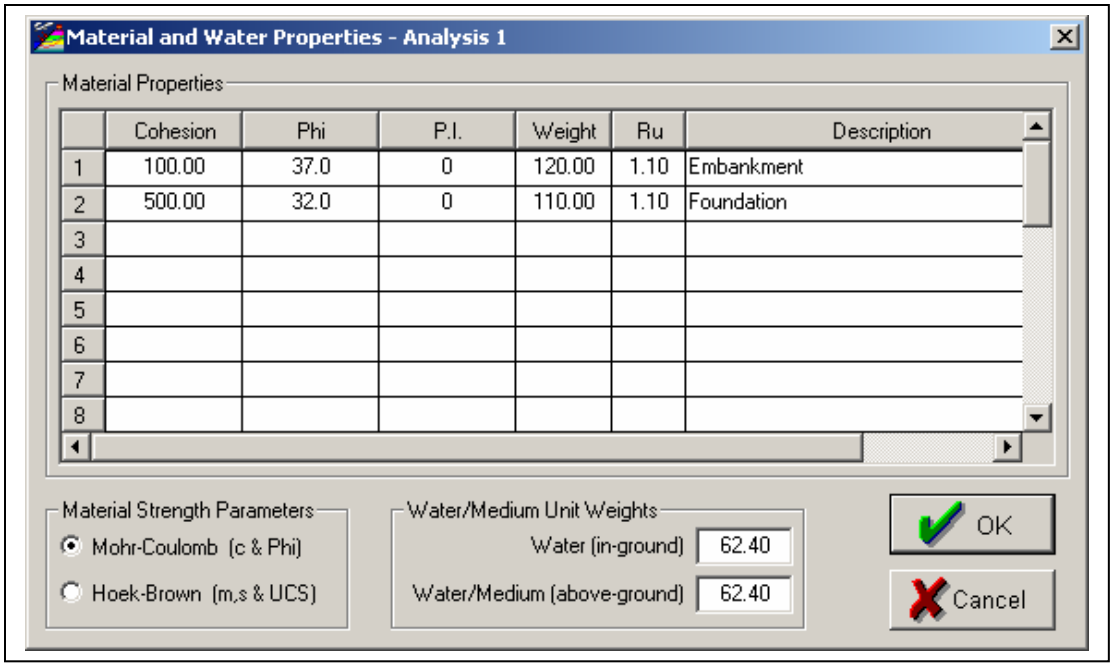
At the top of the Material and Water Properties window is a selection of the material strength parameters to be used when defining Material Properties. The choice is either Mohr-Coulomb (by default) or Hoek-Brown. **Mohr-Coulomb** parameters allow strengths to be defined in terms of cohesion, angle of internal friction (Phi), and Plasticity Index (P.I.).

Hoek-Brown parameters allow strengths to be defined in terms of m, s, and UCS, where m and s are material constants used in the Hoek-Brown failure criteria, and UCS is the material Unconfined Compressive Strength.

This window is also where the **unit weight for water** and/or other medium such as impounded slurry is set. A value in the range of 62.4 to 63 (in imperial U.S. units) would be suitable for most situations. A value for Medium (above ground) in the Water/Medium Unit Weights group must be entered where a Phreatic Surface is to be defined which will exist and extend **above** the Slope Surface as in the example case. This value could represent either water at 62.4 for a water storage dam or riverbank

situation, or a higher value such as 68.5 to represent that of a saturated slurry.

When completed for the example embankment, the Material and Water Properties window should look like this:



i. **Cohesion and Plasticity Index (PI)** – If the cohesion value is entered as a negative number the actual cohesion on the base of each slice in that material profile is computed as a function of the effective overburden pressure at the midpoint of the slice base (i.e. cohesion increases with depth as may be relevant to clays).

The absolute value of the input cohesion value is used as the cohesion intercept value at the surface. Cohesion for normally consolidated clays is calculated according to Skempton (1957) for undrained conditions (i.e. $f = 0$) as:

$$C = c_i + (0.11 + 0.0037 \times P.I.) \times \text{effective overburden pressure}$$

Where: c_i is the absolute value of the input Cohesion value for that material; P.I. is the input Plasticity Index for that material.

The Plasticity Index is only used by Galena if the cohesion is to be calculated as described above and Cohesion is input as a negative value. Otherwise, any dummy value (e.g. 0) can be input for the Plasticity Index.

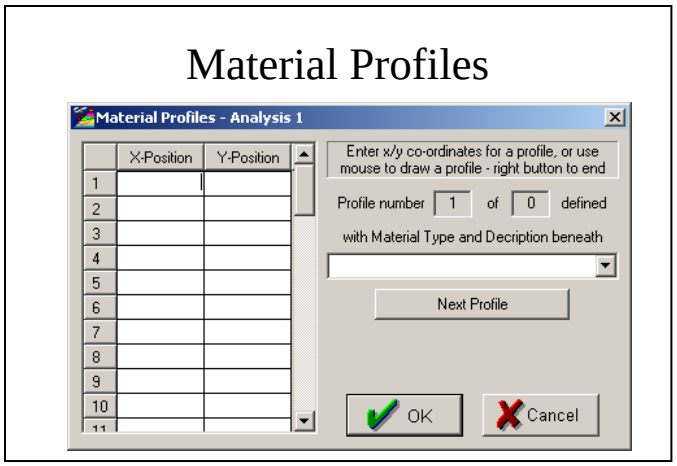
ii. **Pore Pressure (Ru)** – The value of 1.1 for the pore pressure (Ru) is used to indicate that in this model a phreatic surface applies. If the value of pore pressure ratio (Ru) is entered as 1.1 the actual value of Ru, and therefore the pore water pressure, is calculated directly from the defined phreatic surface. If any other value in the range of -0.5 to 0.5 is entered the pore water pressure is calculated directly from the Ru value entered.

h. **Material Profiles** -- Material profiles are defined as a series of lines, in turn made up of a series of x/y co-ordinate pairs. It is recommended that these profiles be defined according to the original geology or in as simple a manner as possible. For example, the easiest way to define the top material profile is as a horizontal line above the slope surface. This can be achieved by simply defining a line with two points, one at or near the extreme left and one on or near the extreme right of the drawing pane, or at the limits of the slope surface to be defined.

Note: *Only material* ***under the slope surface*** *will be considered in analyses and a material profile can have several Y coordinates for any X coordinate (i.e. it can be over-folded). This is provided there is a logical progression of material profiles from say, profile 1 into profile 2 and then back into profile 1, etc.*

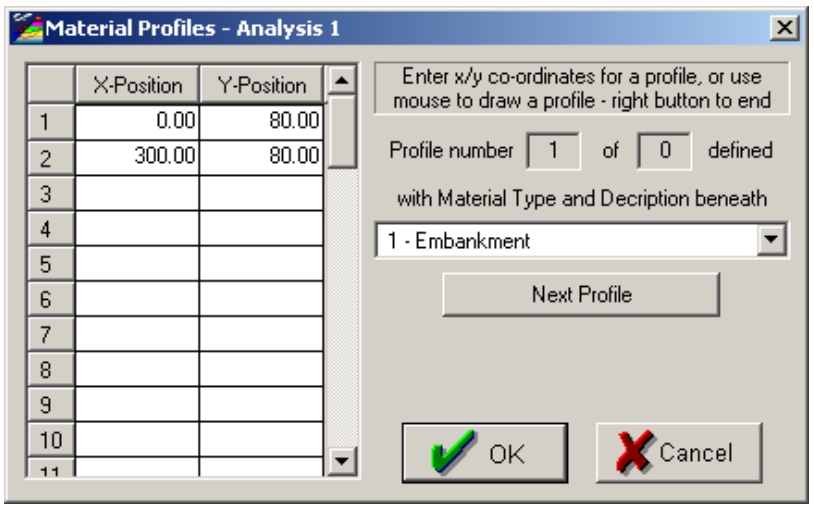
Profiles are displayed as dashed green lines unless a color is specified in the previously described "Material and Water Properties" window. Profiles are displayed on-screen with the profile number displayed and positioned at each co-ordinate point defining the profile. Only material profiles under the slope surface will be drawn when the cross-sectional result image is displayed following analysis. At least one Material Profile **must** be defined for all new models.

All profiles in Galena **can also be entered by mouse line-draw**. For this example we will use keyboard entry.



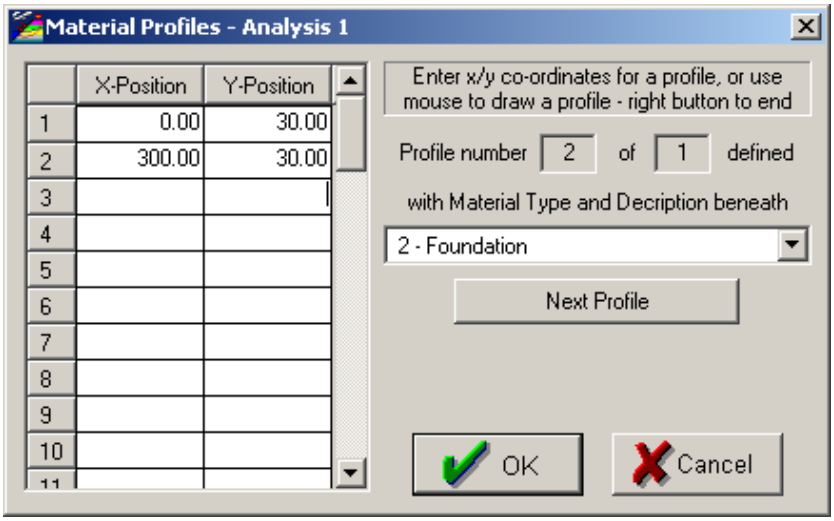
The example embankment has **two soil types**. The material profile for the example embankment should be completed as follows:

Material Profiles - Embankment

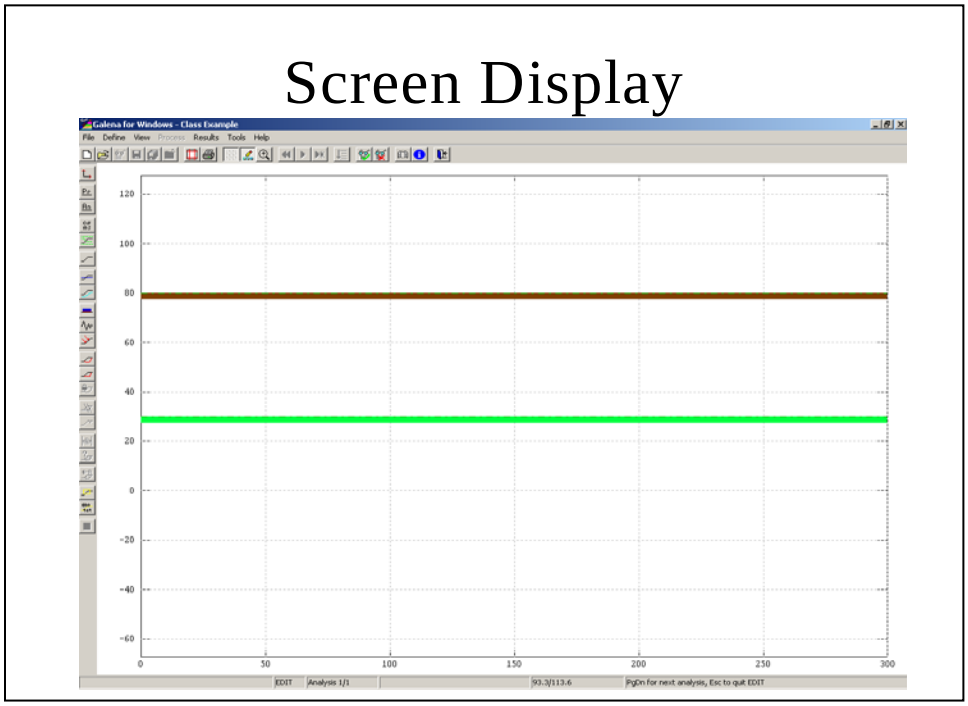


After defining the X/Y coordinates of the embankment, **press "Next Profile."** The next material is the foundation. The material profile for the foundation should be completed as follows:

Material Profiles - Foundation

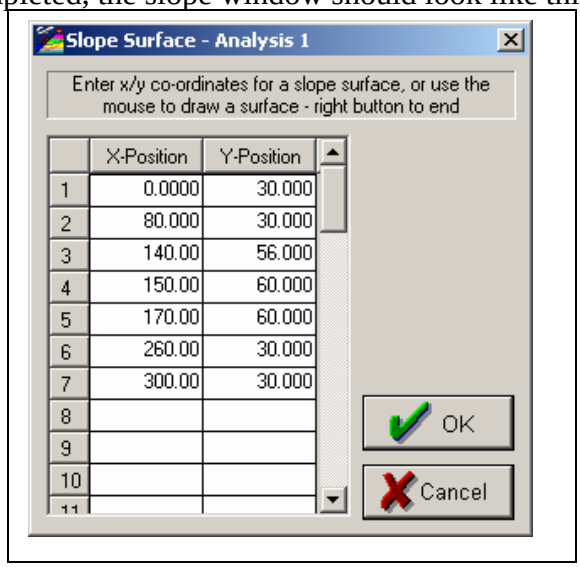


The resulting screen display should look like this (slide 35). I have selected a brown line for the embankment and a green line for the foundation. You can select these colored lines on the “Material and Water Properties” window.



i. **Slope Surface** – The slope surface, displayed as a solid black line, defines the absolute top of the slope and **all materials above this surface will be ignored.**

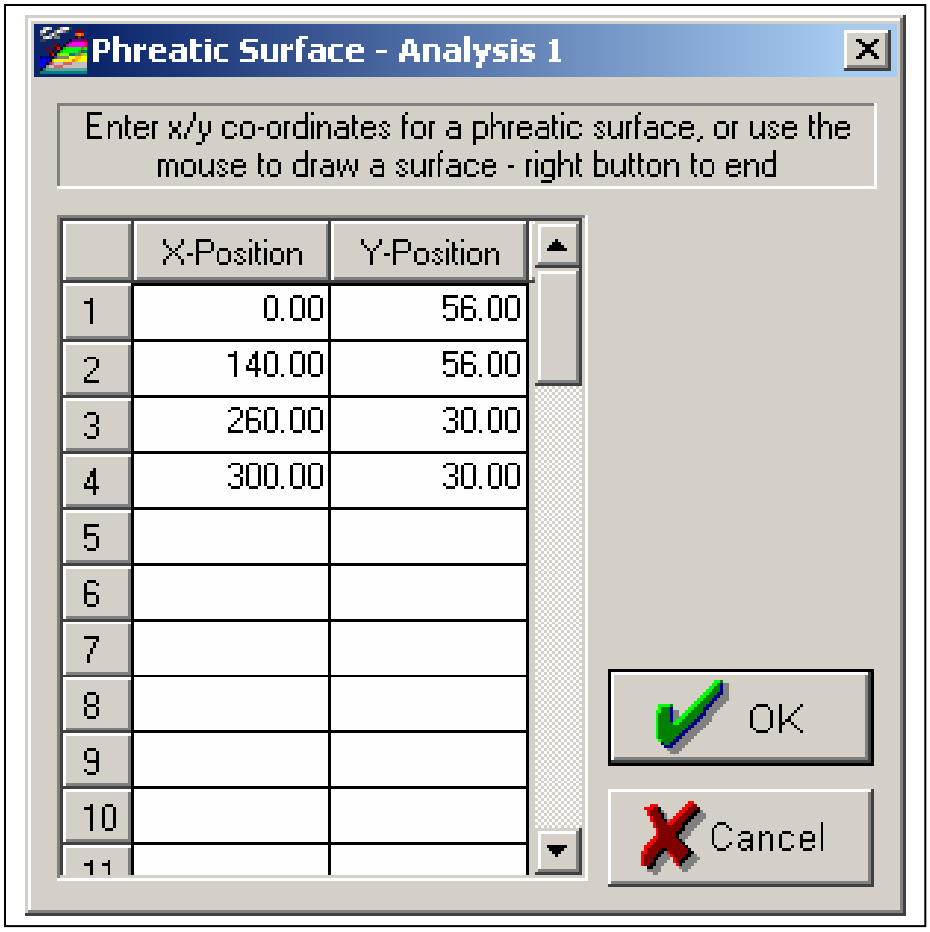
When completed, the slope window should look like this:



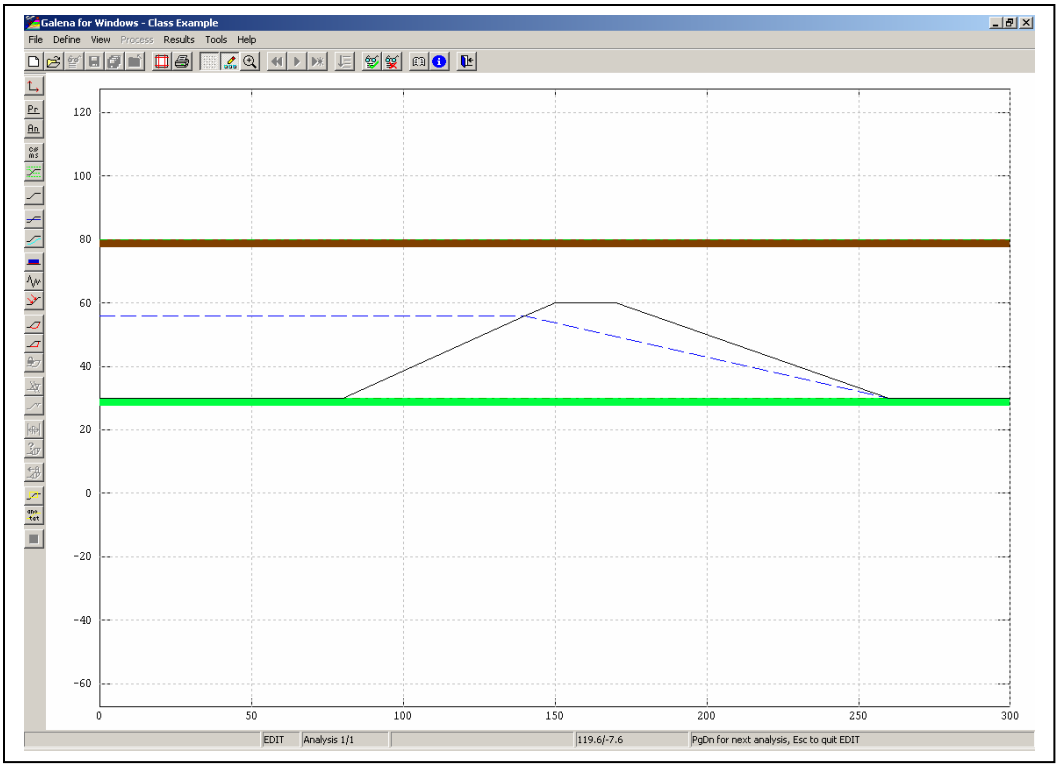
Galena will work with both right-hand rising and left-hand rising slopes, but caution should be exercised when using left-hand rising slopes. Bi-directional slopes such as dams or box cuts can be analyzed together but care should be taken when doing so. For complex models, bi-directional slopes are probably best analyzed as two separate cases. **It is recommended that slopes be input rising to the right (right-hand rising) wherever possible.**

The result of the slope surface input parameters should look like this:

j. **Phreatic Surface** – The phreatic surface indicates the water table level. All material below this level are considered saturated. The phreatic water pressure refers to the head of water below the water table level, as defined by the phreatic surface. This water pressure increases linearly with increasing depth below the phreatic surface, **and applies to all material layers below the Phreatic Surface.**



When completed the model on screen should look like this:



Note that the phreatic surface extends above, below, and congruent to the slope surface. Where it is **above the slope surface**, the water density entered in the Material and Water Properties entry under ***Medium – Above Ground*** applies, but no soil properties apply because the phreatic line is above ground representing impounded water.

Where it is **below or congruent** with the slope surface, the soil properties for Material 1 and/or 2 are used under saturated conditions. In this case, the water density entered in the Material and Water Properties entry under ***Water – In Ground*** is calculated along with the soil properties themselves.

k. **Piezometric Surfaces – This case is not used in the example problem**. However, where there are confined aquifers within a slope or dam, the applicable water pressure could differ significantly between adjacent material layers. In this situation piezometric water pressures would be applicable, and Galena enables a Piezometric Surface to be defined for one or more material layers (profiles).

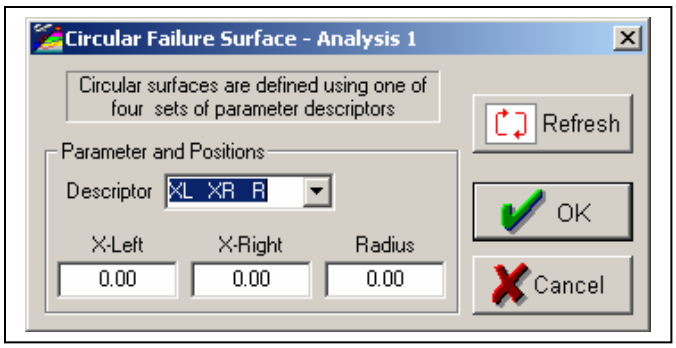
See Section 5.8 of the Galena User's Manual (**Appendix A**).

l. **Model Complete** – At this point our example is constructed and ready to analyze. The next step is to create a hypothetical failure surface at a likely location in the model.

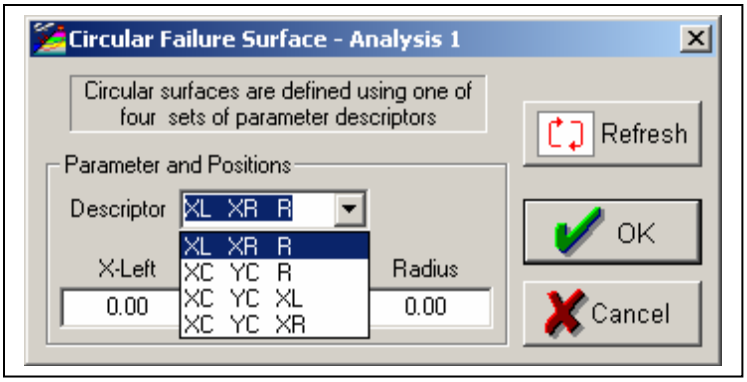
m. **Analysis Choices** – Galena offers several choices
   i. Simplified Bishop – Circular failure surfaces.
   ii. Spencer-Wright – Circular and non-circular failure surfaces.
   iii. Sarma method of non-vertical slices – Non-circular failure surfaces.
   iv. Circular or non-circular failure surface.
   v. Single or multiple analyses.

To begin our example, use Simplified Bishop, single analysis.

Go to "Define Circular Failure Surface."

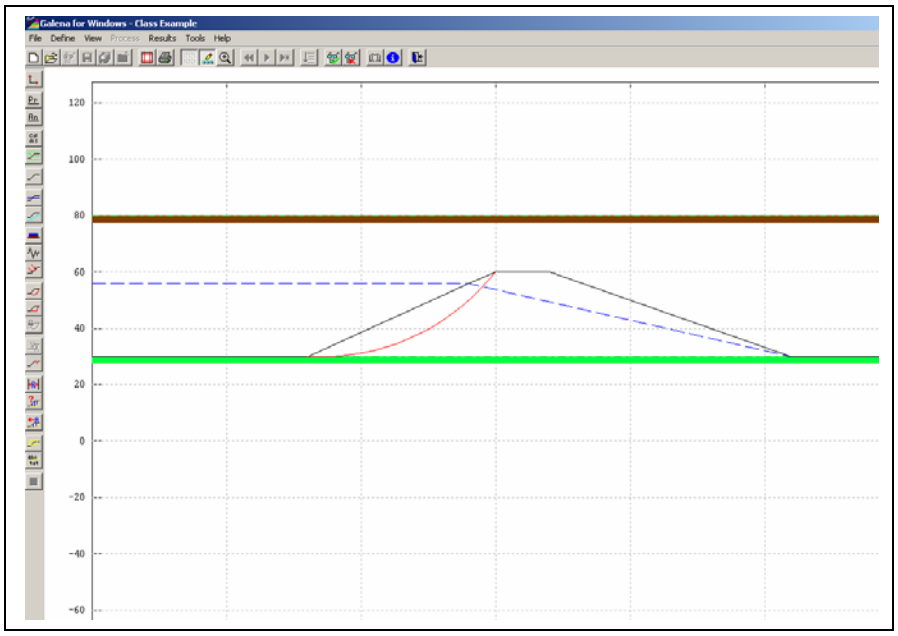


Note the "Descriptor" choices:
(i) **XL XR R** (X-Left, X-Right, Radius)
The left and right *slope surface X co-ordinate intercepts* with the circle is specified, together with a circle radius.
(ii) **XC YC R** (X-Center, Y-Center, Radius)
Circle center x/y co-ordinates are defined together with a circle radius.
(iii) **XC YC XL** (X-Center, Y-Center, X-Left)
Circle center x/y co-ordinates are defined together with the circle's *left slope surface X co-ordinate intercept.*
(iv) **XC YC XR** (X-Center, Y-Center, X-Right)
Circle center x/y co-ordinates are defined together with the circle's *right slope surface X co-ordinate intercep*t.

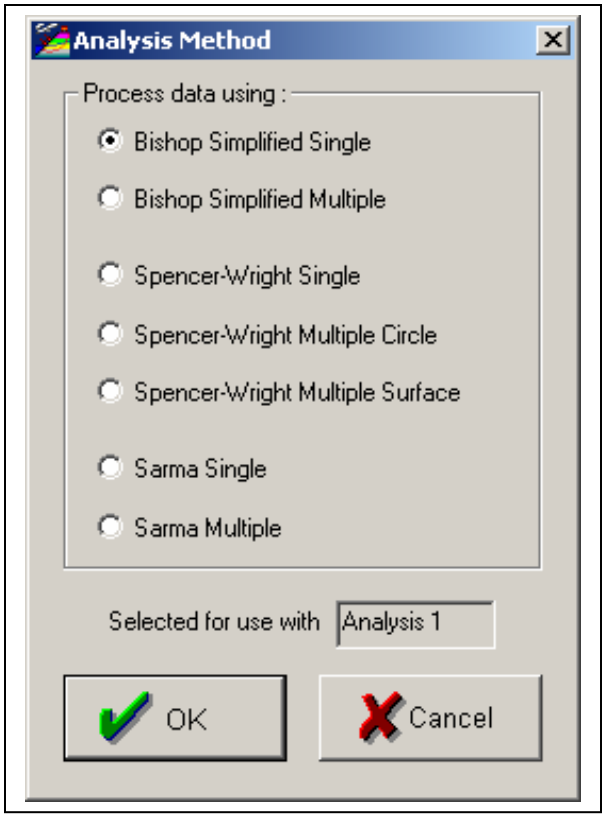


Use XL XR R for the sample case.

Experiment with the values until you get a circle that is your best guess – by using the “Update Display” button.



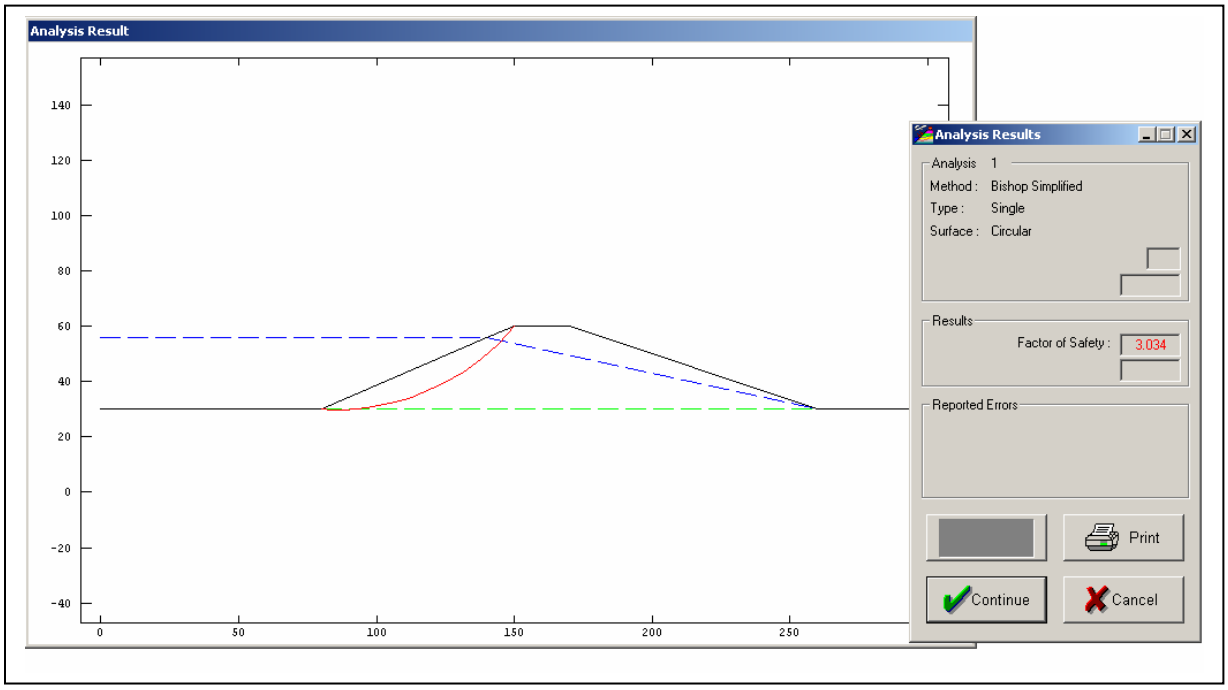
n. Select Analysis Method.



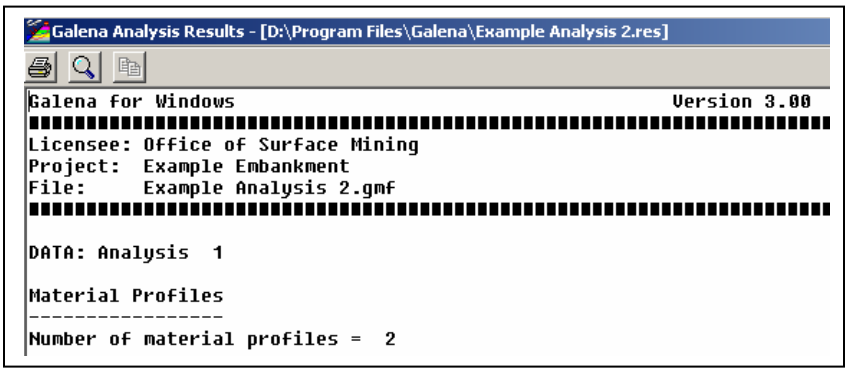
o. Select "Model Definition Complete." – The 'Complete' function in Galena serves three purposes:

- **i.** Signal the end of model definition.
- **ii.** Trigger Galena's file save function
- **iii.** Delete subsequent definitions.

p. Select "Process Model Data." Runs program calculations and generates a completed graphic with Factor of Safety.



q. Select "View Analysis Results." The results header contains the project title, the model file name and the date and time of processing. Detailed information is included for each analysis undertaken including the model parameters, results and slice information for the failure mass.



8. Additional Analyses

a. Additional analyses may be done to test the slope under different circumstances such as:
   i. With distributed loads.
   ii. Seismic case.
   iii. Multiple failure surface analyses.
   iv. Change of analysis method.
   v. Back Analysis -- Back analysis answers the question of, "What strength is required?" rather than "What is the stability?" of a given slope.

b. **Begin Additional Analyses.** To begin another analysis, use the "**Insert a New Analysis"** button.
Note that the Analysis Number at the bottom of the Galena screen will cycle to the next analysis number.

c. Distributed Loads. When selected this option will display a dialog allowing input of left and right endpoints as X co-ordinates, and pressures at each endpoint respectively. The relevant analysis number is also displayed within the dialog.

d. Multiple Analysis. Multiple analysis allows you to check many failure surfaces around an initial failure surface that represents your best guess as to where failure will occur. Analyzing several failure surfaces around your initial surface insures that you find the lowest factor of safety for your case model.

   i. Multiple Analysis Restraints <u>must</u> be set when using the multiple analysis option. Restraints are meant to keep the program from generating impossible surfaces. Such as:
      1) Surfaces extending beyond the defined horizontal range, either of the slope or the material profiles.
      2) Surfaces passing above ground level. This is most commonly caused by benches and berms, toe drains, too short radii when XC, YC, R is defined, or too great a mid-point range in non-circular analyses.
      3) Convex angles or unrealistically tight angles in non-circular surfaces. Galena will still attempt to analyze such surfaces, but will give an appropriate warning, and may fail to achieve a result.

ii. How to Set Multiple Analysis Restraints.

1) In the 'Multi-Analysis Restraints' window there are two rows of data that must be completed. The top row represents the **trial ranges** that you would like the program to test for failure surfaces around each of your 'X-Left,' 'X-Right,' or 'Radius' values of your initial failure surface.

For example, if you enter 20 for the X-Left value Galena will test circles 20 units apart centered on the X-Left value of your original failure surface. That means 10 units to the left and 10 units to the right of the original X-Left value. If your original failure surface had values of X-left = 80, X-Right = 150, and Radius = 85 as in our sample model, a value of 20 in the X-Left trial range box for Multi-Analysis Restraints would test circles with X-Left values ranging from 70 to 90. These values are 10 units to either side of the original X-Left value of 80 from the example.

2) The second row in the Multiple Analysis Restraints window is the **trial positions.** This is the number of failure circles to be tried within the range specified above. Continuing the example above, if the trial positions value is set to 5 then five failure circles would be tried within the full range of 20 feet around the original X-Left value of 80 – Circle trials would be at 70, 75, 80, 85 and 90.

Note: Galena *will always analyze the defined failure surface around which the restraints apply (specified by the Define-Failure Surface option). If any of the three trial position values are* ***even*** *numbers* Galena *will automatically add an extra analysis to ensure the defined failure surface is analyzed.*

iii. Restraint Values in the Example

1) The X-Right and Radius **trial range** values are set to 50 to test 25 feet to either side of the original circle intersect values. The X-Left value is set to 0 to test the **original failure value only**. Since this is the point where the circle passes through the toe of the slope, it is the most likely failure location.

2) The X-Right and Radius **trial position** values are set to 21 to test 10 different circles on either side of the original X-Right and Radius values plus the original failure surface

(10 + 10 + 1 = 21). The X-Left value is set to 1 to test the original failure circle X-Left intercept only. Again, this is to restrict the failure circle trials to the toe of the slope.

e. **Seismic Case.** Earthquake loading can be simulated using a pseudo-static approach where an earthquake seismic coefficient is defined to generate a de-stabilizing horizontal force "g" times the weight of the assumed failure mass, where g is the earthquake seismic coefficient. The seismic coefficient is obtained from the Algermissen, et al map of the United States in **Appendix B**.

9. Spencer-Wright Analysis

a. To perform a Spencer analysis, simply change the analysis method to Spencer and try both single and multiple analyses.

b. Time permitting, open some of the example cases that come with Galena and try them with different analyses.

   In particular, try the Example06.gmf Spencer example.

10. Sarma Analysis.

Try the Example05.gmf Sarma example for a highwall analysis.

11. Back Analysis

a. A back analysis is a method for determining the soil engineering values that are required to meet a specified factor of safety. It is a way to work backward through a slope problem.

b. Begin by selecting "Insert a New Analysis" (Define/New Analysis)

c. Select the "Define BackAnalysis Parameters and Method" button (or Define/BackAnalysis on the pull-down menu)

d. Select the material you wish to analyze (Material 1 or 2 in the sample case).

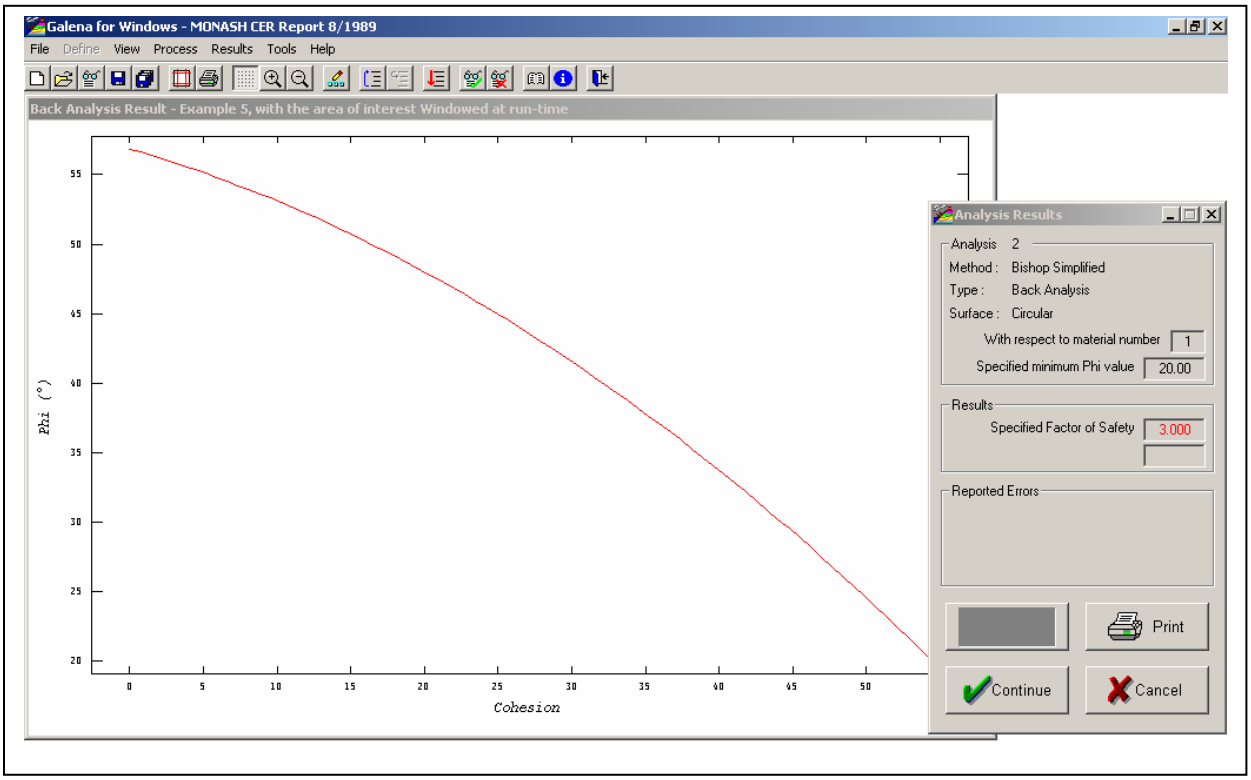
e. Set a minimum phi value to consider. The result will cover many phi values, this screen asks for only the <u>minimum</u> value you wish to consider.

f. Set the Factor of Safety you wish to evaluate.

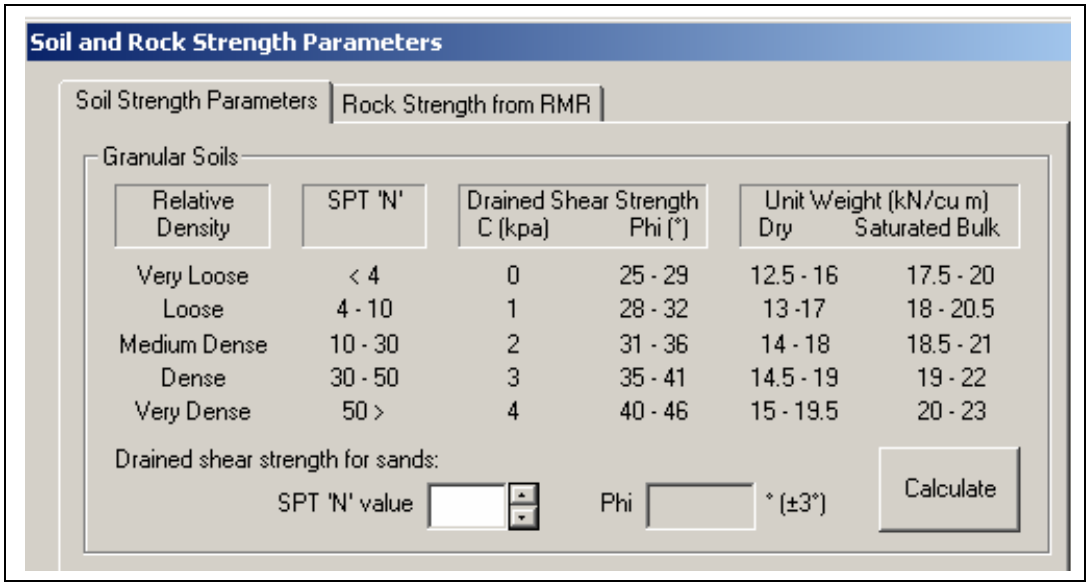
g. Select the Bishop, Spencer, or Sarma analysis method.

h. Choose single or multiple analysis method and press the OK button.

i. The result of the analysis is a chart with a curve showing the resultant values of cohesion vs phi angle for the slope, material, and Factor of Safety specified.



12. Note the Soil and Rock Strengths tables under the "Tools" pulldown in the Galena menu. Values are <u>metric</u>.

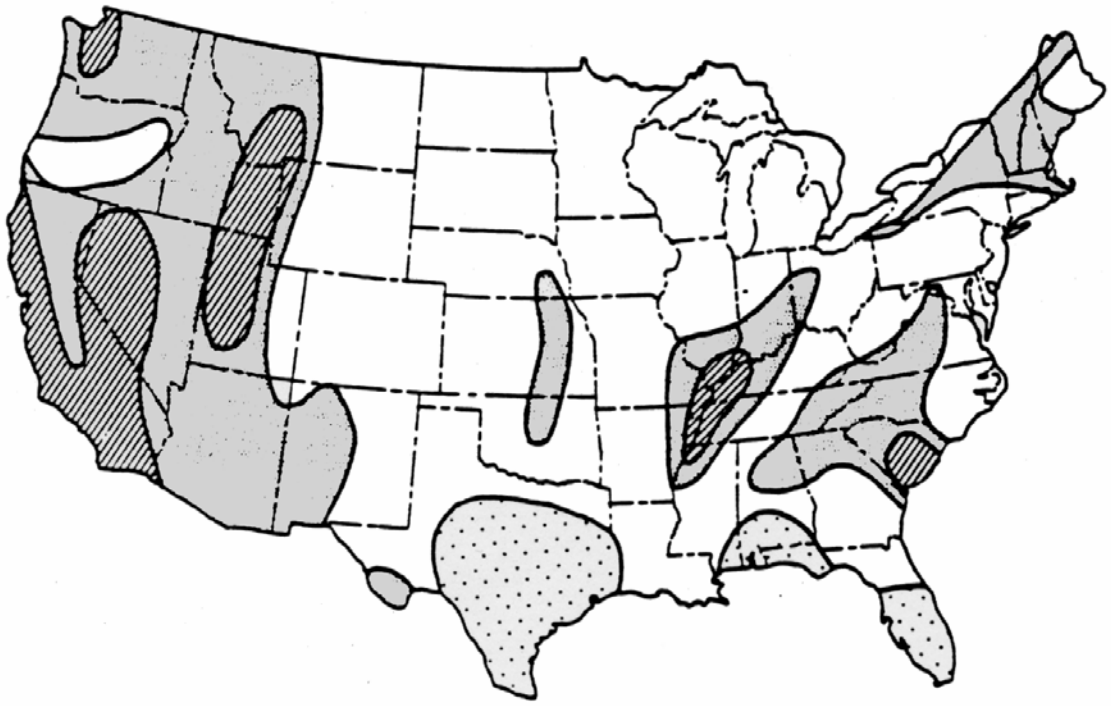


Relative Density	SPT 'N'	Drained Shear Strength C (kpa)	Drained Shear Strength Phi (°)	Unit Weight (kN/cu m) Dry	Unit Weight (kN/cu m) Saturated Bulk
Very Loose	< 4	0	25 - 29	12.5 - 16	17.5 - 20
Loose	4 - 10	1	28 - 32	13 -17	18 - 20.5
Medium Dense	10 - 30	2	31 - 36	14 - 18	18.5 - 21
Dense	30 - 50	3	35 - 41	14.5 - 19	19 - 22
Very Dense	50 >	4	40 - 46	15 - 19.5	20 - 23

Appendix A
Galena User's Guide

Appendix B

Seismic Coefficient Values



ZONE 0 - NO DAMAGE (K ≈ 0)

ZONE 1 - MINOR DAMAGE (K ≈ 0.025)

ZONE 2 - MODERATE DAMAGE (K ≈ 0.05)

ZONE 3 - MAJOR DAMAGE (K ≈ 0.10 TO 0.15)

ZONES OF PROBABLE SEISMIC INTENSITY
UNITED STATES (after ALGERMISSEN)