rocscience

Overall Slope Reliability Tutorial

1. Introduction

This tutorial will demonstrate the Overall Slope probabilistic analysis method in **Slide2.**

In Slide2, 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 Tutorial 08.

A Probabilistic Analysis with Spatial Variability can also be carried out – this is explained in Tutorials 33 and 34.

The finished product of this tutorial can be found in the *Tutorial 11 Overall Slope Reliability.slmd* data file. All tutorial files installed with Slide2 can be accessed by selecting **File > Recent Folders > Tutorials Folder** from the Slide2 main menu.

2. Overall Slope Method

The Overall Slope Probabilistic Analysis Type in Slide2 represents a different approach to the probabilistic analysis of slope stability.

1. With the Overall Slope method in Slide2, 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

When running a Probabilistic Analysis with Spatial Variability, the Overall Slope option is selected by default in order to account for the changing material parameters.

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 Tutorial 08 (Probabilistic Analysis tutorial).

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 (i.e. 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 (i.e. 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 Slide2, 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 Slide2, 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 Slide2 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.

To alleviate this problem, the Response Surface sampling method has been added as an option to Slide2. The Response Surface method uses a small number of strategically

selected computations to create a response surface of factor of safety (FS) values for various combinations of input parameters. It then predicts the factor of safety values for any combination of samples and provides an estimated probability of failure. This method is advantageous in significantly cutting down computation time for an Overall Slope analysis.

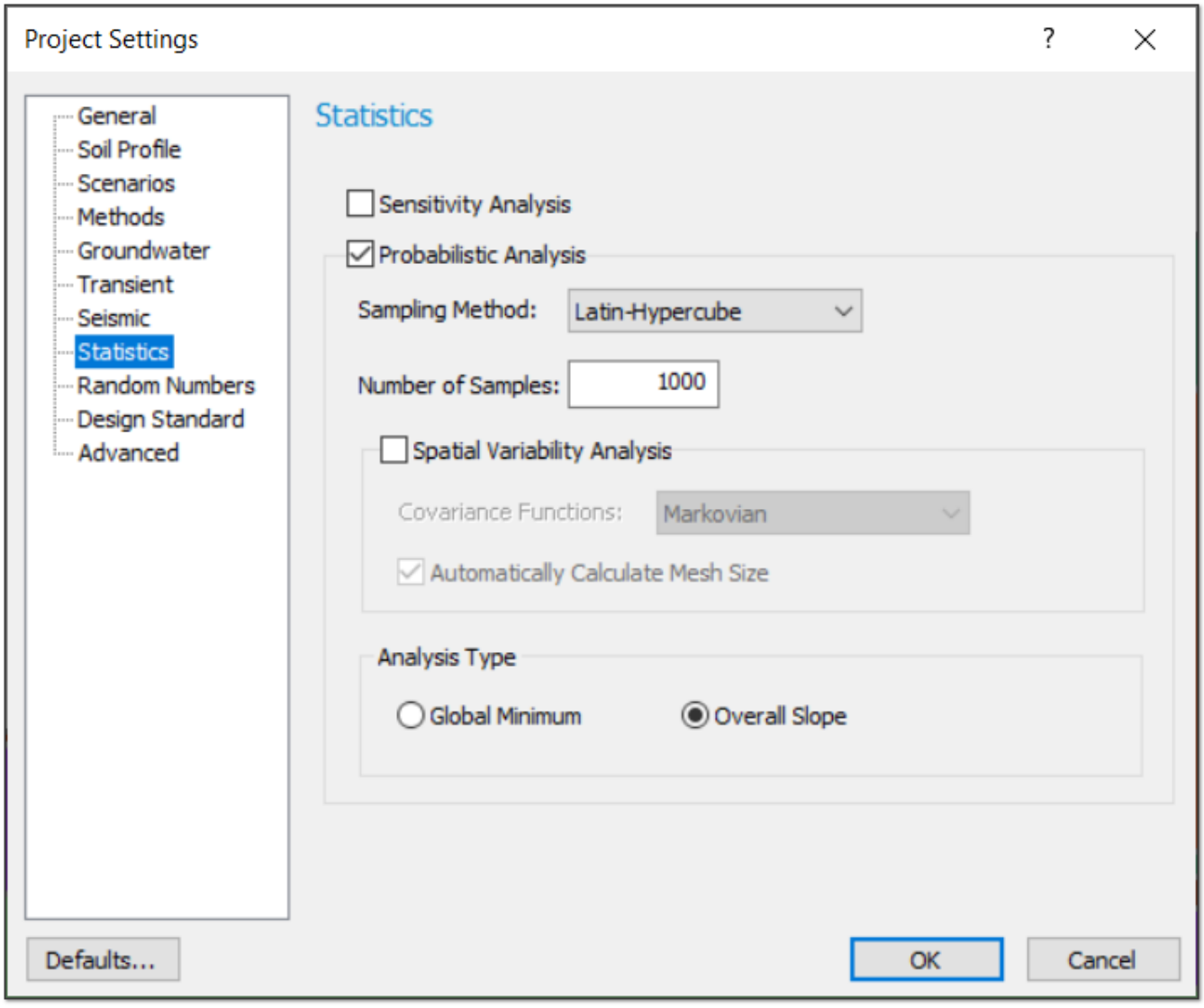
Model

For this tutorial, we will read in a file. Select **File > Recent Folders > Tutorials Folder** from the Slide2 main menu, and open the Tutorial 11 Overall Slope Reliability.slmd file.

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.

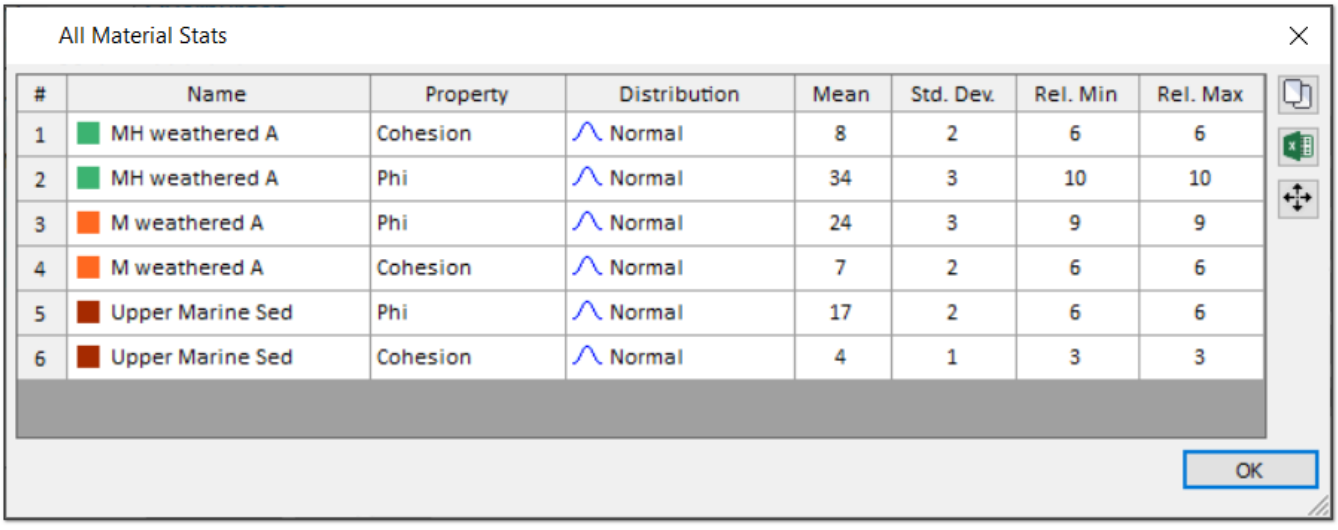


Notice that the **Probabilistic Analysis Type = Overall Slope**. Click **Cancel**.

MATERIAL STATISTICS

Go to the **Material Statistics** dialog (in the **Statistics** menu) and click the **Show All** button. 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. Click **OK.**

Name	Property	Mean	Std. Dev	Rel. Min	Rel. Max
MH Weathered A	Cohesion	8	2	6	6
MH Weathered A	Phi	34	3	10	10
M Weathered A	Phi	24	3	9	9
M Weathered A	Cohesion	7	2	6	6
Upper Marine Sed	Phi	17	2	6	6
Upper Marine Sed	Cohesion	4	1	3	3



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.

Click **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 = 1000.

Select **Cancel** in the dialog.

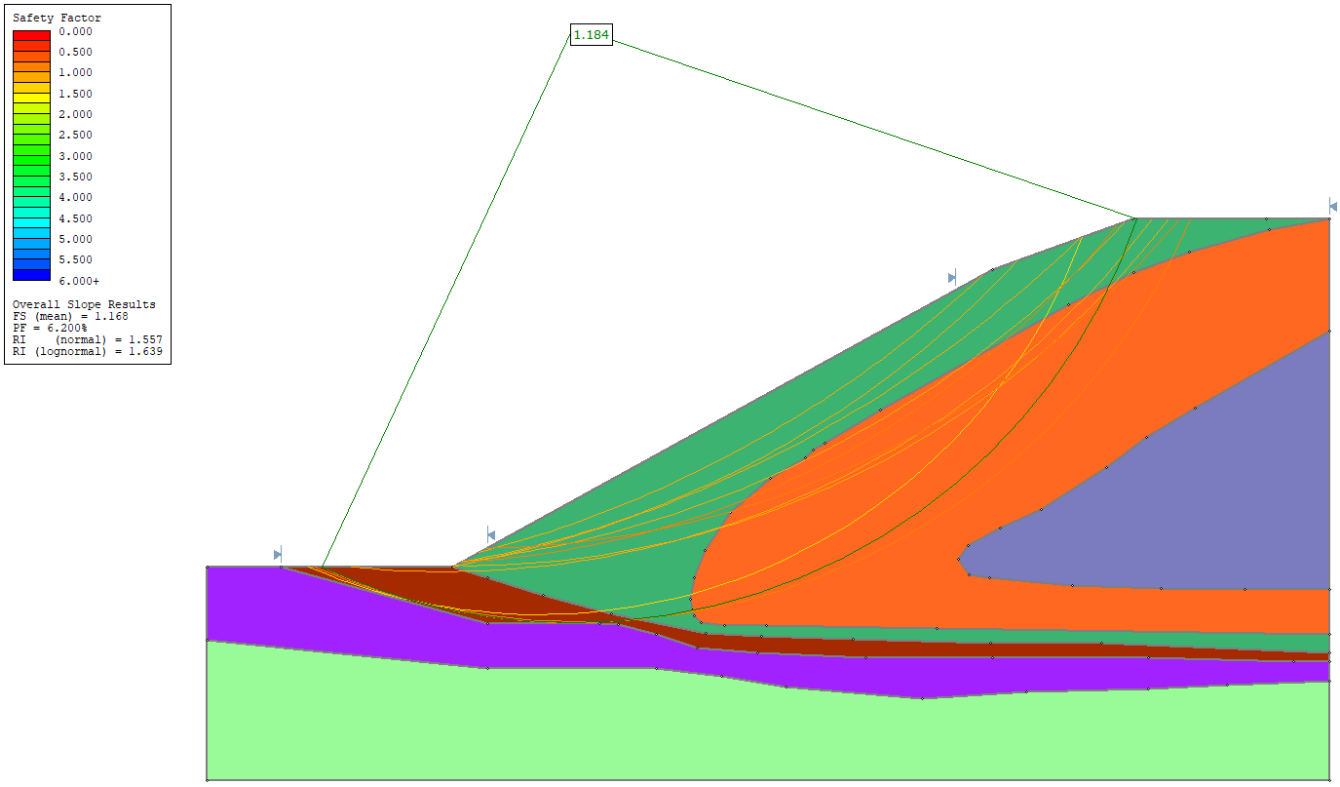
COMPUTE

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, the search method and the number of samples.

This particular model only takes a minute or so to run. Select **Compute** to view the analysis progress.

INTERPRET

Select the Interpret option in the Slide2 Model program, and you should see the following results. Use the Zoom and Pan options to zoom in on the model.



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
- 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 several different Global Minimum surfaces have been located. Furthermore, it is interesting that the slip surfaces are grouped in two distinct bands:

- Several GM surfaces only traverse the upper two materials and exit near the toe of the slope.
- Other GM Surfaces are more deep seated, and exit the slope through the Upper Marine Sediment layer (dark red).

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

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.

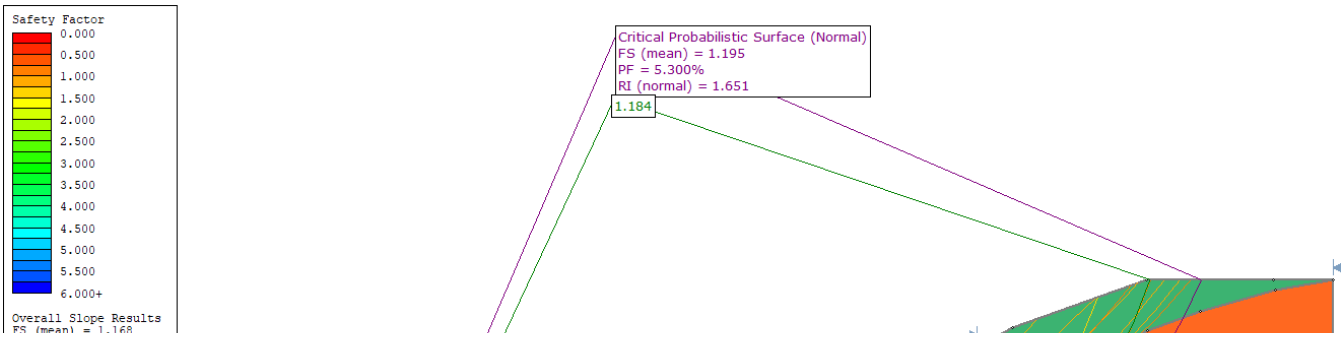
CRITICAL PROBABILISTIC SURFACE

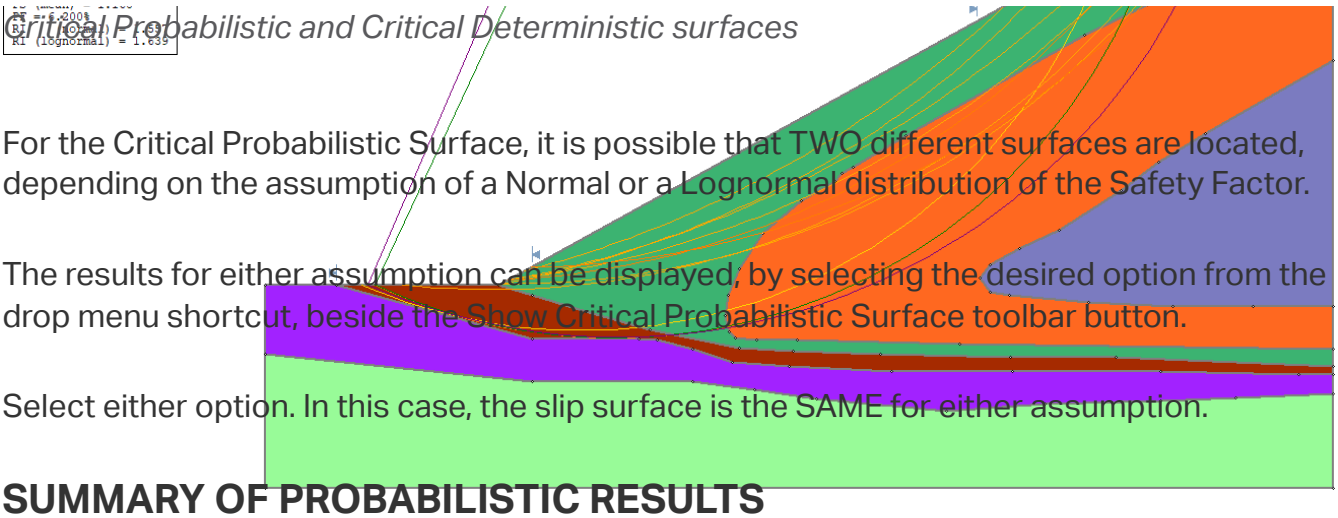
The Critical Probabilistic Surface can also be displayed, after an Overall Slope probabilistic analysis, by selecting the Show Critical Probabilistic Surface option from the toolbar or the Statistics menu.

Select: **Statistics → Critical Probabilistic Surface → Show Critical Probabilistic 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 different.





Critical Probabilistic and Critical Deterministic surfaces

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	6.2	1.557	1.639	1.168
Critical Prob. Surface (Normal)	5.3	1.651	-	1.195
Critical Prob. Surface (Lognormal)	5.3	-	1.757	1.195
Crit. Deterministic Surface	5.2	1.659	1.762	1.186

Summary of probabilistic results.

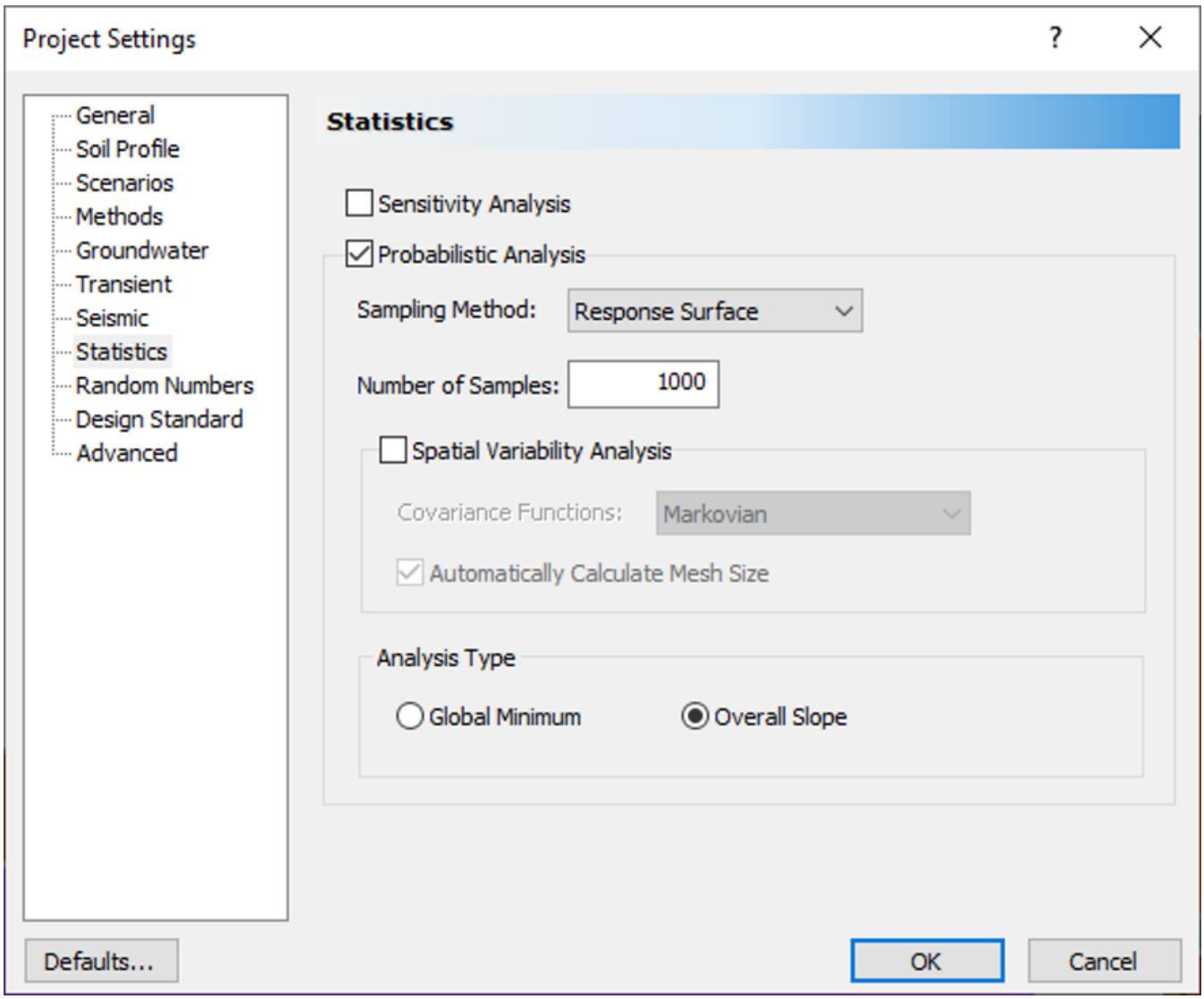
This type of summary is very useful for organizing the main analysis results, after an Overall Slope analysis.

Notice the ranking of the data by Reliability Index: 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.

RESPONSE SURFACE

This example has been set up to be fast in order to be of use as a tutorial. However, as has been mentioned, an Overall Slope analysis can take hours and is generally run overnight. To alleviate this problem, the Response Surface sampling method was introduced into Slide2. This same model can be computed with Response Surface by adding a new scenario and changing the Sampling Method in the Project Settings:



It has been computed here for comparison with the Latin Hypercube sampling method. The results are found below:

Sampling Method	Probability of Failure	Mean FS	Computation Time (sec)
Latin Hypercube	6.2%	1.168	17.5
Response Surface	6.3%	1.167	3.1

In this example the probability of failure and mean FS values are in very good agreement but using Response Surface reduces the computation time by about 80%.

REPORT GENERATOR

More detailed summaries of analysis results are displayed in the Report Generator.

Select: **Analysis → Report Generator**

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

Probabilistic Analysis Results (Overall Slope)

Method: bishop simplified
Factor of Safety, mean: 1.167585
Factor of Safety, standard deviation: 0.107610
Factor of Safety, minimum: 0.815354
Factor of Safety, maximum: 1.526090
Probability of Failure: 6.200% (= 62 failed surfaces / 1000 valid surfaces)
Reliability index: 1.55734 (assuming normal distribution)
Reliability index: 1.63867 (assuming lognormal distribution)
* best fit = Gamma

Critical Probabilistic Surface

Method: bishop simplified
Normal Reliability Index: 1.65073
Probability of Failure: 0.053
Mean Factor of Safety: 1.19529
Center: 66.2607, 106.868
Radius: 118.609
Left Slip Surface Endpoint: 19.1884, -2
Right Slip Surface Endpoint: 175.217, 60
Lognormal Reliability Index: 1.75737
Probability of Failure: 0.053
Mean Factor of Safety: 1.19529
Center: 66.2607, 106.868
Radius: 118.609
Left Slip Surface Endpoint: 19.1884, -2
Right Slip Surface Endpoint: 175.217, 60

Report Generator summary of probabilistic analysis results.

Close the Report Generator 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. Turn OFF the Material Colours (in the sidebar > Display Options > General) so that the surfaces are more easily visible.
3. Zoom in to the slip surfaces (use Zoom Window for example).
4. 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 7.0% of the analyses (70 / 1000) located that surface as the Global Minimum surface. Also, the range of calculated safety factors for the slip surface is displayed.

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.

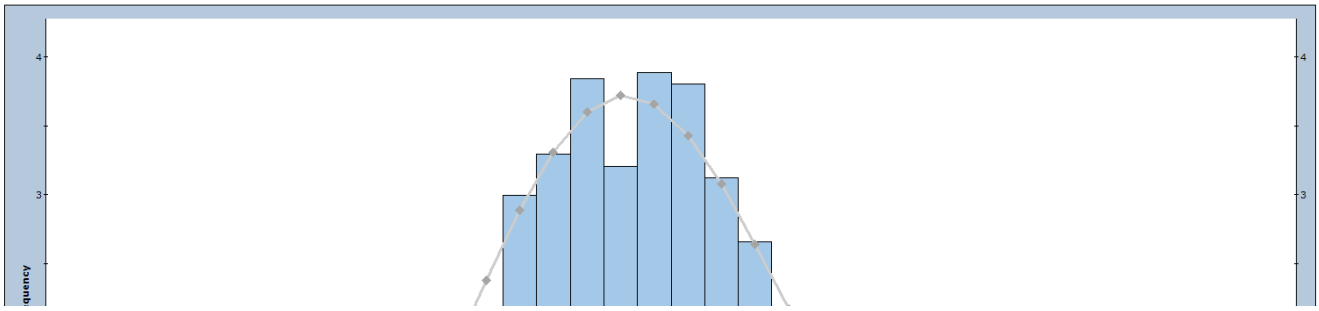
SAFETY FACTOR DATA

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.

To view the below Histogram:

1. Select **Statistics > Histogram Plot.** A new dialog will appear.
2. Select **Factor of Safety** as **Data to plot.**
3. Uncheck **Highlight data.**
4. Click **Plot**.
5. The histogram will appear. Right click the histogram and select **Best Fit Distribution**.



Safety factor distribution – overall results

To plot the distribution of safety factor for individual GM slip surfaces after an Overall Slope Probabilistic analysis, you can use the Pick GM Surfaces option as described below.

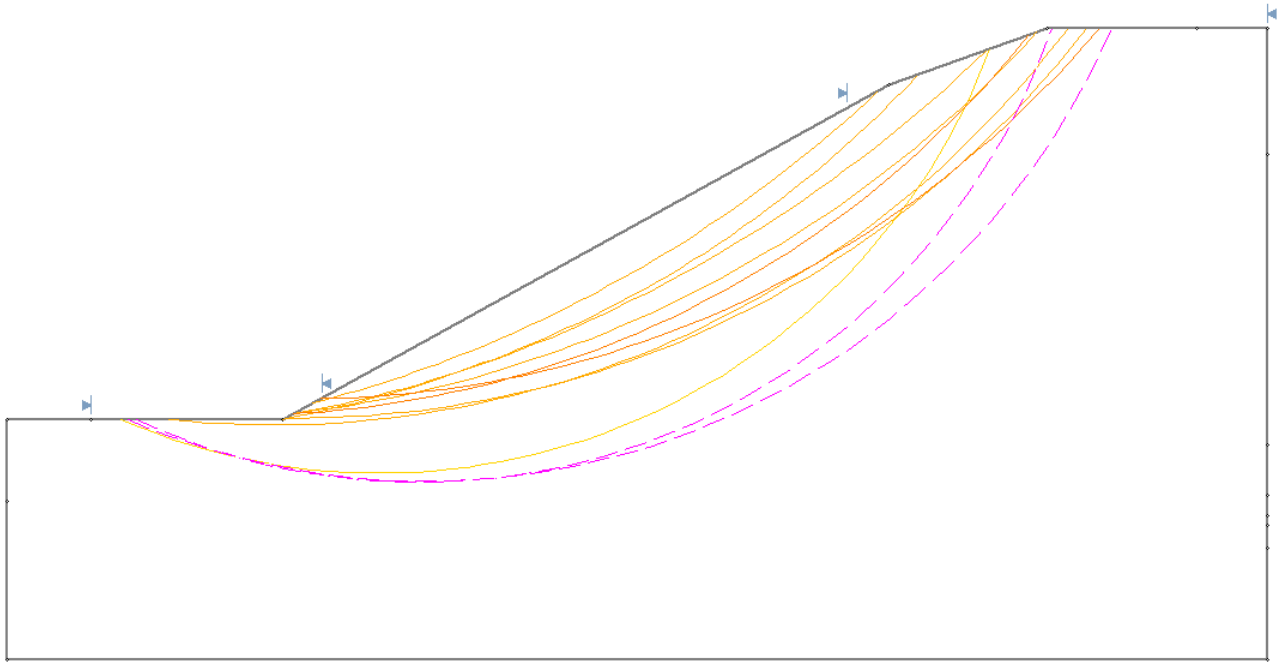
Alternatively, to view the distribution of Safety Factor for the Deterministic Global Minimum slip surface, you can simply re-run the analysis, with the Probabilistic Analysis Type = Global Minimum in Project Settings.

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.

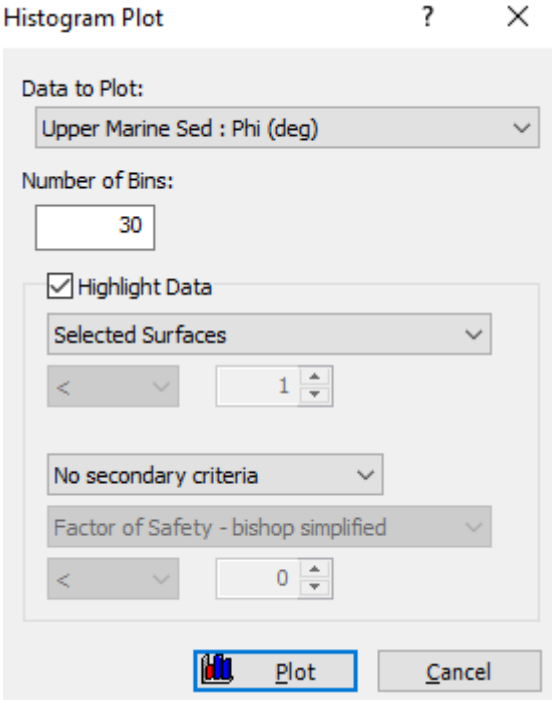
1. Select the Pick GM Surfaces option from the toolbar or the Statistics menu. (The Show GM Surfaces option will automatically be toggled ON, if it was not already).
2. Use the mouse to select these two surfaces. TIP – you may need to zoom in first. Surfaces are selected by clicking on them with the left mouse button. When a surface is selected, it will be highlighted by a dashed line as shown below. (Note: the second surface is the global minimum surface.)



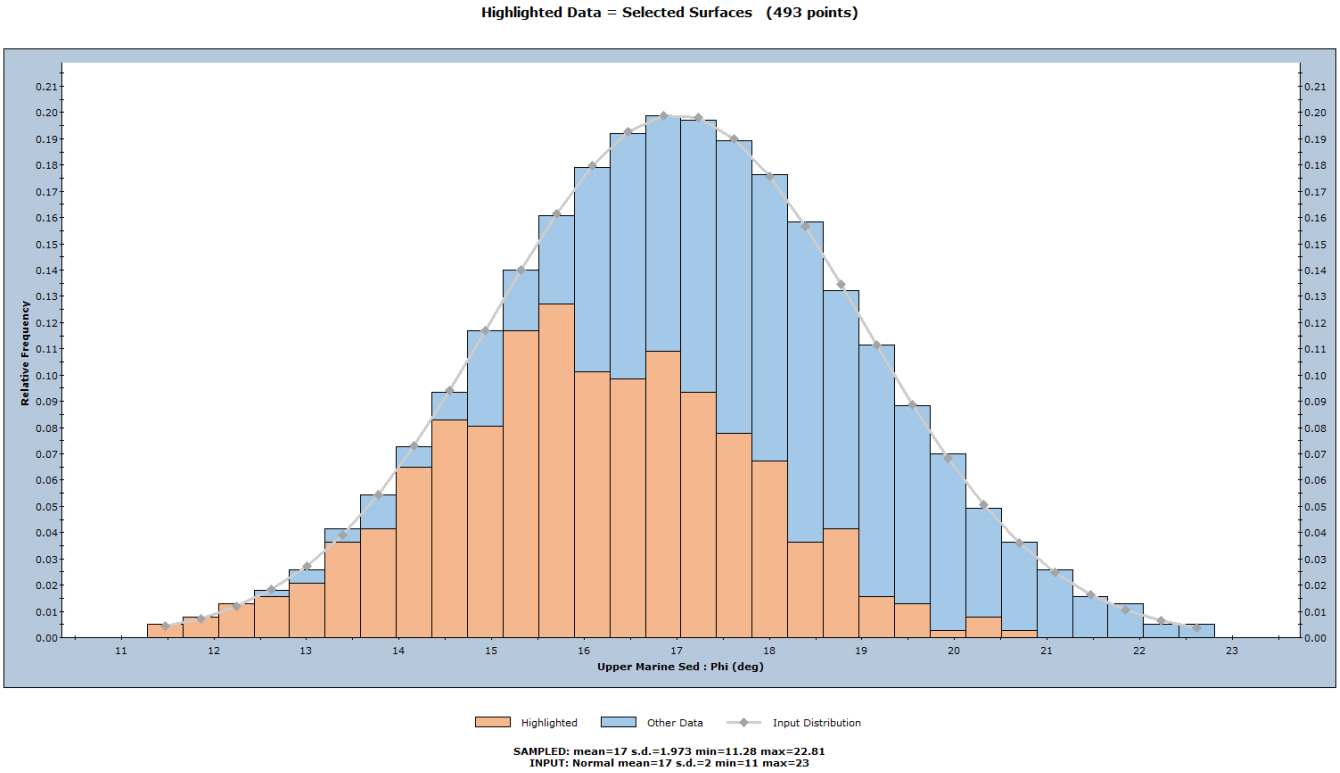
Note

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).

1. 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.
2. Select Histogram Plot and you will see the Histogram Plot dialog
3. In the dialog, select Data to Plot = “Upper Marine Sediment : Phi (deg)”.
4. 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.



5. 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.



Highlighted data for selected surfaces

We have plotted the Friction Angle of the dark red material (Upper Marine Sediment). This is the material through which a significant portion of these two slip surfaces passes through. (Turn the material colours back on again by selecting **Display Options > General > Material Colours** from the sidebar.)

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. Notice at the top of the plot:

Highlighted Data – Selected Surfaces (493 / 1000) = 49.3%

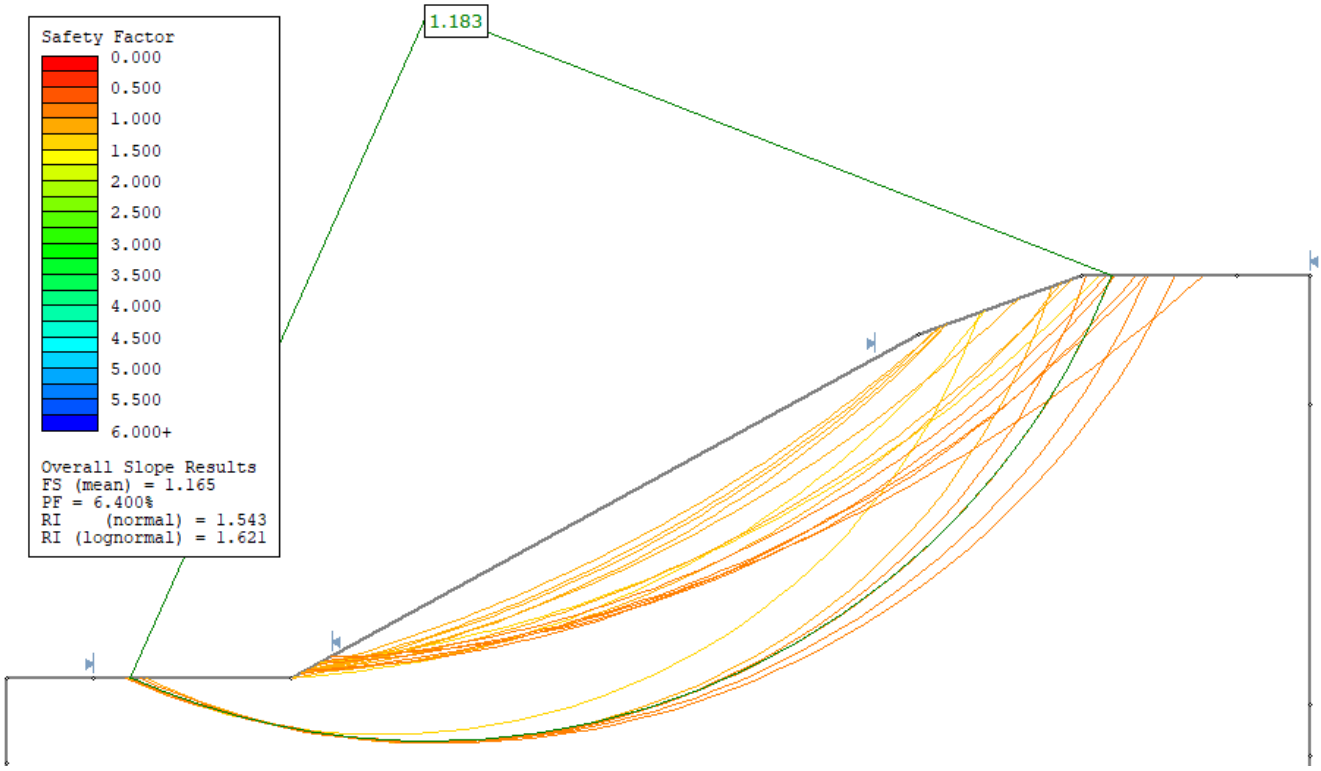
If desired, you can right-click on the plot and select the **Highlighted Data Only** option, to view ONLY the data for the selected surfaces. All other plotting options can also be used (for example, export the data to Excel, or the clipboard, for further processing in other applications).

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 Slide2.

Additional Exercise

Using the same model, enter 2500 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.

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), and the GM surfaces now form two distinct bands.



Analysis with 2500 slip surfaces

Compare the Overall Probability of Failure and Reliability Index, with the numbers presented in this tutorial.

In conclusion, the Overall Slope probabilistic analysis option in Slide2 presents the user with a wide range of powerful analysis and data interpretation options, not previously available in slope stability software. You are encouraged to experiment with and explore these options.