Slide

2D limit equilibrium slope stability
for soil and rock slopes

User's Guide

Part 2

Table of Contents

Introduction

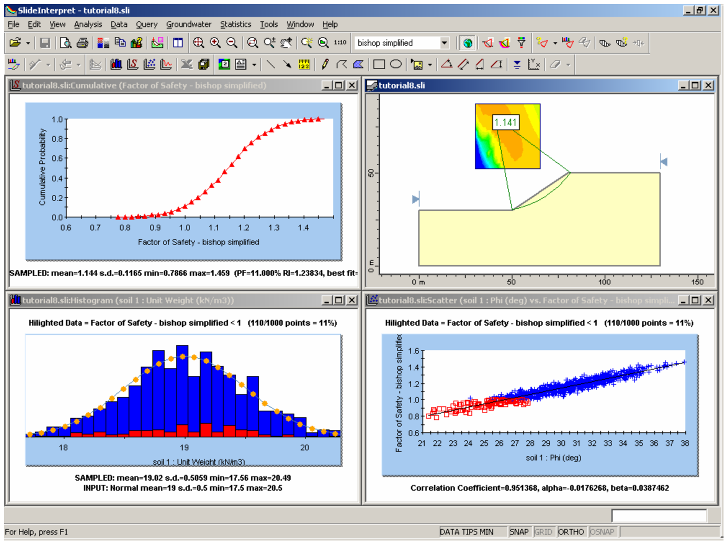
The SLIDE User's Guide – Part 2 contains tutorials which illustrate the Probabilistic Analysis capabilities of SLIDE. The following topics are covered.

FILES	DESCRIPTION
Tutorial 8.sli	**Probabilistic Analysis** – this tutorial will get the user familiar with the basic probabilistic modeling and data interpretation features of SLIDE.
Tutorial 9.sli	**Sensitivity Analysis** – a demonstration of Sensitivity Analysis with SLIDE.
Tutorial 10.sli	**Water Table Statistics** – how to include a Water Table in a probabilistic or sensitivity analysis.
Tutorial 11.sli	**Overall Slope Reliability** – a demonstration of the Overall Slope probabilistic analysis option in SLIDE.

The tutorial files can be found in the EXAMPLES folder in your SLIDE installation folder.

For information on any SLIDE options which are not covered in the SLIDE tutorials, consult the SLIDE Help system.

Probabilistic Analysis



This tutorial will familiarize the user with the basic probabilistic analysis capabilities of SLIDE. It will demonstrate how quickly and easily a probabilistic slope stability analysis can be performed with SLIDE.

<u>MODEL FEATURES:</u>

- homogeneous, single material slope
- no water pressure (dry)
- circular slip surface search (Grid Search)
- random variables: cohesion, phi and unit weight
- type of probabilistic analysis: Global Minimum

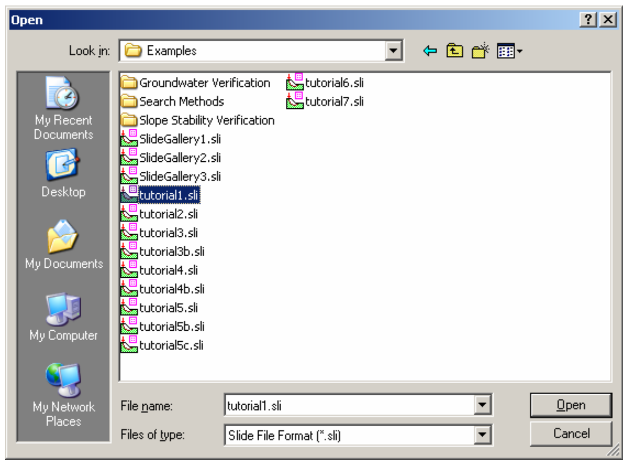
NOTE: the finished product of this tutorial can be found in the **tutorial8.sli** data file, which you should find in the EXAMPLES folder in your SLIDE installation folder.

Model

This tutorial will be based on the same model used for Tutorial 1, so let's first read in the Tutorial 1 file.

Select: File → Open

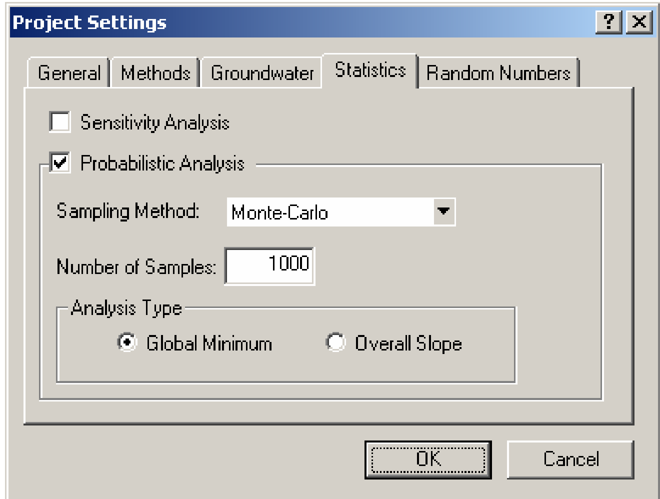
Navigate to the EXAMPLES folder in your SLIDE installation folder, and open the **tutorial1.sli** file.



Project Settings

To carry out a Probabilistic Analysis with SLIDE, the first thing that must be done, is to select the Probabilistic Analysis option in the Project Settings dialog.

Select: Analysis → Project Settings



In the Project Settings dialog, select the Statistics tab, and select the Probabilistic Analysis checkbox. Select OK.

Global Minimum Analysis

Note that we are using the default Probabilistic Analysis options:

- Sampling Method = Monte Carlo
- Number of Samples = 1000
- Analysis Type = Global Minimum

When the Analysis Type = Global Minimum, this means that the Probabilistic Analysis is carried out on the Global Minimum slip surface located by the regular (deterministic) slope stability analysis.

The safety factor will be re-computed N times (where N = Number of Samples) for the Global Minimum slip surface, using a different set of randomly generated input variables, for each analysis.

Notice that a Statistics menu is now available, which allows you to define almost any model input parameter, as a random variable.

Defining Random Variables

In order to carry out a Probabilistic Analysis, at least one of your model input parameters must be defined as a Random Variable. Random variables are defined using the options in the Statistics menu.

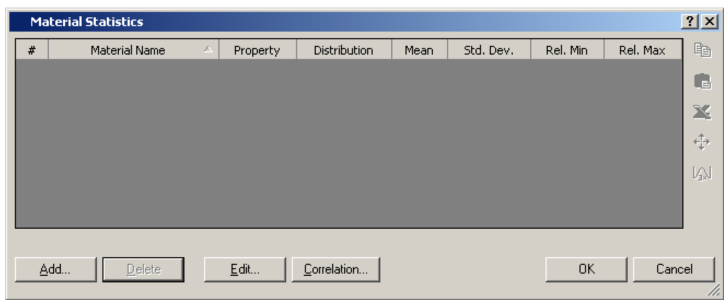
For this tutorial, we will define the following material properties as Random Variables:

- Cohesion
- Friction Angle
- Unit Weight

This is easily done with the Material Statistics dialog.

Select: Statistics → Materials

You will see the Material Statistics dialog.

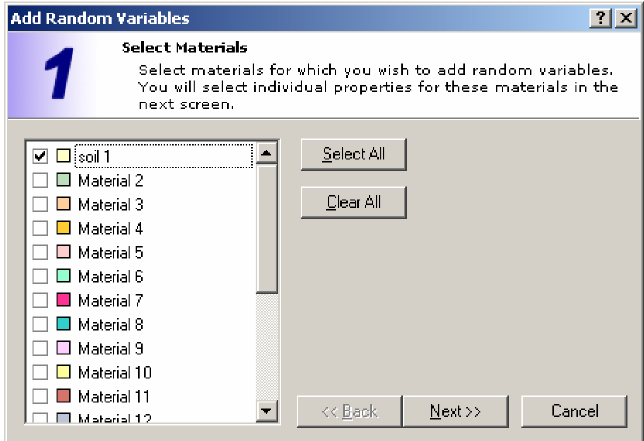


First, you must select the Random Variables that you wish to use. This can be done with either the Add or the Edit options, in the Material Statistics dialog. Let's use the Add option.

Select the Add button in the Material Statistics dialog.

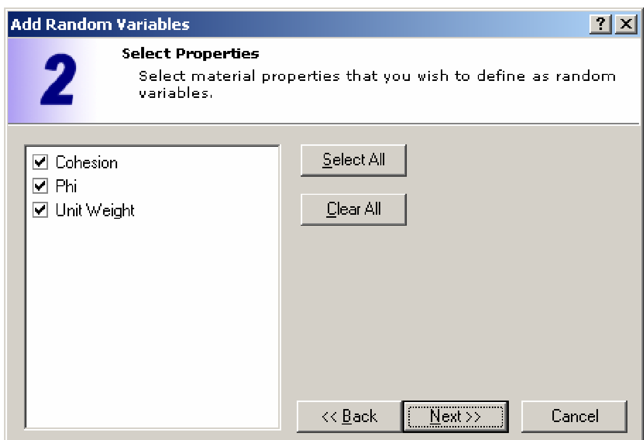
When using the Add option, you will see a series of three dialogs, in a "wizard" format, which allow you to quickly select the material properties that you wish to define as Random Variables.

The first dialog allows you to select the materials.



Select the checkbox for the "soil 1" material (our slope model only uses this one material type). Select the Next button.

The second dialog allows you to select the material properties that you would like to define as Random Variables.

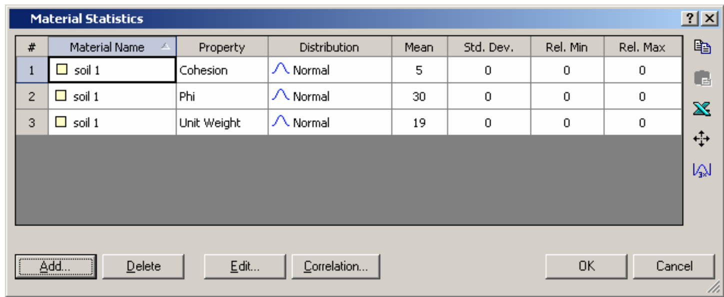


Select the checkboxes for Cohesion, Phi and Unit Weight. Select the Next button.

The final dialog allows you to select a Statistical Distribution for the Random Variables.

We will be using the default (Normal Distribution), so just select the Finish button.

You will be returned to the Material Statistics dialog, which should now appear as follows:



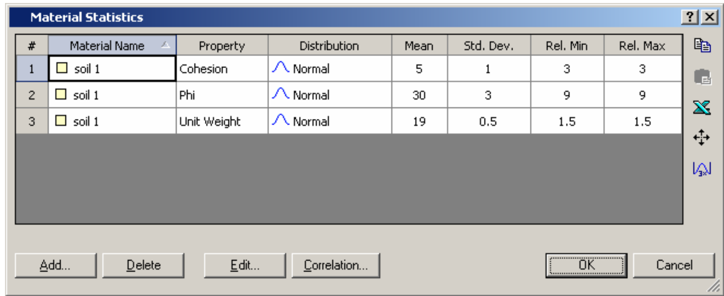
In the Material Statistics dialog, the material properties which you selected as Random Variables, now appear in the dialog in a spreadsheet format. This allows you to easily define the statistical distribution for each random variable.

In order to complete the process of defining the Random Variables, we must enter:

- the Standard Deviation, and
- Minimum and Maximum values

for each variable, in order to define the statistical distribution of each random variable.

Enter the values of Standard Deviation, Relative Minimum and Relative Maximum for each variable, as shown below. When you are finished, select OK.



NOTE:

- The Minimum and Maximum values are specified as RELATIVE values (ie. distances from the MEAN value), rather than as absolute values, because this simplifies data input.

- For a NORMAL distribution, 99.7 % of all samples should fall within 3 standard deviations of the mean value. Therefore it is recommended that the Relative Minimum and Relative Maximum values are equal to at least 3 times the standard deviation, to ensure that a complete (non-truncated) NORMAL distribution is defined.

- For more information about Statistical Distributions, please see the Probabilistic Analysis section of the SLIDE Help system.

That's all we need to do. We have defined 3 Random Variables (cohesion, friction angle and unit weight) with Normal distributions.

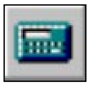
We can now run the Probabilistic Analysis.

Compute

First, let's save the file with a new file name: **prob1.sli**.

Select: File → Save As

Use the Save As dialog to save the file. Now select Compute.



Select: Analysis → Compute

NOTE:

- When you run a Probabilistic Analysis with SLIDE, the regular (deterministic) analysis is always computed first.
- The Probabilistic Analysis automatically follows. The progress of the analysis is indicated in the Compute dialog.

Interpret

To view the results of the analysis:

Select: Analysis → Interpret

This will start the SLIDE INTERPRET program. You should see the following figure.

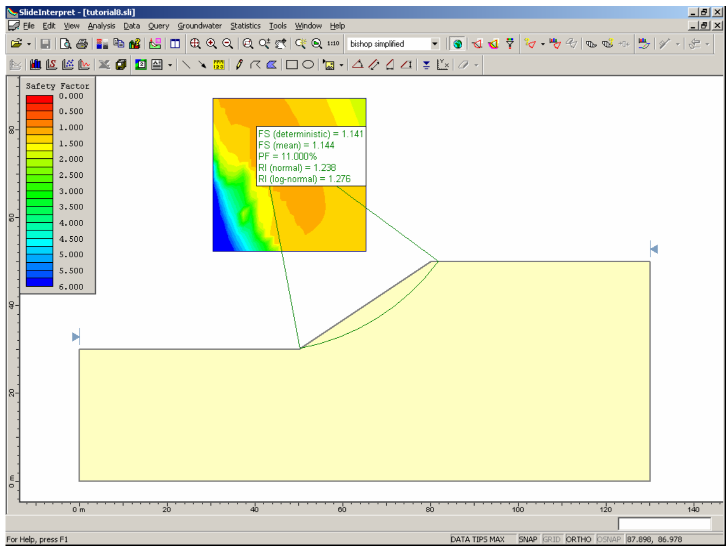


Figure 1-1: Results after probabilistic analysis.

The primary results of the probabilistic analysis, are displayed beside the slip center of the deterministic global minimum slip surface. Remember that when the Probabilistic Analysis Type = Global Minimum, the Probabilistic Analysis is only carried out on this surface.

This includes the following:

- FS (mean) – the mean safety factor
- PF – the probability of failure
- RI – the Reliability Index

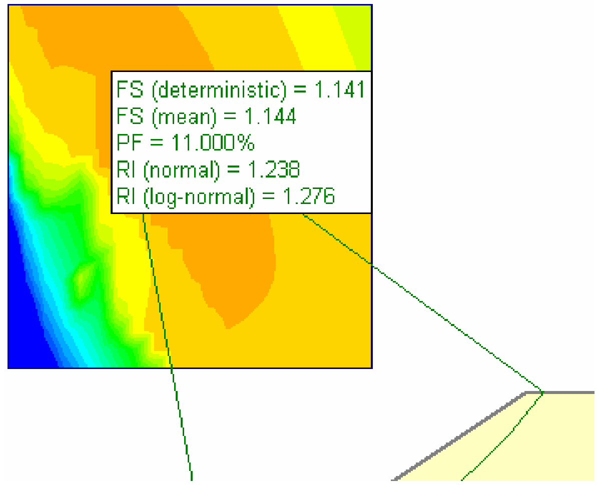


Figure 1-2: Summary of results after probabilistic analysis.

These results are discussed below.

Deterministic Safety Factor

The Deterministic Safety Factor, FS (deterministic), is the safety factor calculated for the Global Minimum slip surface, from the regular (non-probabilistic) slope stability analysis.

This is the same safety factor that you would see if you were only running a regular (deterministic) analysis, and were NOT running a Probabilistic Analysis.

The Deterministic Safety Factor is the value of safety factor when all input parameters are exactly equal to their mean values.

Mean Safety Factor

The Mean Safety Factor is the mean (average) safety factor, obtained from the Probabilistic Analysis. It is simply the average safety factor, of all of the safety factors calculated for the Global Minimum slip surface.

In general, the Mean Safety Factor should be close to the value of the deterministic safety factor, FS (deterministic). For a sufficiently large number of samples, the two values should be nearly equal.

Probability of Failure

The Probability of Failure is simply equal to the number of analyses with safety factor less than 1, divided by the total Number of Samples.

$$PF = \frac{numfailed}{numsamples} \times 100\% \qquad \text{Eqn. 1}$$

For this example, PF = 11%, which means that 110 out of 1000 samples, produced a safety factor less than 1.

Reliability Index

The Reliability Index is another commonly used measure of slope stability, after a probabilistic analysis.

The Reliability Index is an indication of the *number of standard deviations* which separate the Mean Safety Factor from the critical safety factor (= 1).

The Reliability Index can be calculated assuming either a Normal or Lognormal distribution of the safety factor results. The actual best fit distribution is listed in the Info Viewer, and indicates which value of RI is more appropriate for the data.

RI (Normal)

If it is assumed that the safety factors are Normally distributed, then Equation 2 is used to calculate the Reliability Index.

$$\beta = \frac{\mu_{FS} - 1}{\sigma_{FS}} \qquad \text{Eqn. 2}$$

where:

β = reliability index

μ_{FS} = mean safety factor

σ_{FS} = standard deviation of safety factor

A Reliability Index of at least 3 is usually recommended, as a minimal assurance of a safe slope design. For this example, RI = 1.238, which indicates an unsatisfactory level of safety for the slope.

RI (Lognormal)

If it is assumed that the safety factors are best fit by a Lognormal distribution, then Equation 3 is used to calculate the Reliability Index.

$$\beta_{LN} = \frac{\ln\left[\frac{\mu}{\sqrt{1+V^2}}\right]}{\sqrt{\ln(1+V^2)}} \qquad \text{Eqn. 3}$$

where μ = the mean safety factor, and V = coefficient of variation of the safety factor (= σ / μ).

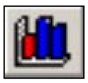
For more information about the Reliability Index, see the SLIDE Help system.

Histogram Plots

Histogram plots allow you to view:

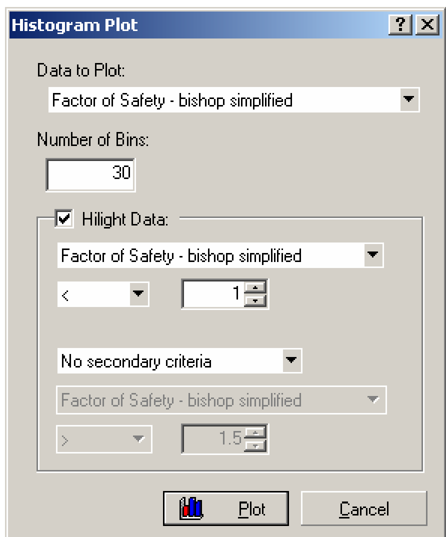
- The distribution of samples generated for the input data random variable(s).
- The distribution of safety factors calculated by the probabilistic analysis.

To generate a Histogram plot, select the Histogram Plot option from the toolbar or the Statistics menu.



Select: Statistics → Histogram Plot

You will see the Histogram Plot dialog.



Let's first view a histogram of Safety Factor. *Set the Data to Plot = Factor of Safety – Bishop Simplified. Select the Highlight Data checkbox. As the highlight criterion, select "Factor of Safety – Bishop Simplified < 1". Select the Plot button, and the Histogram will be generated.*

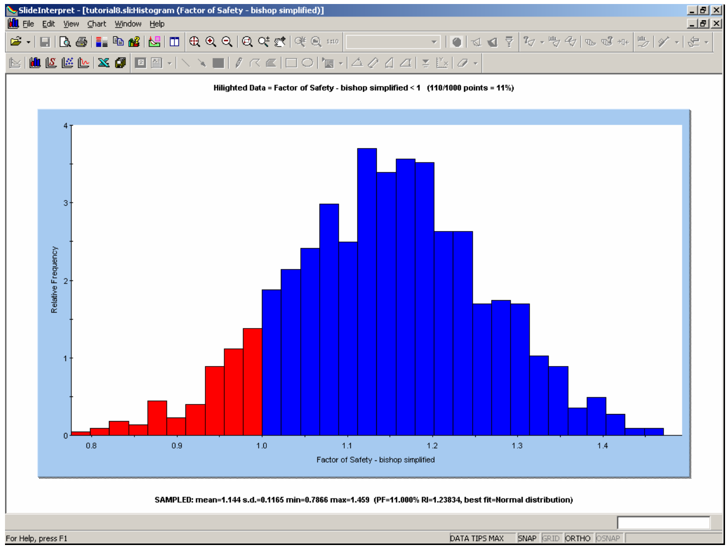


Figure 1-3: Histogram of Safety Factor.

As you can see on the histogram, the highlighted data (red bars) shows the analyses which resulted in a safety factor less than 1.

- This graphically illustrates the Probability of Failure, which is equal to the area of the histogram which is highlighted (FS < 1), divided by the total area of the histogram.

- The statistics of the highlighted data are always listed at the top of the plot. In this case, it is indicated that 110 / 1000 points, have a safety factor less than 1. This equals 11%, which is the PROBABILITY OF FAILURE (for the Bishop analysis method).

In general, the Highlight data option allows you to highlight any user-defined subset of data on a histogram (or scatter plot), and obtain the statistics of the highlighted (selected) data subset.

You can display the Best Fit distribution for the safety factor data, by right-clicking on the plot, and selecting Best Fit Distribution from the popup menu. The Best Fit Distribution will be displayed on the Histogram. In this case, the best fit is a Normal Distribution, as listed at the bottom of the plot.

Let's create a plot of the Cohesion random variable. Right-click on the plot and select Change Plot Data. *Set the Data to Plot = soil 1 : Cohesion. Select Done.*

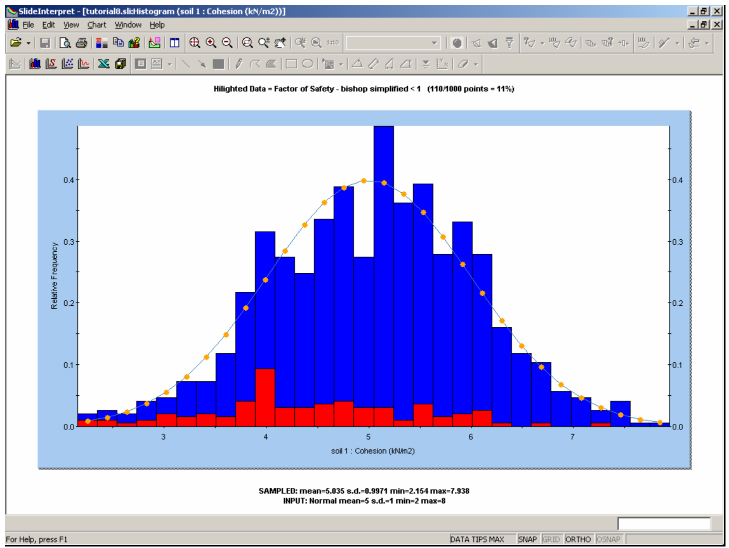


Figure 1-4: Histogram Plot of Cohesion.

This plot shows the actual random samples which were generated by the Monte Carlo sampling of the statistical distribution which you defined for the Cohesion random variable. Notice that the data with Bishop Safety Factor < 1 is still highlighted on the plot.

Note the following information at the bottom of the plot:

- The SAMPLED statistics, are the statistics of the raw data generated by the Monte Carlo sampling of the input distribution.

- The INPUT statistics, are the parameters of the input distribution which you defined for the random variable, in the Material Statistics dialog.

In general, the SAMPLED statistics and the INPUT statistics will not be exactly equal. However, as the Number of Samples increases, the SAMPLED statistics should approach the values of the INPUT parameters.

The distribution defined by the INPUT parameters is plotted on the Histogram. The display of this curve can be turned on or off, by right-clicking on the plot, and toggling the Input Distribution option.

Now right-click on the plot again, and select Change Plot Data. *Change the Data to Plot to soil 1 : Phi. Select Done.*

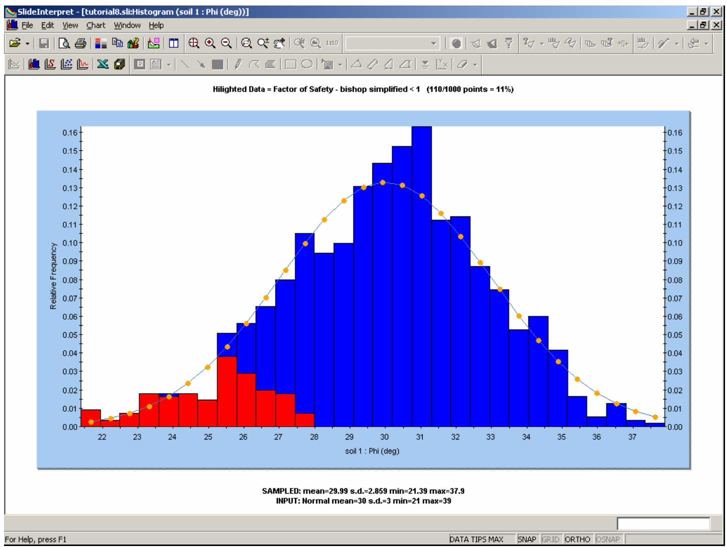
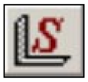


Figure 1-5: Histogram Plot of Friction Angle.

Notice the data with Bishop Safety Factor < 1, highlighted on the plot. With respect to the Friction Angle random variable, it is clear that failure corresponds to the lowest friction angles which were generated by the random sampling.

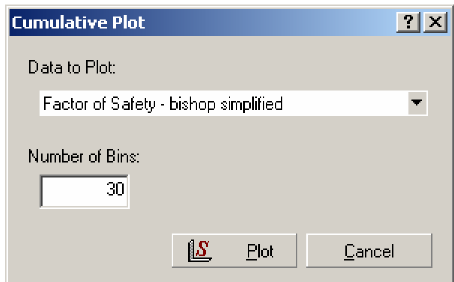
Cumulative Plots

To generate a Cumulative plot, select the Cumulative Plot option from the toolbar or the Statistics menu.



Select: Statistics → Cumulative Plot

You will see the Cumulative Plot dialog.



Select the Data to Plot = Factor of Safety – Bishop Simplified. Select the Plot button.

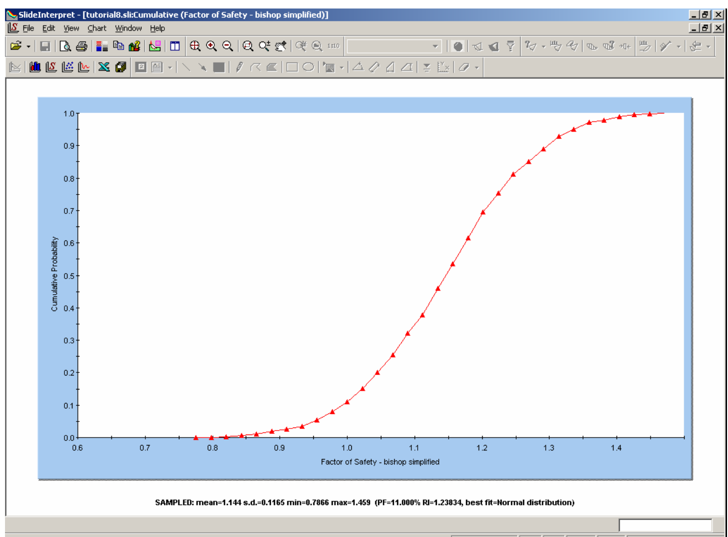


Figure 1-6: Cumulative Plot of Safety Factor.

A Cumulative distribution plot, represents the cumulative probability that the value of a random variable, will be LESS THAN OR EQUAL TO a given value.
When we are viewing a Cumulative Plot of Safety Factor, the Cumulative Probability at Safety Factor = 1, is equal to the PROBABILITY OF FAILURE.

Let's verify this as follows.

Sampler Option

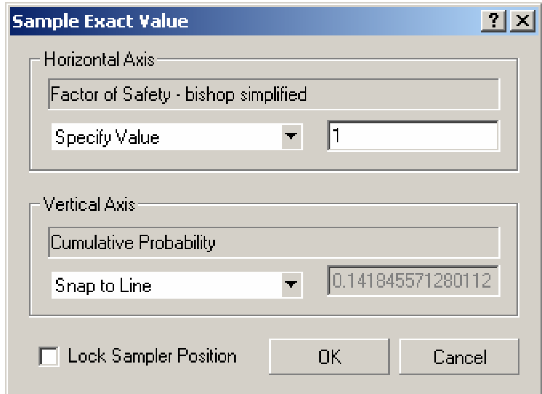
The Sampler Option on a Cumulative Plot, allows you to easily determine the coordinates at any point along the Cumulative distribution curve.

1. Right-click on the Cumulative Plot, and select the Sampler option.

2. You will see a dotted vertical line on the plot. This is the "Sampler", and allows you to graphically obtain the coordinates of any point on the curve. You can do this as follows.

3. Click AND HOLD the LEFT mouse button on the plot. Now drag the mouse along the plot. You will see that the Sampler follows the mouse, and continuously displays the coordinates of points on the Cumulative plot curve.

4. You can also determine exact points on the curve as follows. Right-click on the plot, and select Sample Exact Value. You will see the following dialog.



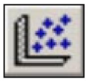
5. Enter 1 as the value for safety factor, and select OK.

6. Notice that the Sampler (dotted line) is now located at exactly Safety Factor = 1. Also notice that the Cumulative Probability = 0.11. This means that the Probability of Failure (Bishop analysis method) = 11%, which is the value we noted earlier in this tutorial, displayed at the slip center of the Global Minimum slip surface.

Scatter Plots

Scatter Plots allow you to plot any two random variables against each other, on the same plot. This allows you to analyze the relationships between variables.

Select the Scatter Plot option from the toolbar or the Statistics menu.



Select: Statistics → Scatter Plot

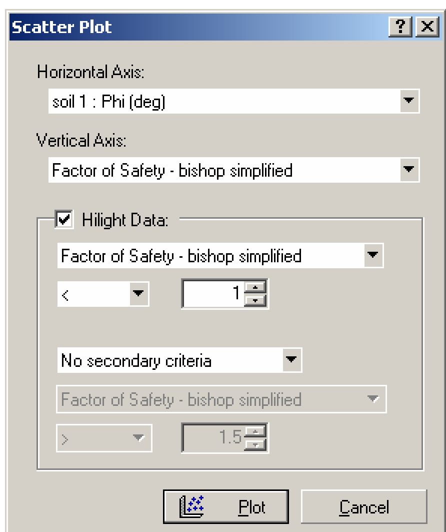
You will see the Scatter Plot dialog. Enter the following data.

1. Set the Horizontal Axis = soil 1 : Phi.

2. Set the Vertical Axis = Factor of Safety – Bishop.

3. Select Highlight Data, and select "Factor of Safety – Bishop Simplified < 1".

4. Select Plot.



You should see the following plot.

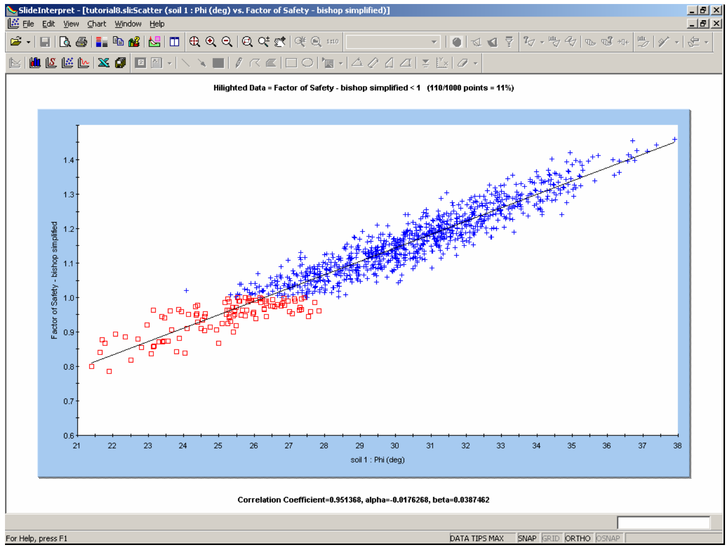


Figure 1-7: Scatter Plot – Friction Angle versus Safety Factor.

There is a well defined relationship between Friction Angle and Safety Factor. Notice the parameters listed at the bottom of the plot.

- The Correlation Coefficient indicates the degree of correlation between the two variables plotted. A Correlation Coefficient close to 1 (or -1) indicates a high degree of correlation. A Correlation Coefficient close to zero, indicates little or no correlation.

- The parameters Alpha and Beta, are the slope and y-intercept, respectively, of the best fit (linear) curve, to the data. This line can be seen on the plot. It's display can be toggled on or off, by right-clicking on the plot and selecting the Regression Line option.

Also notice the highlighted data on the plot. All data points with a Safety Factor less than 1, are displayed on the Scatter Plot as a RED SQUARE, rather than a BLUE CROSS.

Now let's plot Phi versus Cohesion on the Scatter Plot.

Right-click on the plot and select Change Plot Data. On the Vertical Axis, select soil 1 : Cohesion. Select Done. The plot should look as follows:

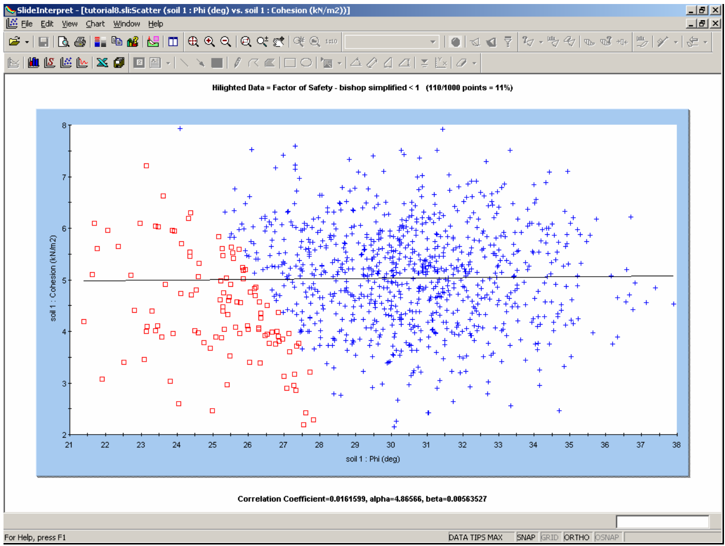


Figure 1-8: Scatter Plot – Friction Angle versus Cohesion.

This plot indicates that there is no correlation between the sampled values of Cohesion and Friction Angle. (The Correlation Coefficient, listed at the bottom of the plot, is a small number close to zero).

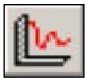
In reality, the Cohesion and Friction Angle of Mohr-Coulomb materials are generally correlated, such that materials with low Cohesion often have high Friction Angles, and vice versa.

In SLIDE, the user can define a correlation coefficient for Cohesion and Friction Angle, so that when the samples are generated, Cohesion and Friction Angle will be correlated. This is discussed at the end of this tutorial.

Convergence Plots

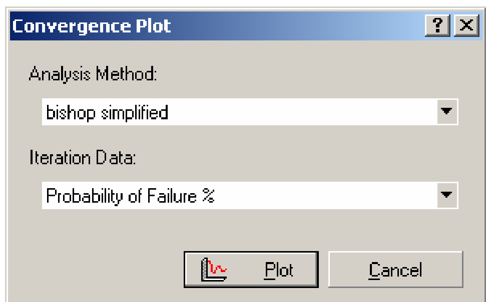
A Convergence Plot is useful for determining whether or not your Probabilistic Analysis is converging to a final answer, or whether more samples are required.

Select the Convergence Plot option from the toolbar or the Statistics menu.



Select: Statistics → Convergence Plot

You will see the Convergence Plot dialog. *Select Probability of Failure. Select Plot.*



You should see the following plot.

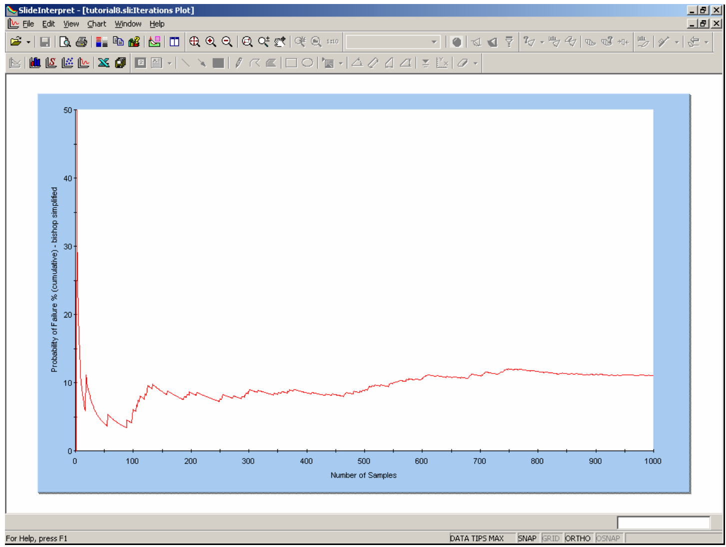


Figure 1-9: Convergence plot – Probability of Failure.

A convergence plot should indicate that the final results of the Probabilistic Analysis, are converging to stable, final values (ie. Probability of Failure, Mean Safety Factor etc.)
If the convergence plot indicates that you have not achieved a stable, final result, then you should increase the Number of Samples, and re-run the analysis.

Right-click on the plot and select the Final Value option from the popup menu. A horizontal line will appear on the plot, which represents the final value (in this case, Probability of Failure = 11%), which was calculated for the analysis.

For this model, it appears that the Probability of Failure has achieved a constant final value. To verify this, increase the Number of Samples (eg. 2000), and re-run the analysis. This is left as an optional exercise.

Additional Exercises

The user is encouraged to experiment with the Probabilistic Analysis modeling and data interpretation features in SLIDE. Try the following exercises.

Correlation Coefficient (C and Phi)

Earlier in this tutorial, we viewed a Scatter Plot of Cohesion versus Friction Angle (see Figure 1-8).

Because the random sampling of these two variables, was performed entirely independently, there was no correlation between the two variables.

In reality, the Cohesion and Friction Angle of Mohr-Coulomb materials are generally correlated, such that materials with low Cohesion tend to have high Friction Angles, and vice versa.

In SLIDE, the user can easily define a correlation coefficient for Cohesion and Friction Angle, so that when the samples are generated, Cohesion and Friction Angle will be correlated.

This can be demonstrated as follows:

1. In the SLIDE MODEL program, select the Material Statistics option in the Statistics menu.

2. In the Material Statistics dialog, select the Correlation option. This will display a dialog, which allows you to define a correlation coefficient, between cohesion and friction angle (this is only applicable for materials which use the Mohr-Coulomb strength type).

3. In the correlation dialog, select the Apply checkbox for soil 1. We will use the default correlation coefficient of –0.5. Select OK in the Correlation dialog. Select OK in the Material Statistics dialog.

4. Re-compute the analysis.

5. In the SLIDE INTERPRET program, create a Scatter Plot of Cohesion versus Friction Angle. You should see the following.

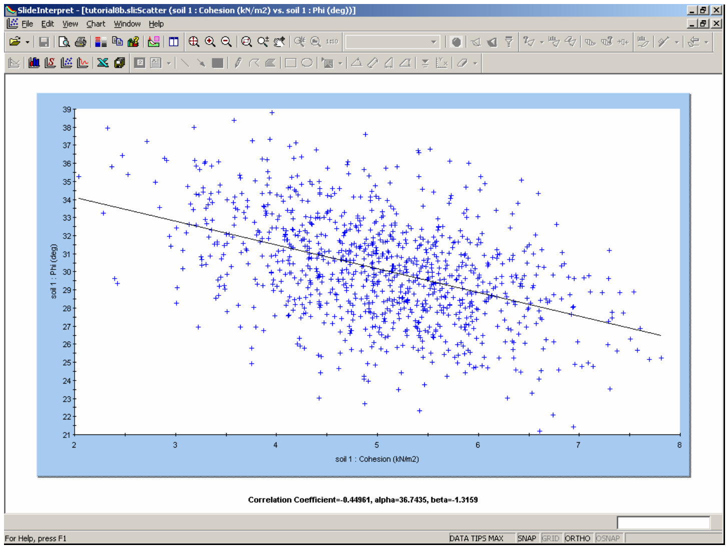


Figure 1-10: Cohesion vs. Phi (Correlation = – 0.5).

As you can now see, Cohesion and Friction Angle are no longer independent of each other, but are loosely correlated. NOTE:

- The actual correlation coefficient generated by the sampling, is listed at the bottom of the plot. It is not exactly equal to – 0.5, because we are using Monte Carlo sampling, and a relatively small number of samples (1000).

- A NEGATIVE correlation coefficient simply means that when one variable increases, the other is likely to decrease, and vice versa.

Now try the following:

1. Re-run the analysis using correlation coefficients of – 0.6 , – 0.7, – 0.8 , – 0.9, – 1.0. View a scatter plot of Cohesion versus Friction Angle, after each run.

2. You will see that the two variables will be increasingly correlated. When the correlation coefficient = – 1.0, the Scatter Plot will result in a straight line.

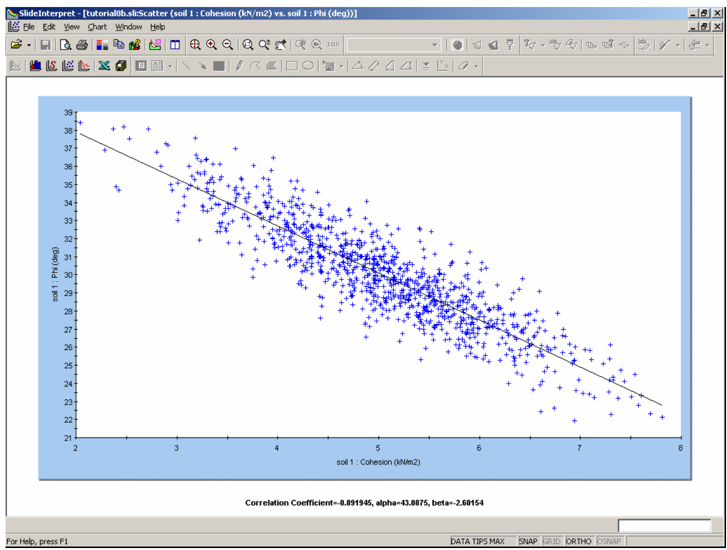


Figure 1-11: Cohesion vs. Phi (Correlation = – 0.9).

In general, it is recommended that a correlation coefficient is defined between Cohesion and Friction Angle, for a Mohr-Coulomb material. This will generate values of Cohesion and Friction Angle, which are more likely to occur in the field.

Finally, it is interesting to note that the Probability of Failure, for this model, decreases significantly, as the correlation between cohesion and friction angle increases (ie. closer to –1).

This implies that the use of a correlation coefficient, and the generation of more realistic combinations of Cohesion and Phi, tends to decrease the calculated probability of failure, for this model.

Sampling Method

In this tutorial we used the default method of Random Sampling, known as Monte Carlo Sampling. Another sampling method is available in SLIDE – the Latin Hypercube method.

For a given number of samples, Latin Hypercube sampling results in a smoother, more uniform sampling of the probability density functions which you have defined for your random variables, compared to the Monte Carlo method.

To illustrate this, do the following:

1. In the SLIDE MODEL program, select Project Settings > Statistics, and set the Sampling Method to Latin Hypercube.

2. Re-compute the analysis.

3. View the results in INTERPRET, and compare with the previous (Monte Carlo) results. In particular, plot histograms of your input random variables (Cohesion, Phi, Unit Weight).

4. Notice that the input data distributions which you defined for your input random variables, are much more smoothly sampled by Latin Hypercube sampling, compared to Monte Carlo sampling.

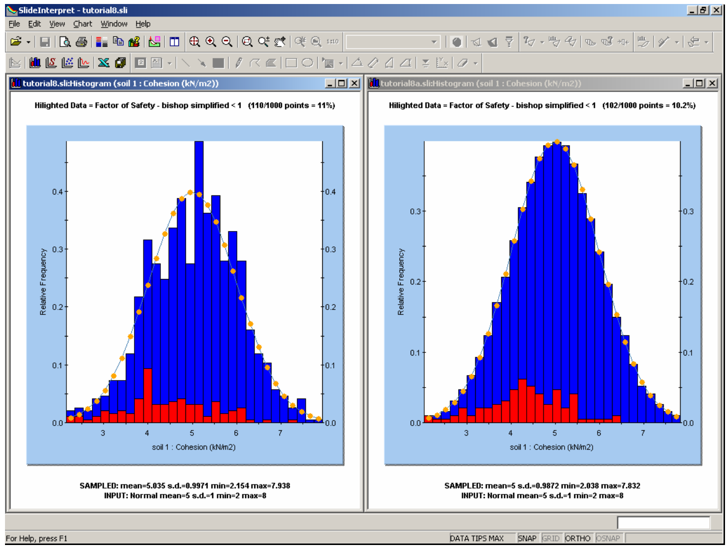


Figure 1-12: Comparison of Monte Carlo sampling (left) and Latin Hypercube sampling (right) – Cohesion random variable – 1000 samples.

As you can see in Figure 1-12, for 1000 samples, the Latin Hypercube sampling is much smoother than the Monte Carlo sampling.

This is because the Latin Hypercube method is based upon "stratified" sampling, with random selection within each stratum. Typically, an analysis using 1000 samples obtained by the Latin Hypercube technique will produce comparable results to an analysis of 5000 samples using the Monte Carlo method.

In general, the Latin Hypercube method allows you to achieve similar results to the Monte Carlo method, with a significantly smaller number of samples.

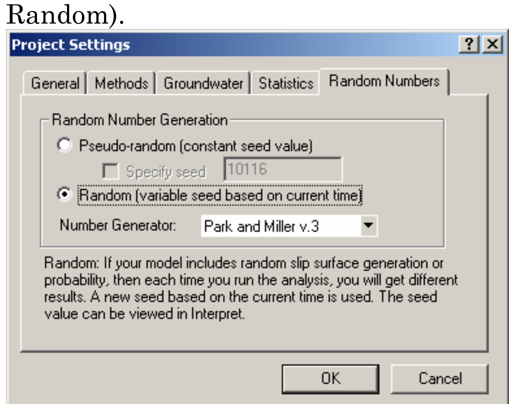
Random Number Generation

The sampling of the statistical distributions of your input data random variables, is achieved by the generation of random numbers. You may wonder why the results in this tutorial are reproducible, if they are based on random numbers?

The reason for this, is because we have been using the Pseudo-Random option, in Project Settings. Pseudo-random analysis means that the same sequence of random numbers is always generated, because the same "seed" value is used. This allows the user to obtain reproducible results for a Probabilistic Analysis.

Try the following:

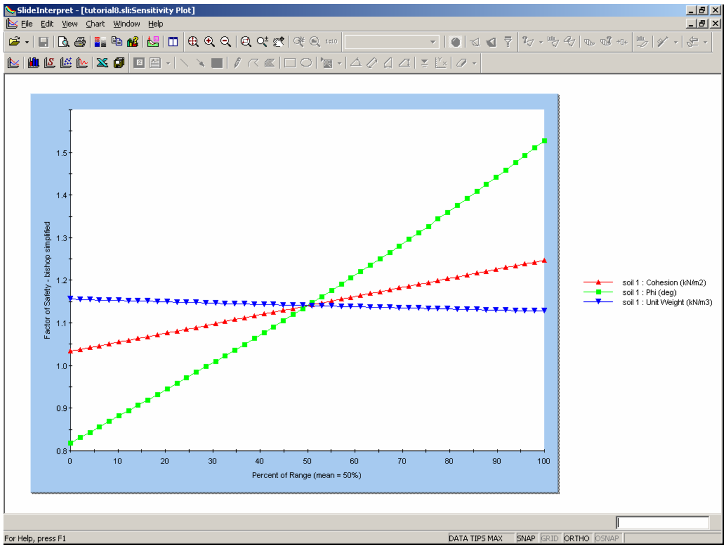
1. Select Project Settings > Random Numbers, and select the Random option (instead of Pseudo-Random).



2. Re-compute the analysis.

3. You will notice that each time you re-compute, analysis results will be different. This is because a different "seed" value is used each time. This will give a different sequence of random numbers, and therefore a different sampling of your random variables, each time you re-run the analysis.

Sensitivity Analysis



Sensitivity analysis is extremely easy to perform with SLIDE. Any input parameter which can be defined as a random variable (for a Probabilistic Analysis) can also be defined as a variable for a Sensitivity Analysis.

A Sensitivity Analysis simply means the following:

1. For one or more selected input parameters, the user specifies a Minimum and a Maximum value.

2. Each parameter is then varied in uniform increments, between the Minimum and Maximum values, and the safety factor of the Global Minimum slip surface is calculated at each value. NOTE: while a parameter is being varied, ALL OTHER input parameters are held constant, at their MEAN values.

3. This results in a plot of safety factor versus the input parameter(s), and allows you to determine the "sensitivity" of the safety factor, to changes in the input parameter(s).

4. A steeply changing curve on a Sensitivity Plot, indicates that the safety factor is sensitive to the value of the parameter.

5. A relatively "flat" curve indicates that the safety factor is not sensitive to the value of the parameter.

A sensitivity analysis indicates which input parameters may be critical to the assessment of slope stability, and which input parameters are less important.

A Sensitivity Plot can be used to easily determine the value of a parameter which corresponds to a specified Factor of Safety (eg. Factor of Safety = 1).

NOTE: the finished product of this tutorial can be found in the **tutorial9.sli** data file, which you should find in the EXAMPLES folder in your SLIDE installation folder.

Model

We will use the same example discussed in the previous tutorial.

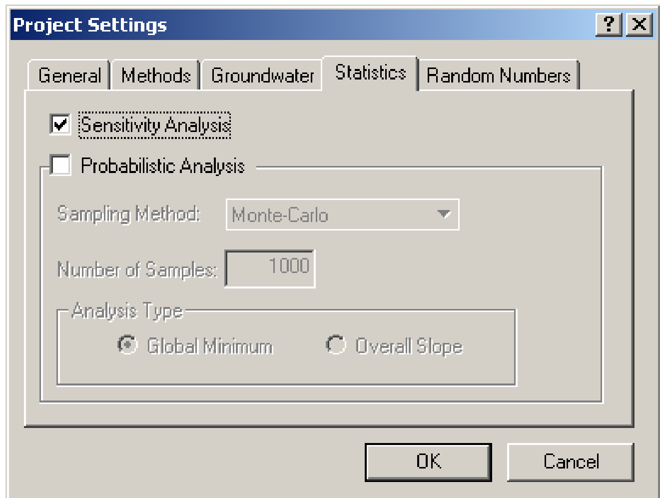
Select: File → Open

Open the **tutorial8.sli** file, which you will find in the EXAMPLES folder in your SLIDE installation folder

Project Settings

To enable a Sensitivity Analysis with SLIDE, you must first select the Sensitivity Analysis checkbox in Project Settings.

Select: Analysis → Project Settings



In the Project Settings dialog, select the Statistics tab, and select the Sensitivity Analysis checkbox. Clear the Probabilistic Analysis checkbox. Select OK.

NOTE:

- You can perform BOTH a Sensitivity Analysis and a Probabilistic Analysis, at the same time, using the same variables. This is discussed at the end of this tutorial.

However, for this example, we will just run the Sensitivity Analysis only.

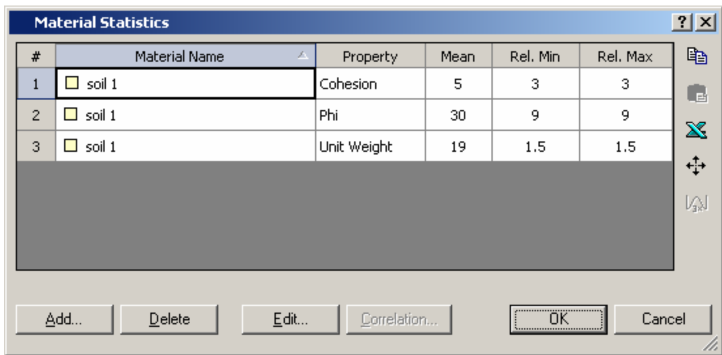
Defining Sensitivity Variables

The procedure for selecting and defining variables for a Sensitivity Analysis, is exactly the same as the procedure described in the previous tutorial, for a Probabilistic Analysis. However, note that:

- For a Sensitivity Analysis, ONLY a Minimum and Maximum value is required for each variable.
- A Statistical Distribution and Standard Deviation is NOT applicable for Sensitivity Analysis.

Let's examine the Material Statistics dialog.

Select: Statistics → Materials



Notice that the 3 variables which we defined previously for the Probabilistic Analysis (for the **tutorial8.sli** file), are still displayed in the Material Statistics dialog.

Because we are only considering a Sensitivity Analysis, the statistical distribution and standard deviation, is no longer displayed in the dialog. Only the mean, minimum and maximum values are necessary for the Sensitivity Analysis.

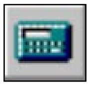
We will not make any changes to this data, so select OK or Cancel in the dialog.

Compute

Before we run the analysis, first save the file with a new file name: **sens1.sli**.

Select: File → Save As

Use the Save As dialog to save the file. Now select Compute.



Select: Analysis → Compute

NOTE:

- When you run a Sensitivity Analysis with SLIDE, the regular (deterministic) analysis is always computed first. This is necessary in order to determine the Global Minimum slip surface. Remember that the Sensitivity Analysis is performed on the Global Minimum slip surface.

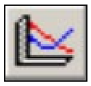
- The Sensitivity Analysis automatically follows. The progress of the analysis is indicated in the Compute dialog. A Sensitivity Analysis usually only takes a very small amount of time, so you may not even notice the calculation in the Compute dialog.

Interpret

To view the results of the analysis:

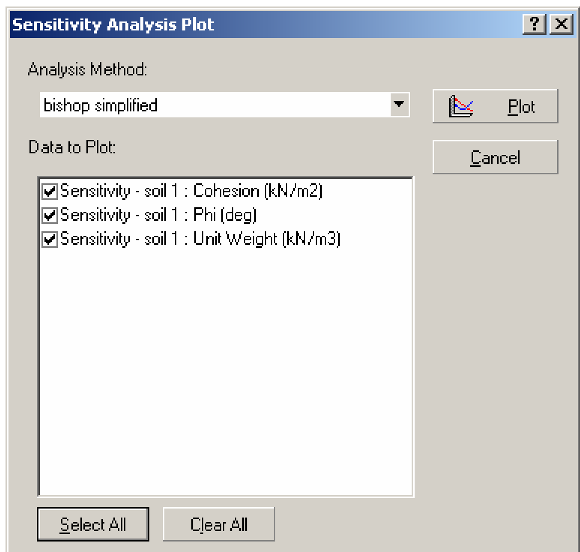
Select: Analysis → Interpret

The results of the Sensitivity Analysis are viewed by selecting the Sensitivity Plot option, from the toolbar or the Statistics menu.



Select: Statistics → Sensitivity Plot

You will see the following dialog.



Select the checkboxes for all 3 variables. TIP – you can use the Select All button to automatically select all checkboxes. Select the Plot button.

You should see the following sensitivity plot.

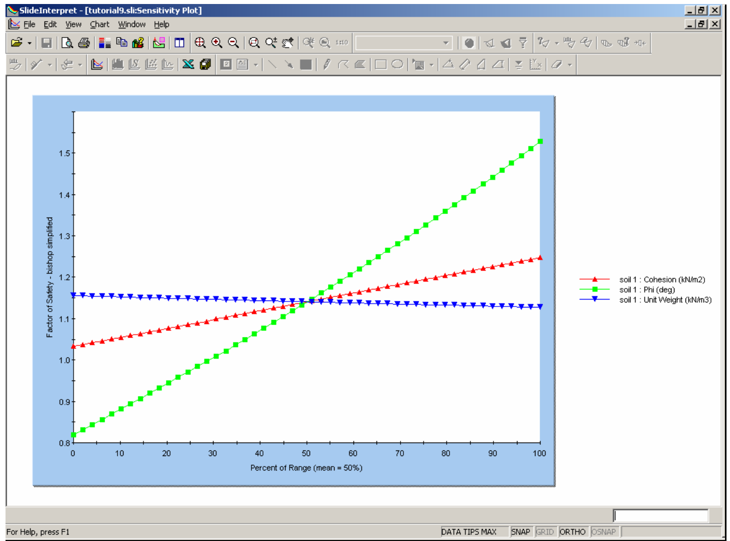


Figure 2-1: Sensitivity Plot of 3 variables.

As you can see from the plot, the safety factor is most sensitive to the Friction Angle (steepest curve), and least sensitive to the Unit Weight (curve is almost flat).

Note the following about the Sensitivity Plot:

1. When multiple variables are plotted, the horizontal axis of the plot is in terms of Percent of Range.

2. Percent of Range = 0 represents the Minimum value of each variable, and Percent of Range = 100 represents the Maximum value of each variable.

3. Notice that all 3 curves intersect at Percent of Range = 50%. Percent of Range = 50% ALWAYS represents the MEAN value of each variable.

If you wish to see the actual value of a variable on the horizontal axis, then you must only plot ONE Sensitivity variable at a time (only select ONE checkbox in the Sensitivity Plot dialog). Let’s do that now.

1. Right-click on the plot and select Change Plot Data from the popup menu.

2. Clear the checkboxes for Cohesion and Unit Weight, so that only Phi is selected. Select Done.

The Sensitivity Plot now only displays the curve for Friction Angle. Notice that the Horizontal Axis is now in terms of the actual unit of the variable (degrees).

Sampler

The Sampler option allows you to easily obtain the coordinates of any point on a Sensitivity Plot curve.

1. Right-click on the plot and select the Sampler option.

2. Notice that a horizontal dotted line is now displayed on the plot. This is the Sampler line, and allows you to graphically obtain the coordinates along the curve.

3. Click and HOLD the LEFT mouse button on the plot, and drag the mouse. As you move the mouse, the Sampler will continuously display the coordinates of the current location on the curve.

4. You can also sample exact locations on the curve. Right-click on the plot and select Sample Exact Value.

5. In the dialog, enter a Safety Factor = 1 for the Vertical Axis. Select OK.

6. The Sampler now shows the Friction Angle for Safety Factor = 1. The Friction Angle = 26.22 degrees. This is the critical Friction Angle, if all other variables are assumed to be equal to their mean values.

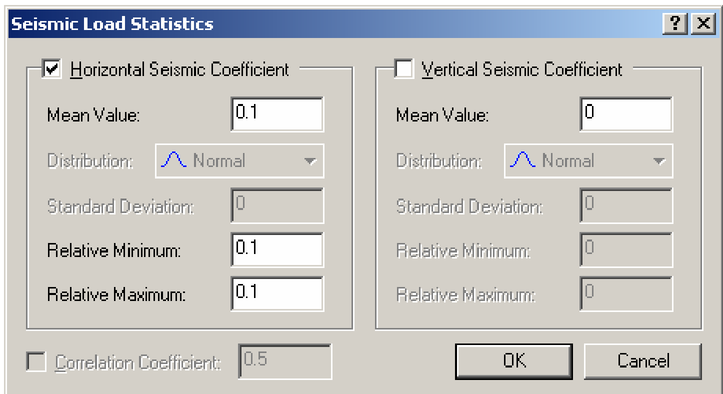
Seismic Coefficient Sensitivity

Let's add one more Sensitivity Analysis variable, and re-run the analysis. Return to the SLIDE MODEL program, and select the Seismic option from the Statistics menu.

Select: Statistics → Seismic Load

1. In the dialog, select the checkbox for Horizontal Seismic Coefficient.

2. Enter a Mean Value = 0.1. Also enter Relative Minimum = 0.1 and Relative Maximum = 0.1. Select OK.



3. When the Sensitivity Analysis is run, the Horizontal Seismic Coefficient will be varied between 0 and 0.2. Select Compute to run the analysis, and then view the results in INTERPRET.

4. Create a Sensitivity Plot (only select the checkbox for Horizontal Seismic Coefficient).

5. The plot should appear as shown in Figure 2-2.

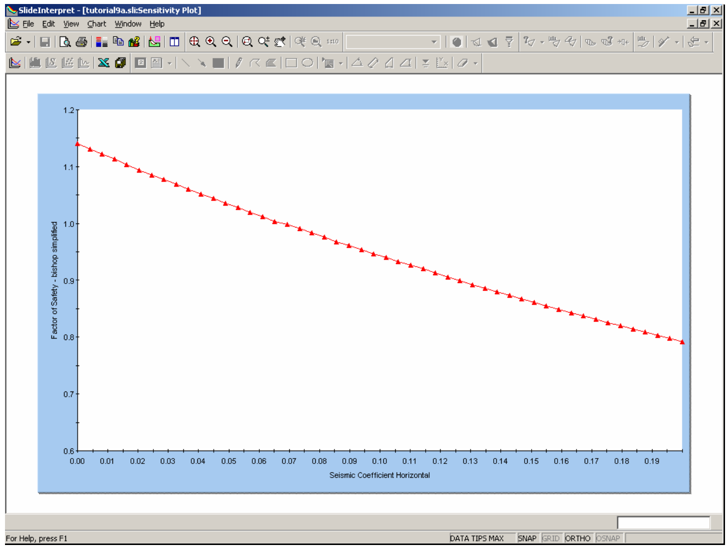


Figure 2-2: Sensitivity Plot of Horizontal Seismic Coefficient.

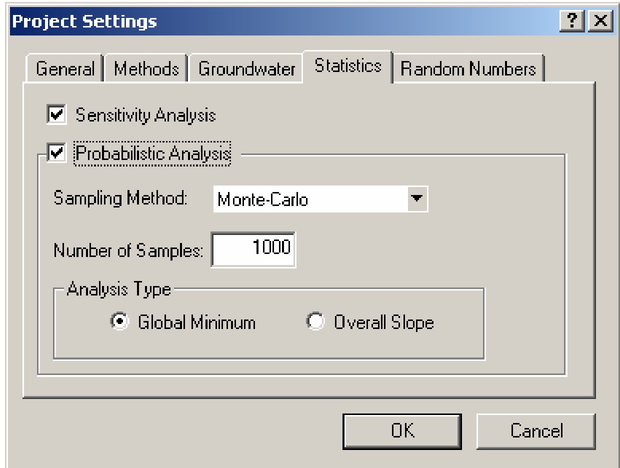
Sensitivity and Probabilistic Analysis

A Sensitivity Analysis should not be confused with a Probabilistic Analysis. Remember:

- A Sensitivity Analysis simply involves the variation of individual variables between minimum and maximum values. A Sensitivity Analysis is performed on ONLY ONE VARIABLE AT A TIME.

- A Probabilistic Analysis involves the statistical sampling of distributions that you have defined for your random variables. A Probabilistic Analysis uses sampled values of ALL random variables, for each iteration of the Probabilistic Analysis.

However, you can perform BOTH a Sensitivity Analysis, AND a Probabilistic Analysis, at the same time, by selecting both checkboxes in Project Settings.



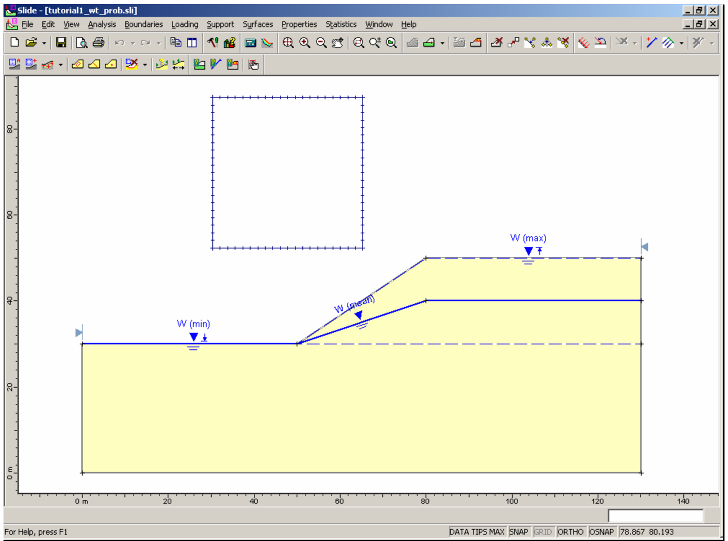
If you do this, note the following:

- The Sensitivity analysis will use the same variables that you have selected for the Probabilistic Analysis.

- The Sensitivity Analysis will only use the Minimum and Maximum values that you have defined for each variable. It will ignore the statistical distributions and standard deviations that you have entered to define the random variables for the Probabilistic Analysis.

This is convenient, because if you have already performed a Probabilistic Analysis on a model, then you can also perform a Sensitivity Analysis, using all of the same variables, simply by selecting the Sensitivity Analysis checkbox in Project Settings.

Water Table Statistics



In SLIDE it is very easy to account for a variable water table location, in either a Sensitivity or Probabilistic Analysis.

1. The Minimum and Maximum locations of the Water Table are specified graphically, by drawing the location of the limiting boundaries on the model.

2. A single random variable (a Normalized Elevation ranging between 0 and 1), is then used to generate Water Table elevations between the Minimum and Maximum boundaries, according to the statistical parameters entered in the Water Table Statistics dialog.

NOTE: the finished product of this tutorial can be found in the file **tutorial10.sli** which you should find in the EXAMPLES folder in your SLIDE installation folder.

Sensitivity Analysis

First, we will demonstrate a simple Sensitivity Analysis, using a Water Table. We will start with the **tutorial1.sli** file.

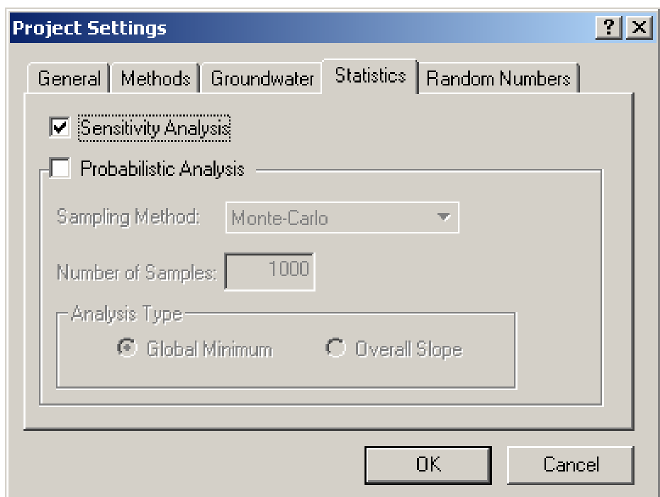
Select: File → Open

Open the **tutorial1.sli** file, which you will find in the EXAMPLES folder in your SLIDE installation folder.

Project Settings

To enable a Sensitivity Analysis with SLIDE, you must first select the Sensitivity Analysis checkbox in Project Settings.

Select: Analysis → Project Settings



In the Project Settings dialog, select the Statistics tab, and select the Sensitivity Analysis checkbox. Select OK.

Water Table Boundaries

In order to define the upper and lower limits of a Water Table for the Sensitivity Analysis, we must define the Maximum and Minimum Water Table boundaries.

Select: Statistics → Water Table → Draw Max Water Table

We will create the Maximum Water Table, by snapping to the vertices along the slope.

1. First, right-click the mouse and make sure the Snap option is enabled.

2. Now left click the mouse, and snap the Maximum Water Table to the slope vertices at (0 , 30) , (50 , 30) , (80 , 50) and (130 , 50).

3. Right-click and select Done from the popup menu, and the boundary will be added to the model.

Now let's create the Minimum Water Table boundary.

Select: Statistics → Water Table → Draw Min Water Table

1. Snap the Minimum Water Table, to the slope vertices at (0 , 30) and (50 , 30).

2. Now enter the point (130 , 30) in the prompt line. (Or alternatively, right-click the mouse and make sure the Ortho Snap option is enabled. Hover the mouse near the point (130 , 30) at the right edge of the model. When the Ortho Snap icon appears, click the mouse and you will snap exactly to the point (130, 30) on the boundary.)

3. Right-click and select Done from the popup menu.

4. You will see the Assign Water Table dialog. Select OK to automatically assign the Water Table to all slope materials (only one material is actually used in this model).

You have now defined the Maximum and Minimum Water Table boundaries. When BOTH boundaries have been defined, you will notice that a THIRD boundary, the MEAN Water Table, is automatically calculated, and appears on the model.

Your screen should appear as follows.

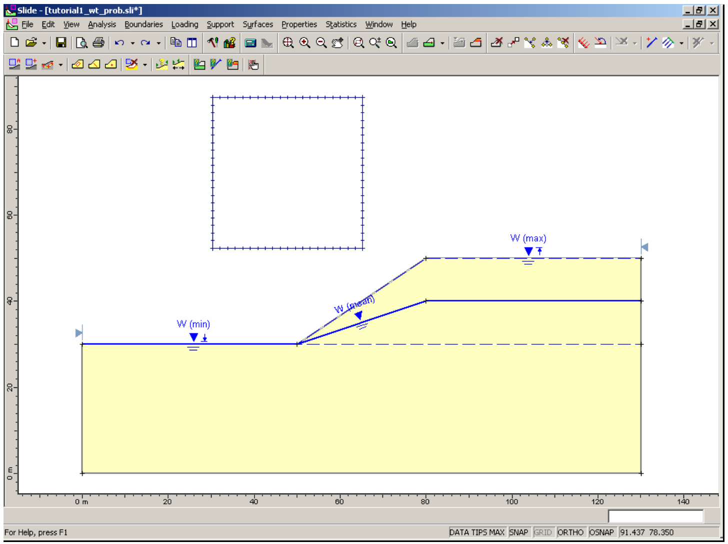


Figure 3-1: Maximum, Minimum and Mean Water Table boundaries.

Mean Water Table

So, how has the Mean Water Table been calculated? First, let's look at the Water Table Statistics dialog.

Select: Statistics → Water Table → Statistical Properties

NOTE: a convenient shortcut to access this dialog, is to right-click the mouse on any of the three Water Table boundaries – Maximum, Mean or Minimum – and select Statistical Properties from the popup menu.

Normalized Mean

In the Water Table Statistics dialog, you will notice the Normalized Mean parameter.

The definition of the Normalized Mean water table location, is illustrated in the following figure. The Normalized Mean is simply the relative elevation of the Mean Water Table, *along any vertical line* between the Minimum and Maximum water table boundaries.

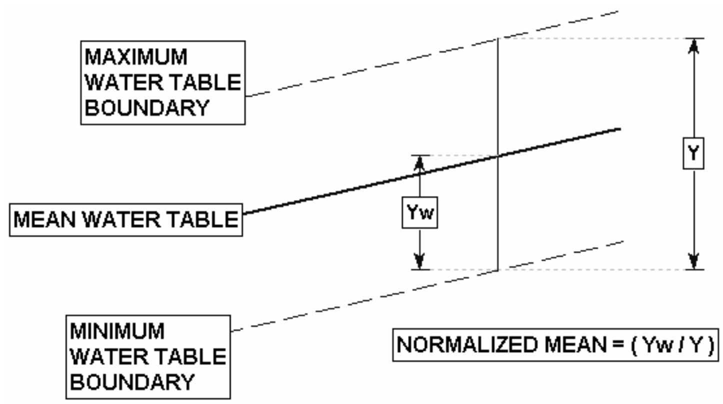


Figure 3-2: Definition of Normalized Mean water table location.

The default Normalized Mean (= 0.5) produces a Mean Water Table which is exactly midway between the Minimum and Maximum boundaries, at all locations.

The Normalized Mean must have a value between 0 and 1.

Compute

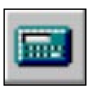
Before we run the analysis, it is important to note the following:

- The MEAN Water Table will be used as the Water Table in the Deterministic Analysis.
- The Sensitivity Analysis is then performed on the Global Minimum slip surface located by the Deterministic Analysis.
- The Sensitivity Analysis is carried out by varying the Water Table location between the Minimum and Maximum Water Table boundaries, in 50 equal increments, and calculating the safety factor of the Global Minimum slip surface, for each location of the Water Table.

First save the file with a new file name: **wt_sens.sli**.

Select: File → Save As

Use the Save As dialog to save the file. Now select Compute.



Select: Analysis → Compute

When the analysis is complete, view the results in Interpret.

Select: Analysis → Interpret

Interpret

You should see the following results.

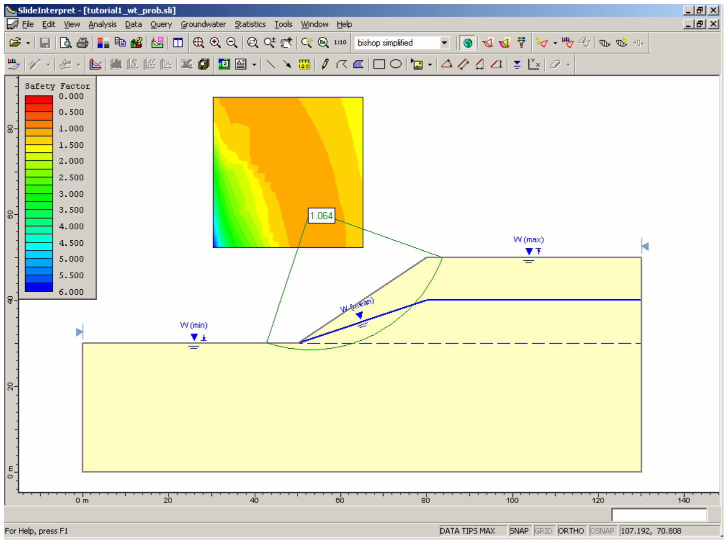
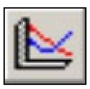


Figure 3-3: Analysis results using Mean Water Table.



Let's view the Sensitivity Plot of the Water Table location.
Select: Statistics → Sensitivity Plot

Select the checkbox for "Sensitivity – Water Table Location". Select the Plot button.

You should see the following Sensitivity Plot. NOTE:

- The Sensitivity Variable which represents the Water Table location (elevation), is a Normalized Variable with a range of [0 , 1].
- ZERO represents the Minimum Water Table boundary.
- ONE represents the Maximum Water Table boundary.

- Intermediate values represent the relative elevation of the Water Table, along any vertical line, between the Minimum and the Maximum boundaries.

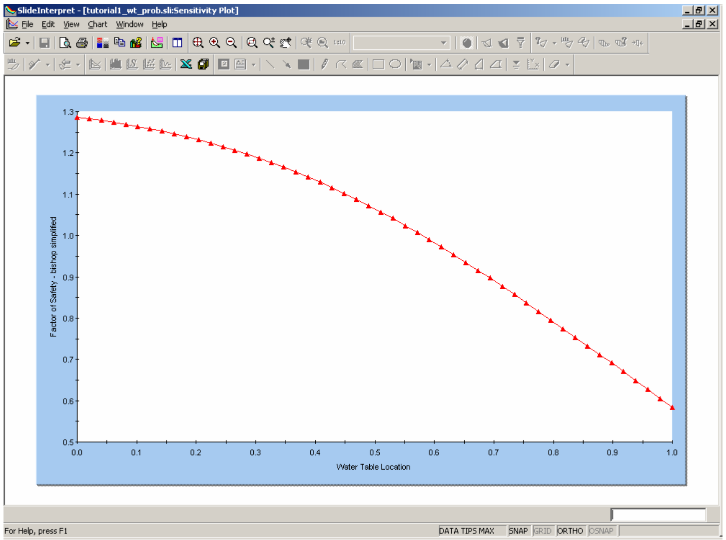


Figure 3-4: Sensitivity Plot of Normalized Water Table elevation.

As you would expect, the highest safety factor occurs when the Water Table location = 0 (Minimum Water Table), and the lowest safety occurs when the Water Table location = 1 (Maximum Water Table).

If you want to determine the Water Table elevation which corresponds to a Safety Factor = 1, you can do this as follows:

1. Right-click on the plot and select the Sample Exact Value option.

2. In the dialog, enter a Safety Factor = 1, and select OK.
3. A horizontal dotted line will appear on the plot. This is the Sampler line, and allows you to determine the coordinates of any point on the Sensitivity curve.

4. As displayed by the Sampler, a Normalized Water Table location = 0.58 corresponds to a Safety Factor (Bishop) = 1.

5. This Water Table location (0.58) is just slightly above the Mean Water Table Location (= 0.5). This makes sense, because the Deterministic Safety Factor of the Global Minimum slip surface, is only slightly above 1 (equal to 1.064). Therefore only a slightly higher Water Table is necessary to reach critical equilibrium.

That concludes this simple demonstration of a Sensitivity Analysis using a Water Table.

Next, we will demonstrate a Probabilistic Analysis using the Water Table.

Probabilistic Analysis

The Normalized Water Table elevation, discussed in the first part of this tutorial (Sensitivity Analysis), can also be treated as a true random variable.

That is, in addition to the Mean location, it may also be assigned a Statistical Distribution and a Standard Deviation. Random samples are then generated, so that the variation of the Water Table elevation between the Minimum and Maximum Water Table boundaries, is modeled as a true random variable.

For this demonstration, we will read in a different file, the **tutorial2.sli** file.

Select: File → Open

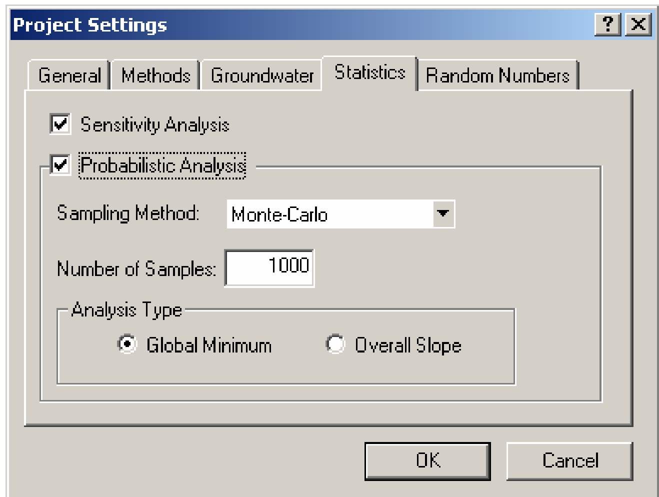
Open the **tutorial2.sli** file, which you will find in the EXAMPLES folder in your SLIDE installation folder.

Notice that the file we have read in, already includes a Deterministic Water Table. We will incorporate the existing Water Table into the Probabilistic Analysis.

Project Settings

To enable a Probabilistic Analysis with SLIDE, you must first select the Probabilistic Analysis checkbox in Project Settings.

Select: Analysis → Project Settings



In the Project Settings dialog, select the Statistics tab, and select the Probabilistic Analysis checkbox. Also select the Sensitivity Analysis checkbox. Select OK.

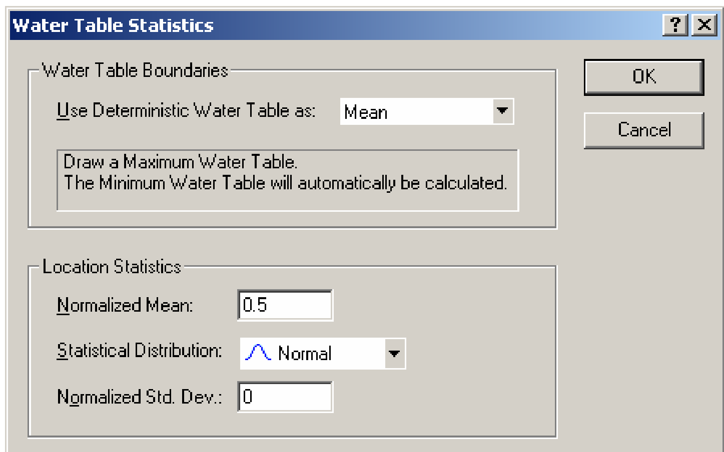
Water Table Boundaries

Notice that the file we have read in, already includes a Deterministic Water Table. We can incorporate the existing Water Table into the Probabilistic Analysis.

Select: Statistics → Water Table → Statistical Properties

TIP – you can also right-click on the Water Table and select Statistical Properties from the popup menu.

In the Water Table Statistics dialog, the *Use Deterministic Water Table As* option allows you to specify that the Deterministic Water Table is to be used as the Mean, Minimum or Maximum Water Table boundary, in the Probabilistic Analysis.



By default, *Use Deterministic Water Table = Mean*. As indicated in the text tip in the dialog, you must now:

- Draw the Maximum Water Table boundary
- The Minimum Water Table boundary will then be automatically calculated from the Maximum and the Mean boundaries.

We will return to this dialog in a moment. For now, just select OK and we will define the Maximum Water Table boundary.

Select: Statistics → Water Table → Draw Max Water Table

We will create the Maximum Water Table, by snapping to the vertices along the slope.

1. First, right-click the mouse and make sure the Snap option is enabled.

2. Now left click the mouse, and snap the Maximum Water Table to the slope vertices at (5, 28) , (43 , 28) , (67 , 40) and (100 , 40).

3. Right-click and select Done from the popup menu.

4. You will see the Assign Water Table dialog. Select OK to automatically assign the Water Table to all materials.

Now observe the following:

- The Maximum Water Table which we have just drawn, is defined along the slope surface.

- The original (deterministic) Water Table is now labeled as the Mean Water Table.

- The Minimum Water Table boundary has been automatically calculated.

Automatic Minimum Water Table

As you can see, once we have defined the first two boundaries (in this case, the Mean Water Table and the Maximum Water Table), the THIRD Water Table boundary is automatically calculated (in this case, the Minimum Water Table boundary). Your screen should appear as follows.

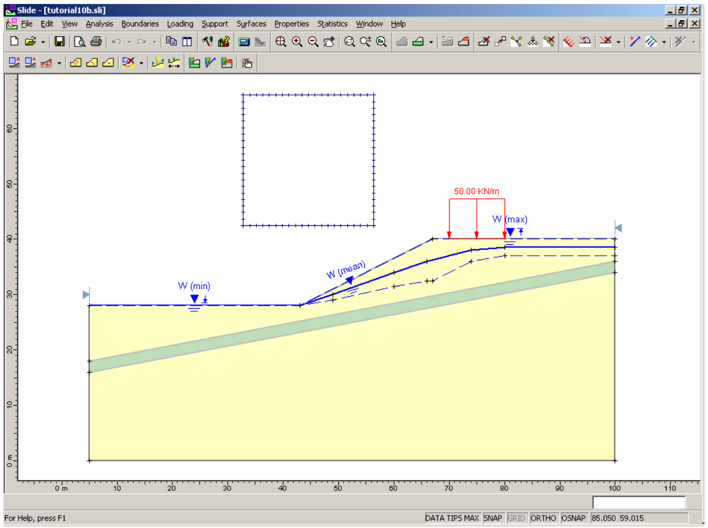


Figure 3-5: Maximum, Minimum and Mean Water Table boundaries.

The Minimum Water Table boundary has been calculated, by assuming that the MEAN Water Table is at a relative elevation equal to the Normalized Mean in the Water Table Statistics dialog.

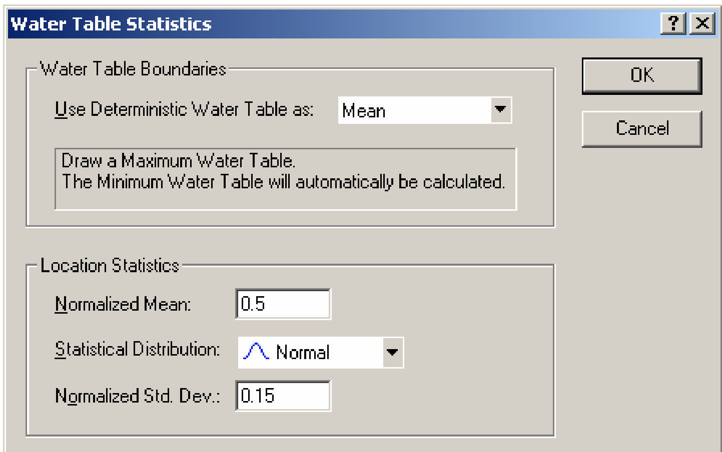
Because the Normalized Mean = 0.5 (the default), the Minimum Water Table has been generated such that the Mean Water Table is exactly halfway between the Minimum and Maximum Water Table boundaries, at all locations.

Water Table Statistics

The statistical distribution of the Water Table location is specified by defining a Normalized Random Variable with a range of 0 to 1. ZERO represents the location of the Minimum Water Table boundary, ONE represents the location of the Maximum Water Table boundary. The distribution of the Random Variable between 0 and 1, specifies the distribution of the Water Table elevation, between the Minimum and the Maximum Water Table boundaries.

Let's return to the Water Table Statistics dialog, to enter a Standard Deviation for the Water Table random variable.

As a shortcut, you can right-click the mouse on any Water Table boundary (Minimum, Maximum or Mean), and select Statistical Properties from the popup menu.



We will use the default Statistical Distribution = Normal. Enter a Normalized Standard Deviation = 0.15. Select OK.

Normalized Standard Deviation

Because the Water Table location is specified using a normalized Random Variable with a range of 0 to 1, the Standard Deviation must also be specified as a Normalized value. Although the concept of a Normalized Standard Deviation may be a bit harder to grasp than the concept of a Normalized Mean, it is very simple, just remember:

- The Statistical Distribution you are defining for the Water Table location, is really for a Random Variable with a range of 0 to 1.
- Therefore, the Normalized Standard Deviation is defined accordingly.

For example: for a Normal Distribution, the Minimum and Maximum values should be located at approximately 3 Standard Deviations away from the Mean, in order to define a complete (non-truncated) Normal Distribution. For a Random Variable with a Minimum = 0 , Mean = 0.5 and Maximum = 1, a Standard Deviation of approximately (0.5 / 3) = 0.17, will generate normally distributed samples of the Water Table location, between the Minimum and Maximum Water Table boundaries.

In effect, we will be generating a distribution of Water Table elevations, between the Minimum and Maximum Water Table boundaries, as illustrated in Figure 3-6.

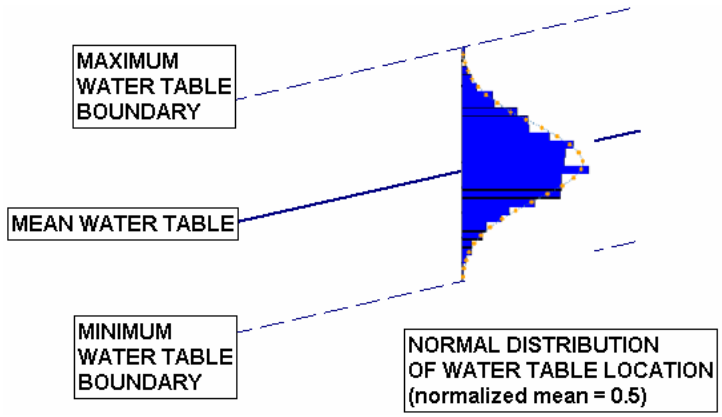


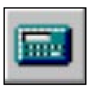
Figure 3-6 Normal Distribution of Water Table elevation.

Compute

First save the file with a new file name: **wt_prob.sli**.

Select: File → Save As

Use the Save As dialog to save the file. Now select Compute.



Select: Analysis → Compute

When the analysis is complete, view the results in Interpret.

Select: Analysis → Interpret

Interpret

You should see the following figure.

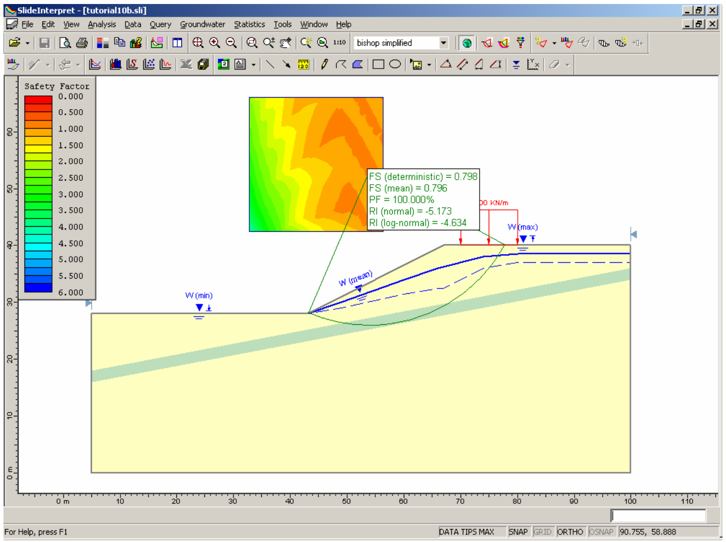
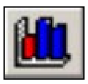


Figure 3-7: Results after Probabilistic Analysis.

Let's view a histogram of the Water Table location random variable.



Select: Statistics → Histogram

In the Histogram Plot dialog, select "Water Table Location" as the Data to Plot. Select the Plot button.

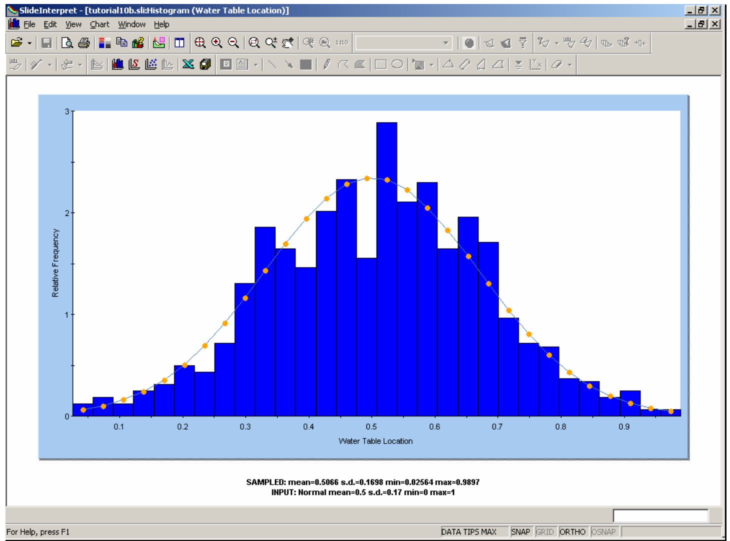
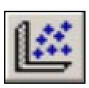


Figure 3-8: Histogram of Normalized Water Table elevation.

As you can see, the Water Table random variable has a possible range of 0 to 1. A Normal distribution of samples has been generated, around the mean value of 0.5.

For each iteration of the Probabilistic Analysis, the value of the Water Table random variable determines the elevation of the Water Table between the Minimum and Maximum Water Table boundaries. In this way, the elevation of the Water Table is controlled by a single random variable, which makes it very simple to model a probabilistic Water Table in SLIDE.

Let's view a Scatter Plot.



Select: Statistics → Scatter Plot

In the Scatter Plot dialog, select Water Table Location versus Factor of Safety – Bishop. Select Plot.

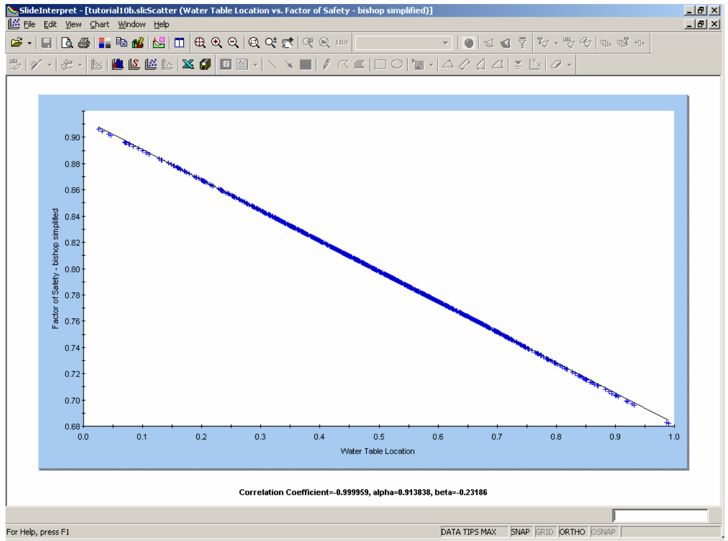


Figure 3-9: Water Table elevation versus Safety Factor.

For this model, there is a direct, linear correlation between the Water Table elevation, and the Factor of Safety of the Global Minimum slip surface.

Because there are no other random variables involved in this analysis, there is no scatter of data in Figure 3-9. If we included other random variables in the analysis, then you would see scatter of the data points on this plot.

NOTE: if you generate a Sensitivity Plot of the Water Table elevation, it will be essentially the same plot as the Scatter Plot shown in Figure 3-9. Again, this is because our Probabilistic Analysis only involved ONE random variable (the Water Table elevation).

Additional Exercises

Here are some additional features to consider, related to probabilistic Water Table analysis.

Exponential Distribution

For this analysis, we used a Normal Distribution of the Water Table elevation random variable.

It should be noted that an Exponential Distribution can also be useful for modeling the elevation of a Water Table. An Exponential Distribution could be used to simulate the infrequent occurrence of high water tables, and introduce a time dimension to the probabilistic analysis.

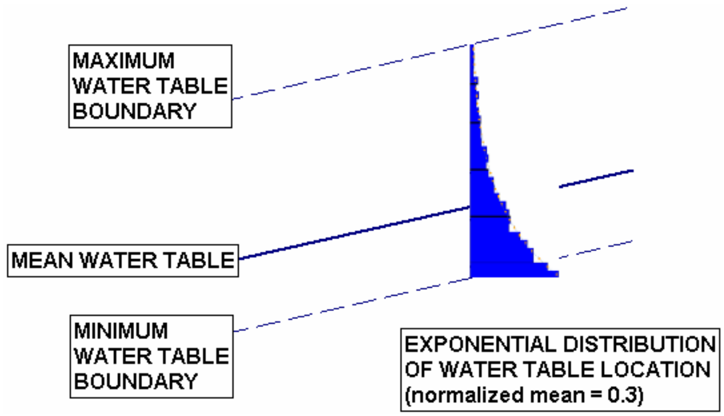


Figure 3-10: Exponential Distribution of Water Table elevation.

Re-run the analysis, using an Exponential Distribution for the Water Table random variable, and a Normalized Mean = 0.3. NOTE that a Standard Deviation is not entered for an Exponential Distribution, because by definition, the Standard Deviation = the Mean for an Exponential Distribution.

Because the Normalized Mean = 0.3, you will notice that the Minimum Water Table which is automatically generated, is now closer to the Mean Water Table, compared to the previous analysis with Normalized Mean = 0.5.

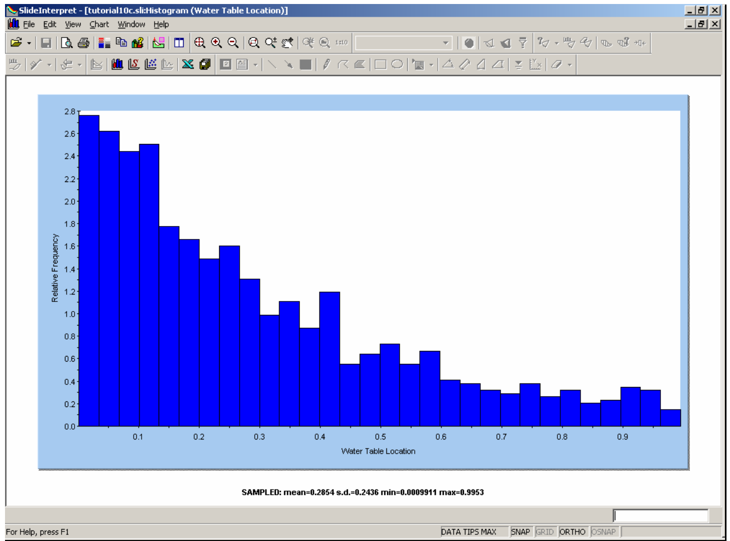


Figure 3-11: Histogram of samples generated by Exponential Distribution.

The exponential distribution simply implies that most of the Water Tables which are generated during the Probabilistic Analysis, will be towards the lower elevations, and relatively few samples will be generated at the higher elevations.

Ponded Water / Drawdown Analysis

A variable height of Ponded Water above a slope, can also be modeled in a Sensitivity or Probabilistic Water Table analysis with SLIDE.

If the Maximum Water Table boundary is located ABOVE the slope at any location, then Ponded water will be automatically created, as necessary, between the Water Table and the slope, in exactly the same manner, as for a regular (DETERMINISTIC) Water Table.

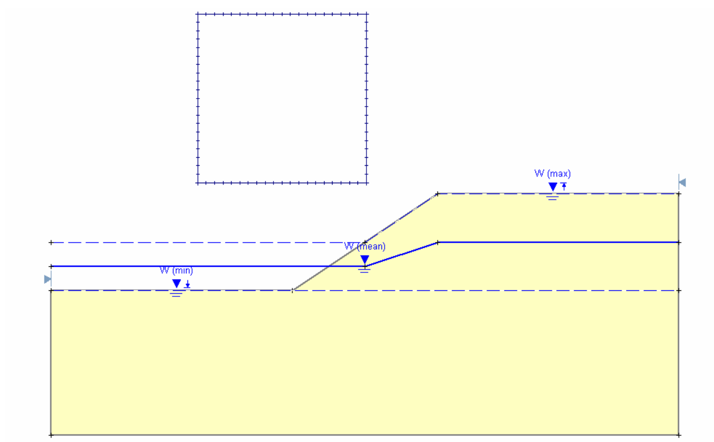


Figure 3-12: Variable ponded water elevation.

NOTE: to ensure that the (variable) ponded water surface remains horizontal, for all possible water tables which are generated, the Minimum Water Table boundary should include a horizontal segment which has the same lateral extents as the ponded water surface of the Maximum Water Table.

Using a Sensitivity Analysis, a drawdown scenario could be quickly analyzed in this manner.

Also note: when you define probabilistic Water Table boundaries above a slope, Ponded Water is NOT graphically displayed on the model. Ponded water will be automatically created and taken into account during the analysis, whenever necessary, but it will not be visible on the model.

Tension Crack Statistics

Finally, we will note that the statistical analysis of a variable Tension Crack boundary, is carried out in exactly the same way as for a Water Table, as described in this tutorial.

In addition, the water level in the Tension Crack can also be specified as a random variable. This is left as an optional exercise for the user to experiment with.

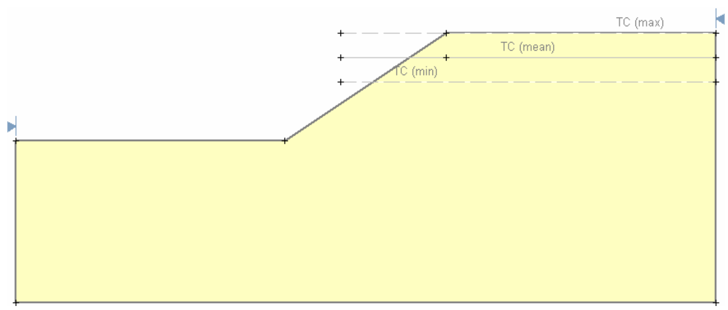
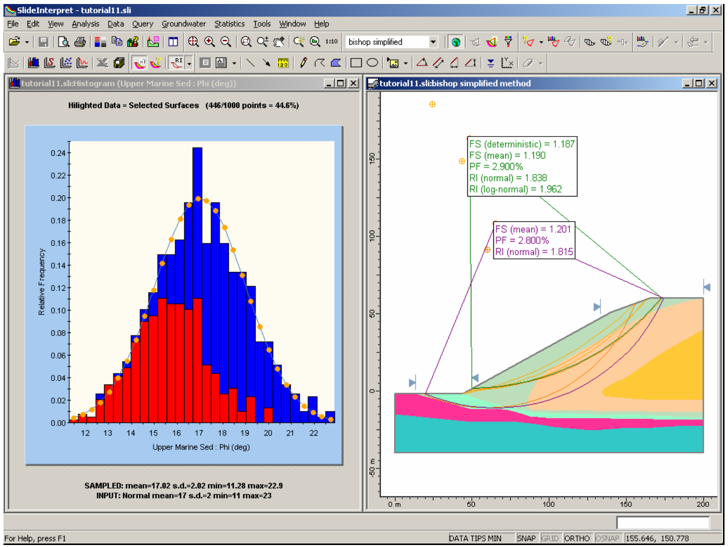


Figure 3-13: Variable tension crack elevation.

See the SLIDE Help system for more information about Water Table and Tension Crack statistics.

Overall Slope Reliability



This tutorial will demonstrate the Overall Slope probabilistic analysis method in SLIDE.

NOTE: the finished product of this tutorial can be found in the **tutorial11.sli** data file, which you should find in the EXAMPLES folder in your SLIDE installation folder.

Introduction

In SLIDE, there are two types of Probabilistic Analysis which can be carried out.

1. Probabilistic Analysis Type = Global Minimum

2. Probabilistic Analysis Type = Overall Slope

With the Global Minimum method, the probabilistic analysis is carried out ONLY on the deterministic Global Minimum slip surface.

It is assumed that the Probability of Failure (or the Reliability) of the deterministic Global Minimum slip surface, is representative of the Probability of Failure for the slope.

This method is a commonly used approach to probabilistic slope stability, and was demonstrated in the first tutorial in this User's Guide.

Overall Slope Method

The Overall Slope Probabilistic Analysis Type in SLIDE represents a different approach to the probabilistic analysis of slope stability.

1. With the Overall Slope method in SLIDE, the ENTIRE SEARCH for a Global Minimum slip surface, is repeated N times (where N = Number of Samples). For each search iteration, a new set of random variable samples is first loaded, and the search is carried out.

2. A Global Minimum slip surface, FOR EACH SEARCH iteration, is then determined. This will generally result in the location of SEVERAL different Global Minimum slip surfaces (for example, 10 to 50 surfaces might typically be located), corresponding to different values of the sampled input data random variables.

There are two important results which are derived from the Overall Slope Probabilistic Analysis:

- The Overall Slope Reliability

- The Critical Probabilistic Surface

Overall Slope Reliability

The Overall Slope Reliability is based on the distribution of safety factors obtained from ALL of the Global Minimum slip surfaces located by the analysis.

Because multiple Global Minimum slip surfaces will (in general) be located, the Overall Slope Reliability is not associated with a specific slip surface, but instead, can be considered truly representative of the entire slope. Hence the name “Overall Slope” analysis method.

From the Overall Slope analysis, we may calculate both:

- Probability of Failure
- Reliability Index

The definition of the Probability of Failure, for the Overall Slope method, is the same as for the Global Minimum method. That is, the Probability of Failure is the number of analyses which result in a safety factor less than 1, divided by the total Number of Samples.

Similarly, the Reliability Index is calculated using the same equations discussed in the first tutorial (see the Probabilistic Analysis tutorial, the first tutorial in this User’s Guide).

Just remember that the PF and RI calculated for the Overall Slope, are not associated with a specific slip surface, but include the safety factors of ALL Global Minimum slip surfaces from the Overall Slope Probabilistic Analysis.

Critical Probabilistic Surface

Another result which follows from an Overall Slope Probabilistic Analysis, is the Critical Probabilistic slip surface.

The Critical Probabilistic Surface is the individual slip surface which has the Minimum Reliability Index (and also the maximum Probability of Failure).

It is important to note that the Critical Probabilistic Surface IS NOT NECESSARILY THE SAME AS THE CRITICAL DETERMINISTIC SLIP SURFACE. In general, the Critical Probabilistic Surface and the Critical Deterministic Surface (ie. the deterministic Global Minimum slip surface), can be different surfaces.

Critical Deterministic Surface

During the Overall Slope probabilistic analysis, the program also keeps track of the Probability of Failure and Reliability Index for the Critical Deterministic Surface (ie. the deterministic Global Minimum slip surface – the slip surface with the minimum safety factor, when all input parameters are equal to their mean values).

The Probability of Failure and Reliability Index which are calculated for this surface, are the same as would be calculated by running the Global Minimum probabilistic analysis method.

Summary of Results

An Overall Slope probabilistic analysis with SLIDE, therefore provides THREE distinct sets of results.

We can rank these results from LOWEST Reliability Index to HIGHEST Reliability Index (OR the equivalent, HIGHEST probability of failure, to LOWEST probability of failure), as follows:

1. The Overall Slope Results – in general, the Overall Slope Results will give the LOWEST Reliability Index (and the HIGHEST Probability of Failure), because "failure" can occur along any surface in the slope. The analysis is not restricted to a single slip surface.

2. The Critical Probabilistic Surface – the Critical Probabilistic Surface will (in general), have a HIGHER Reliability Index than the Overall Slope results (and a lower Probability of Failure).

3. The Critical Deterministic Surface – the Critical Deterministic Surface will (by definition), have a HIGHER Reliability Index than the Critical Probabilistic Surface, IF THE TWO SURFACES ARE DIFFERENT. If the two surfaces are the same, then the results will of course be equal.

The potential advantage of the Overall Slope method, compared to the Global Minimum method, is that the Overall Slope method does NOT assume that the Probability of Failure for the slope, is equal to the Probability of Failure of the Deterministic Global Minimum slip surface.

The interpretation and application of these results for slope design purposes, is the responsibility of the geotechnical engineer. It is not possible to make a general statement regarding which Probability of Failure or Reliability Index should be used, as this may vary considerably, depending on the model, and the goals of the analysis.

Time to Run Analysis

The Overall Slope method involves a substantially greater computation time than the Global Minimum method, because the entire slip surface search is repeated for each set of random samples. Depending on the Number of Samples, and the complexity of your model, the Overall Slope Probabilistic Analysis in SLIDE, can take SEVERAL HOURS to complete.

In general, you may wish to run an Overall Slope probabilistic analysis, at the end of a day, as an overnight run. Remember that the SLIDE Compute Engine can run multiple files in succession, so you can set up several files for an Overall Slope Probabilistic Analysis, and run the analyses overnight.

Model

For this tutorial, we will read in a file.

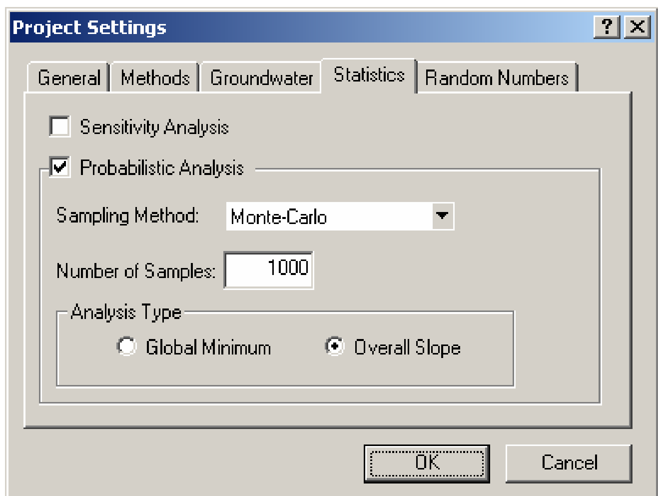
Select: File → Open

Open the **tutorial11.sli** file, which you will find in the EXAMPLES folder in your SLIDE installation folder.

The model is already completed, so we will note the following significant features of the model, and then view the analysis results.

Project Settings

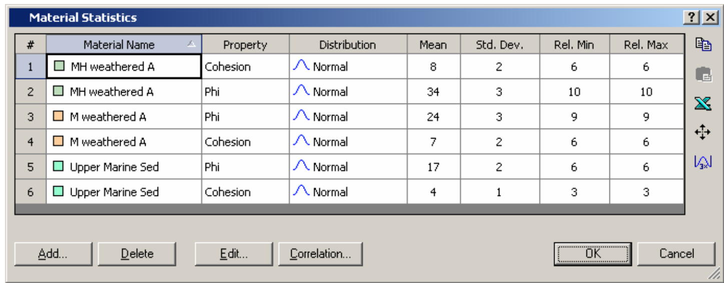
Go to the Project Settings dialog, and select the Statistics tab.



Notice that the Probabilistic Analysis Type = Overall Slope. Select Cancel or Escape.

Material Statistics

Go to the Material Statistics dialog (in the Statistics menu). Notice that we have defined the Cohesion and Friction Angle for 3 different materials, as Random Variables (for a total of 6 Random Variables). All variables have Normal distributions.



Also select the Correlation button in the Material Statistics dialog. We have defined a correlation coefficient of –0.5 for each material, to ensure that the Cohesion and Friction Angle of each material, are correlated during the statistical sampling.

Select Cancel in both dialogs.

Surface Options

Select Surface Options from the Surfaces menu.

Notice that we will be performing a Circular surface search, using the Slope Search method. The Number of Surfaces = 500.

Select Cancel in the dialog.

Compute

As we mentioned earlier, the Overall Slope probabilistic analysis, can take a fairly long time to complete – anywhere from a few minutes, to several hours, depending on the complexity of your model, the number of slip surfaces, and the number of samples.

This particular model takes several minutes to run, so the analysis results have already been supplied with the input file.

So you can skip the Compute, and proceed directly to Interpret. (Or if you wish, you can Compute the file to view the analysis progress).

Interpret

Select the Interpret option in the SLIDE MODEL program, and you should see the following results.

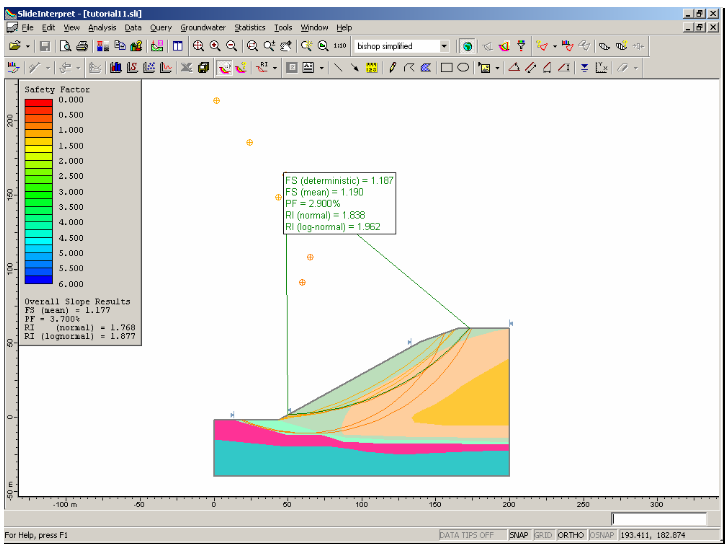


Figure 4-1: Results of Overall Slope probabilistic analysis.

After an Overall Slope probabilistic analysis, you will initially see the following probabilistic results displayed on the model:

- The Overall Slope probabilistic results
- Probabilistic results for the Critical Deterministic Surface

Overall Slope Results

A summary of the Overall Slope probabilistic results is displayed in the Legend. This includes:

- Mean Safety Factor
- Probability of Failure
- Reliability Index (both Normal and Lognormal)

These results correspond to the slip surfaces which you see displayed on the model. These slip surfaces are ALL of the different Global Minimum slip surfaces, located by the Overall Slope probabilistic analysis.

In this case, we can see that 6 different Global Minimum surfaces have been located. Furthermore, it is interesting that the slip surfaces are grouped in two distinct bands:

- Two of the GM Surfaces are deep seated, and exit the slope through the light green layer.
- The other surfaces exit near the toe of the slope, and only traverse the upper two materials.

The display of these surfaces can be toggled ON or OFF with the Show GM Surfaces option in the Statistics menu.

Select: Statistics → Show GM Surfaces

Notice that the summary of Overall Slope results in the Legend, also toggles on and off with the Show GM Surfaces option. Turn the Show GM Surfaces option ON.

Critical Deterministic Surface

A summary of the probabilistic analysis results is also displayed for the Critical Deterministic slip surface (ie. the Deterministic Global Minimum slip surface).

The Critical Deterministic Surface is the slip surface with the lowest safety factor, when all input parameters are equal to their mean values. This is the same surface that you would see displayed if you were only running a Deterministic Analysis.

The probabilistic results for this surface, after an Overall Slope analysis, are THE SAME values that you would obtain if you were only running the Probabilistic Analysis on this surface (ie, Probabilistic Analysis Type = Global Minimum in the Project Settings dialog in the SLIDE MODEL program).

The display of this surface can be toggled on or off with the Global Minimum option in the toolbar or the Data menu. Leave the display on for now.

Critical Probabilistic Surface

The Critical Probabilistic Surface can also be displayed, after an Overall Slope probabilistic analysis, by selecting the Show Critical Probabilistic Surface option from the toolbar or the Statistics menu.

Select: Statistics → Crit.Prob.Surface → Show Crit.Prob.Surface

The Critical Probabilistic Surface is the individual slip surface with the LOWEST Reliability Index, of all surfaces analyzed.

It is important to note that the Critical Probabilistic Surface, and the Critical Deterministic Surface, ARE NOT NECESSARILY THE SAME SURFACE. For this analysis, the two surfaces are quite different.

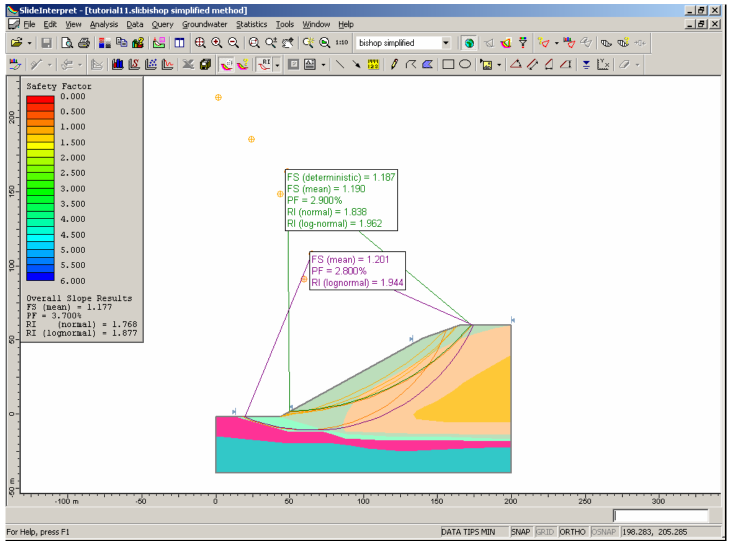


Figure 4-2: Critical Probabilistic and Critical Deterministic surfaces.

Notice that the Reliability Index (lognormal) of the Critical Probabilistic Surface, is slightly less than the Reliability Index (lognormal) of the Critical Deterministic Surface.

For the Critical Probabilistic Surface, it is possible that TWO different surfaces are located, depending on the assumption of a Normal or a Lognormal distribution of the Safety Factor.

The results for either assumption can be displayed, by selecting the desired option from the drop menu shortcut, beside the Show Critical Probabilistic Surface toolbar button.

Select either option. In this case, the slip surface is the SAME for either assumption.

Summary of Probabilistic Results

The following table summarizes all of the results which are presented after an Overall Slope probabilistic analysis, for this model.

	PF (%)	RI (normal)	RI (lognormal)	FS (mean)
Overall Slope	3.7	1.768	1.877	1.177
Crit. Prob. Surface (Normal)	2.8	1.815	–	1.201
Crit. Prob Surface (lognormal)	2.8	–	1.944	1.201
Crit. Det. Surface	2.9	1.838	1.962	1.19

This type of summary is very useful for organizing the main analysis results, after an Overall Slope analysis.

Notice that the ranking of the data by Reliability Index, is as we discussed earlier in this tutorial. The Overall Slope results give the LOWEST Reliability Index, followed by the Critical Probabilistic and Critical Deterministic results.

Similarly, the Overall Slope results show the HIGHEST probability of failure.

Info Viewer

More detailed summaries of analysis results are displayed in the Info Viewer.

Select: Analysis → Info Viewer

Scroll down to the bottom of the Info Viewer. There you will find a more detailed summary of the Overall Probabilistic Analysis Results, and the Critical Probabilistic Surface Results.

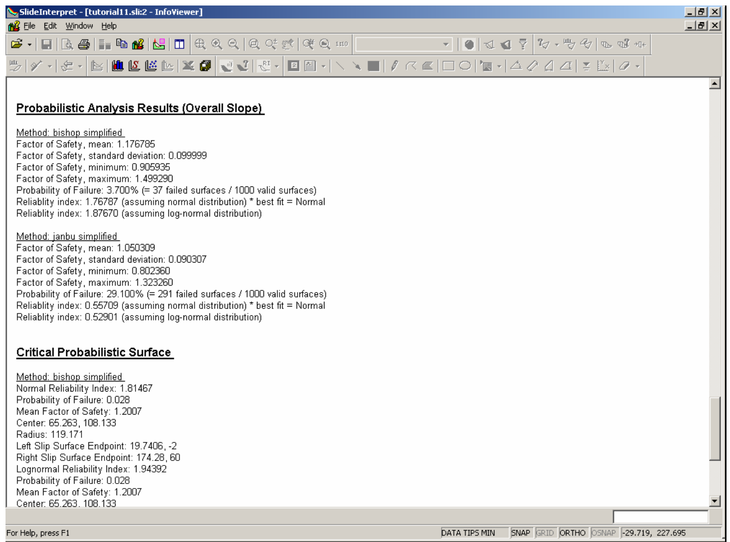


Figure 4-3: Info Viewer summary of probabilistic analysis results.

Close the Info Viewer view.

Number of Analyses Per Surface

The slip surfaces displayed by the Show GM Surfaces option, represent all of the different Global Minimum slip surfaces which were located by the Overall Slope probabilistic analysis.

In general, each of these slip surfaces will correspond to multiple runs of the probabilistic analysis. The actual number of runs of the probabilistic analysis, which correspond to each Global Minimum slip surface, can be interactively viewed as a data tip, by simply hovering the mouse over any surface.

First do the following:

1. Turn OFF the display of the Critical Deterministic and Critical Probabilistic surfaces, if they are still displayed.

2. Zoom in to the slip surfaces (use Zoom Window for example).

3. Make sure the Data Tips option is enabled in the Status Bar. (Click on the Data Tips box until either Data Tips Min or Data Tips Max is displayed. Data Tips can also be toggled in the View menu).

Now hover the mouse over any of the GM slip surfaces which are displayed.

For example, hover the mouse over the lowest slip surface on the model. The data tip should indicate that 23% of the analyses (230 / 1000) located that surface as the Global Minimum surface. Also, the range of calculated safety factors for the slip surface is displayed.

Hover the mouse over each surface, to see how many analyses correspond to each surface. In this case, the Critical Deterministic Surface, corresponds to the greatest number of analyses (409 / 1000). This information is very important, with respect to the Overall Slope probabilistic results.

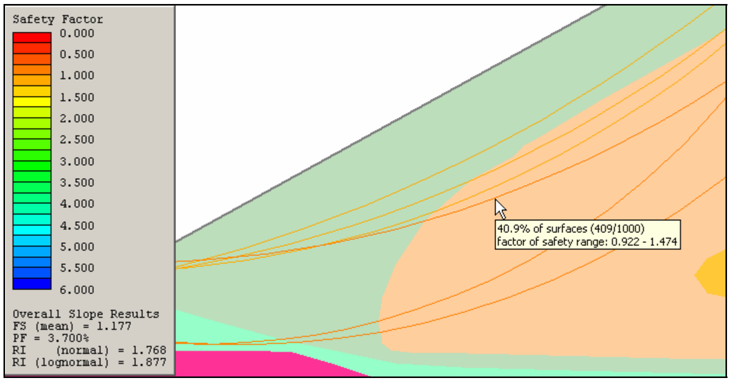


Figure 4-4: Data tip display – number of analyses per surface.

When a slip surface displayed by the Show GM Surfaces option has a relatively large number of corresponding analyses, then this surface should be given the appropriate consideration in the slope design.

Conversely, some of the slip surfaces displayed by the Show GM Surfaces option, may only correspond to one or two analyses. This would indicate a very small probability of that surface occurring as a potential failure surface, and therefore may not need to be considered in the slope design.

Safety Factor Data

It is important to realize that the Safety Factor data, after an Overall Slope Probabilistic analysis, is the data obtained from all of the different surfaces displayed by the Show GM Surfaces option.

For example, if you plot a Histogram of Safety Factor, the distribution of Safety Factors, and the Mean Safety Factor, apply to the Overall Slope results.

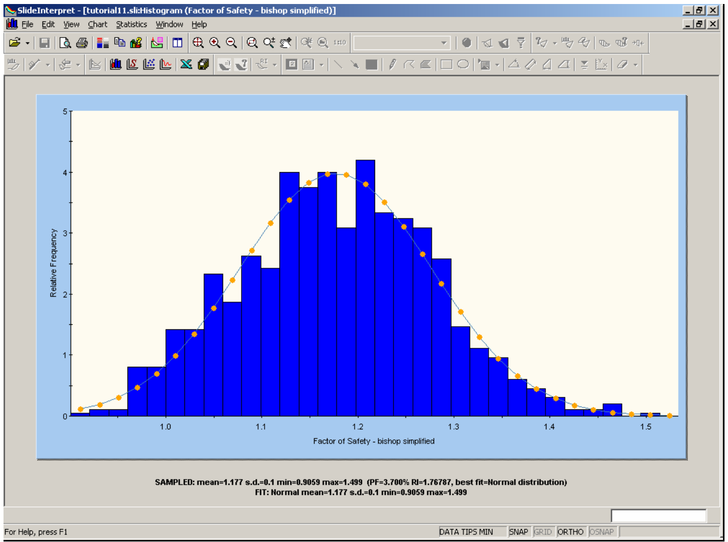


Figure 4-5 Safety factor distribution – overall results.

You cannot plot the distribution of safety factor, for individual slip surfaces, after an Overall Slope Probabilistic analysis.

If you wish to view the distribution of Safety Factor for the Deterministic Global Minimum slip surface, then you can simply re-run the analysis, with the Probabilistic Analysis Type = Global Minimum in Project Settings.

Pick GM Surfaces

The Pick GM Surfaces option allows you to view the Probabilistic Analysis results associated with any individual surface or any combination of surfaces displayed by the Show GM Surfaces option.

For example, let's say that we wanted to find out which randomly generated material properties corresponded to the two deep-seated Global Minimum surfaces. You could do this as follows.

1. Select the Pick GM Surfaces option from the toolbar or the Statistics menu. (The Show GM Surfaces option will automatically be toggled ON, if it was not already).

2. Use the mouse to select these two surfaces. TIP – you may need to zoom in first. Surfaces are selected by clicking on them with the left mouse button. When a surface is selected, it will be highlighted by a dashed line.

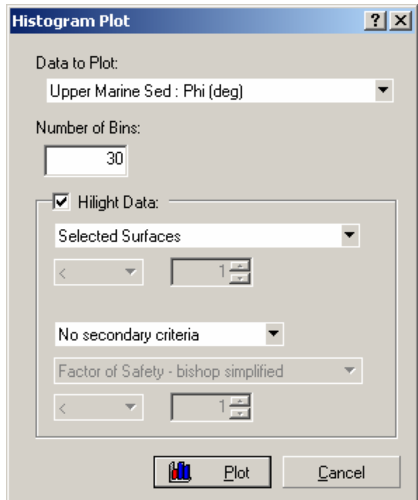
3. NOTE: if you accidentally select surfaces that you did not want to select, simply click on the surface(s) again with the left mouse button, and the surface(s) will no longer be selected (highlighted).

4. When the desired surfaces are selected, RIGHT CLICK the mouse. You will see a popup menu, with two plotting options available – Histogram Plot or Scatter Plot.

5. Select Histogram Plot and you will see the Histogram Plot dialog.

6. In the dialog, select Data to Plot = "Upper Marine Sediment : Phi (deg)".

7. Now (this is the important part !!!) – in the dialog, select the Highlight Data checkbox. Click on the drop-down list of data to highlight. At the BOTTOM of this list, you will see an option called Selected Surfaces. Select this option.



8. Now select the Plot button in the dialog, and the desired plot will be generated. The highlighted data on the plot, is the data corresponding to the two GM surfaces that you have selected. The plot should appear as in the following figure.

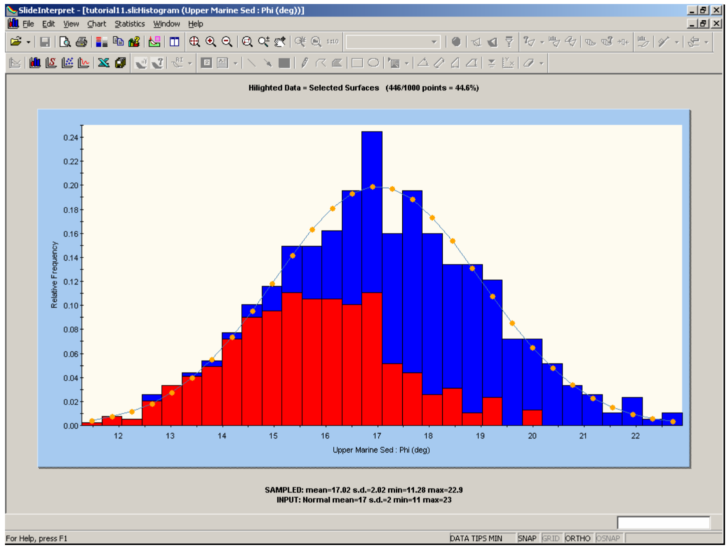


Figure 4-6: Highlighted data for selected surfaces.

We have plotted the Friction Angle of the light green material (Upper Marine Sediment). This is the material through which a significant portion of these two slip surfaces passes through.

The highlighted data on the plot indicates that predominantly LOW Friction Angles of the Upper Marine Sediment material, are associated with these two slip surfaces. This is consistent with the analysis results.

Also notice at the top of the plot, it indicates:

Highlighted Data – Selected Surfaces (446 / 1000) = 44.6%

If you return to the model view, and hover the mouse over each of these two surfaces, you will find that the number of analyses corresponding to each surfaces is 230 and 216. The sum of these numbers = 446, the total number of highlighted data samples indicated on the Histogram, for the two selected surfaces.

If desired, you can right-click on the plot and select the Highlighted Data Only option, to view ONLY the data for the selected surfaces. All other plotting options can also be used (for example, export the data to Excel, or the clipboard, for further processing in other applications).

In conclusion, the Pick GM Surfaces option is useful for determining which subsets of probabilistic input data, or safety factor, correspond to any individual surface, or any group of surfaces, displayed by the Show GM Surfaces option.

That concludes this demonstration of the Overall Slope probabilistic analysis method in SLIDE.

Additional Exercise

In this example, the number of slip surface used in the Slope Search, was a relatively low number (500).

This was done so that the analysis could be computed relatively quickly. However, this number should really be increased, to carry out the analysis more thoroughly.

Using the same model, enter 1000 surfaces in the Surface Options dialog, and re-run the analysis. Depending on the speed of your computer, this may take a bit of time, half an hour to an hour approximately.

Now view the analysis results. You will see that the Overall Slope Analysis has now located several additional Global Minimum surfaces (displayed by the Show GM Surfaces option). Compare the Overall Probability of Failure and Reliability Index, with the numbers presented in this tutorial.

If you have the time, try re-running the analysis with even more surfaces (eg. 5000), as an overnight analysis.

The Overall Slope probabilistic analysis option in SLIDE presents the user with a wide range of powerful analysis and data interpretation options, not previously available in slope stability software. The user is encouraged to experiment with and explore these options.