RocSupport

Rock support interaction and deformation
analysis for tunnels in weak rock

Tutorial Manual

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Introduction

RocSupport is a quick and simple to use program for estimating the deformation of circular tunnels in weak rock, and visualizing the tunnel interaction with various support systems.

The analysis method used in *RocSupport* is often referred to as "rock support interaction" or "convergence-confinement" analysis. This analysis method is based on the concept of a "ground reaction curve" or "characteristic line", obtained from the analytical solution for a circular tunnel in an elasto-plastic rock mass under a hydrostatic stress field.

Applicability of Method

The main assumptions in the analysis method are as follows:

- tunnel is circular
- in-situ stress field is hydrostatic (i.e. equal stress in all directions)
- rock mass is isotropic and homogeneous. Failure is not controlled by major structural discontinuities.
- support response is elastic-perfectly plastic
- support is modeled as an equivalent uniform internal pressure around the entire circumference of the circular tunnel

This last assumption in particular (that support is uniform around the entire circumference of the tunnel), should be carefully considered by the user, when comparing actual tunnel behavior, and calculated results using *RocSupport*.

The assumption of uniform support pressure implies that:

- shotcrete and concrete linings are closed rings
- steel sets are complete circles
- mechanically anchored rockbolts are installed in a regular pattern which completely surrounds the tunnel.

Because this will not usually be the case, actual support capacities will be lower, and deformations larger, than those assumed in *RocSupport*.

The idealized model used for a *RocSupport* analysis is not intended to replace detailed final design and analysis requirements for tunnel support. In general, this will require numerical analysis (e.g. finite element), particularly for tunnels with large strain.

However, a great deal can be learned about the interaction of tunnels in weak rock, with various support systems, by carrying out parametric studies using *RocSupport*, in which different combinations of in-situ stress levels, rock mass strengths and support characteristics are evaluated.

Methods of Support Design

Although there are no clearly defined rules for tunnel support and lining design at the present time, three general methods have emerged over recent years. These can be described as:

1. Closed form solution methods that are based upon the calculation of the extent of “plastic” failure in the rock mass surrounding an advancing tunnel, and the support pressures required to control the extent of the plastic zone and the resulting tunnel deformation.

2. Numerical analysis of the progressive failure of the rock mass surrounding an advancing tunnel and of the interaction of temporary support and final lining with this failing rock mass.

3. Empirical methods based upon observations of tunnel deformation and the control of this deformation by the installation of various support measures.

RocSupport belongs to the first category of solution methods, i.e. “rock support interaction” or “convergence-confinement” methods.

A good example of a numerical analysis program which belongs to the second category, is *Phase²*, a finite element stress analysis and support design program for underground excavations, also available from Rocscience.

Each of these methods has advantages and disadvantages, and the optimum solution for a given tunnel design, may involve a combination of different methods, at different stages of the design. For example, a preliminary analysis of temporary support requirements could be carried out with *RocSupport*, and detailed final design, including plastic failure of the rock mass, and yielding support, can be carried out with *Phase²*.

In spite of the limitations discussed above, rock support interaction analysis has many attractions, and when used in conjunction with numerical analyses, it can provide valuable insights into the mechanics of rock support, and reasonable guidelines for the design of this support.

Rock Support Interaction

A starting point for a discussion of the "rock support interaction" method, is to discuss the deformation which occurs in the vicinity of an advancing tunnel face, for an unsupported tunnel. This is illustrated in the following figure.

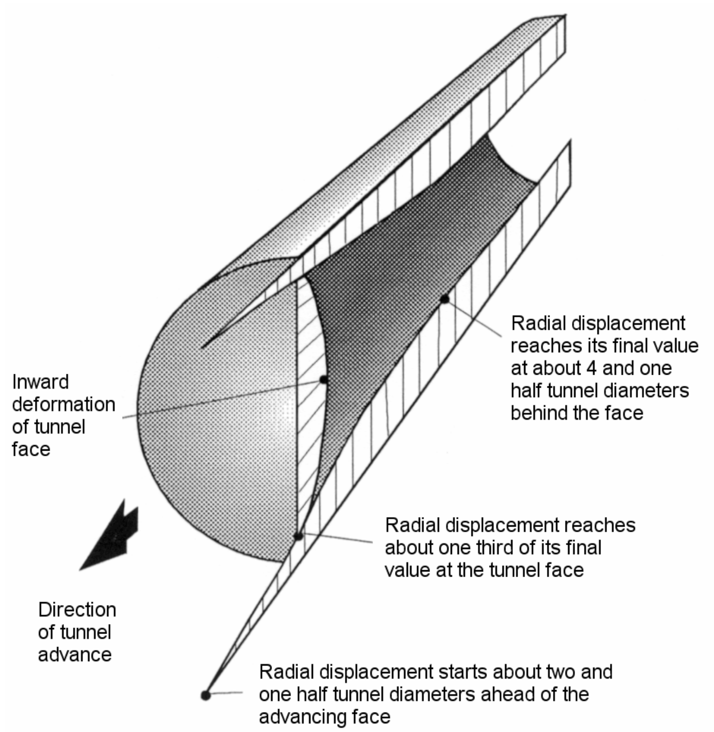


Figure 1-1: Radial displacements around an advancing tunnel face (not to scale). (Hoek, 1998).

Note that the radial displacement:

- begins a certain distance ahead of the tunnel face (about two and one-half tunnel diameters)
- reaches about one third of its final value AT the tunnel face
- reaches its maximum value at about four and one-half tunnel diameters behind the face

It is important to note that even for an unsupported tunnel, the tunnel face provides an “apparent support pressure”. It is this apparent support pressure that provides the stability to give sufficient stand-up time for the actual support to be installed.

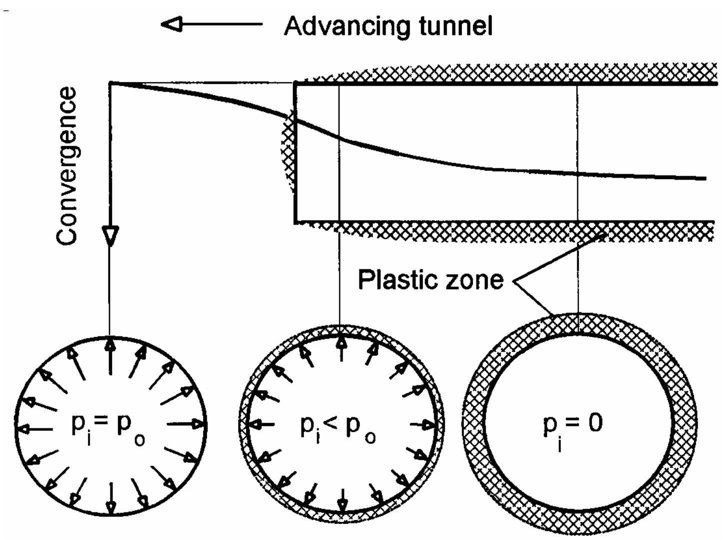


Figure 1-2: Support pressure p_i at different positions relative to the advancing tunnel face (not to scale). (Hoek, 1999a)

Observe that the apparent support pressure:

- is equal to the in-situ stress (i.e. $p_i = p_o$) at a certain distance (about two and one-half tunnel diameters) within the rock mass, ahead of the advancing face
- is equal to about one-quarter of the in-situ stress, at the tunnel face
- gradually reduces to zero at a certain distance behind the face.

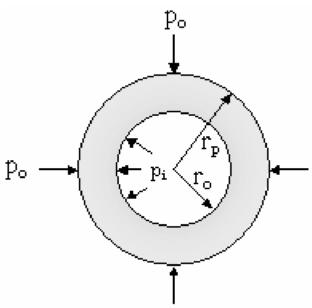
Note that plastic failure of the rock mass surrounding a tunnel does not necessarily mean that the tunnel collapses. The failed material can still have considerable strength, and provided that the thickness of the plastic zone is small compared with the tunnel radius, the only evidence of failure may be a few fresh cracks and a minor amount of raveling or spalling.

On the other hand, when a large plastic zone is formed and when large inward displacements of the tunnel wall occur, the loosening of the failed rock mass can lead to severe spalling and raveling and eventual collapse of an unsupported tunnel.

The primary function of support is to control the inward displacement of the walls and to prevent the loosening, which can lead to collapse of the tunnel. The installation of support (e.g. rockbolts, shotcrete lining or steel sets) cannot prevent failure of the rock surrounding a tunnel subjected to significant overstressing, but these support types do play a major role in controlling tunnel deformation (Hoek et. al. 1995).

Ground Reaction Curve

At the heart of the "rock support interaction" analysis method used in *RocSupport*, is the "ground reaction curve" or "characteristic line", which relates internal support pressure to tunnel wall convergence. The general derivation of the ground reaction curve, is as follows.



Assume that a circular tunnel of radius r_o is subjected to hydrostatic in-situ stress p_o and a uniform internal support pressure p_i, as illustrated in the margin figure.

Failure of the rock mass surrounding the tunnel occurs when the internal pressure provided by the tunnel lining is less than a critical support pressure p_{cr}.

If the internal support pressure p_i is greater than the critical support pressure p_{cr}, no failure occurs, and the behaviour of the rock mass surrounding the tunnel is elastic. The inward radial elastic displacement of the tunnel wall is given by:

$$u_{ie} = \frac{r_o(1+\nu)}{E}(p_o - p_i) \qquad \text{Eqn. 1.1}$$

When the internal support pressure p_i is less than the critical support pressure p_{cr}, failure occurs and a plastic zone of radius r_p is formed around the tunnel. The inward radial plastic displacement u_{ip} is then defined by the ground reaction curve between $p_i = p_{cr}$ and $p_i = 0$.

A typical ground reaction curve is shown in Figure 1-3.

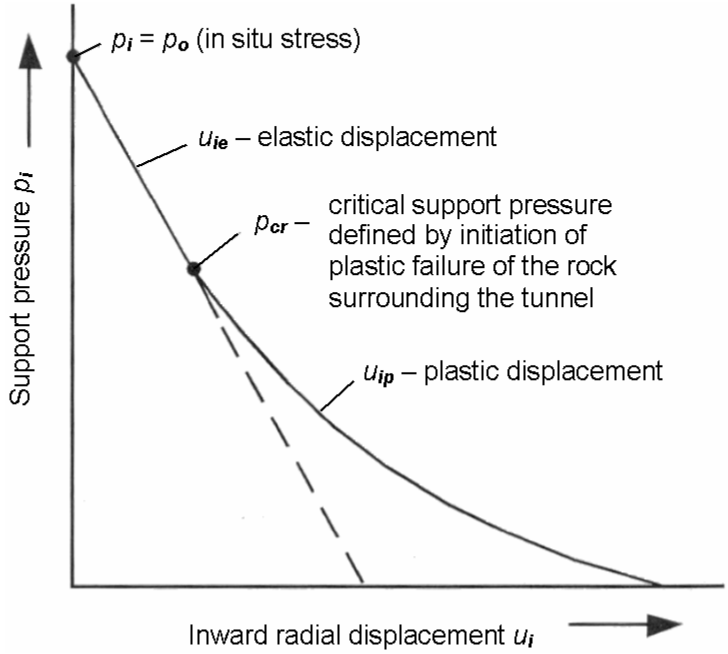


Figure 1-3: Ground reaction curve showing relationship between support pressure and tunnel wall convergence (Hoek et. al. 1995).

This plot shows:

- zero displacement when the support pressure equals the hydrostatic stress ($p_i = p_o$)
- elastic displacement u_{ie} for $p_o > p_i > p_{cr}$
- plastic displacement u_{ip} for $p_i < p_{cr}$
- maximum displacement when the support pressure equals zero

For a given tunnel radius and in-situ stress, the shape of the ground reaction curve depends on the rock mass failure criterion which is assumed and the specific rock mass characteristics.

The following are dependent on the rock mass failure criterion and characteristics:

- the critical support pressure p_{cr}
- the radius of the plastic zone r_p
- the shape of the ground reaction curve in the plastic region ($p_i < p_{cr}$)

See the Solution Methods topic, later in this Introduction, for an overview of the two different solution methods used in *RocSupport*. These correspond to Mohr-Coulomb or Hoek-Brown rock mass failure criteria, and have been derived for the rock support interaction problem.

Support Reaction

In order to complete the rock support interaction analysis, the reaction curve for the rock support must be determined. This is a function of three components:

1. The tunnel wall displacement that has occurred before the support is installed.

2. The stiffness of the support system.

3. The capacity of the support system.

Referring back to Figure 1-1, remember that a certain amount of deformation takes place ahead of the advancing face of the tunnel. At the face itself, approximately one-third of the total deformation has taken place, and this cannot be recovered. In addition, there is almost always a stage of the excavation cycle in which there is a gap between the face and the closest installed support element. Therefore, further deformation occurs before the support becomes effective. This total initial displacement will be called u_{so} and is shown in Figure 1-4.

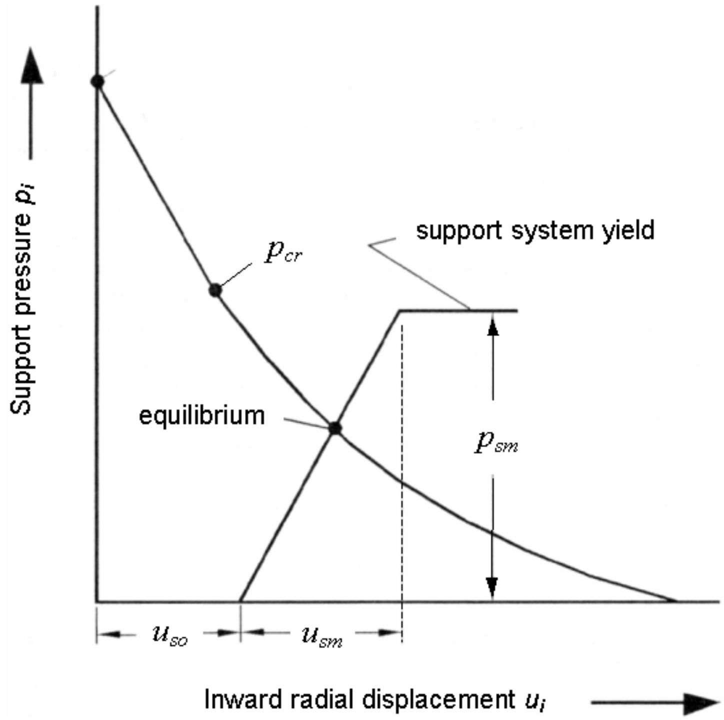


Figure 1-4: Response of support system to tunnel wall displacement, resulting in establishment of equilibrium (Hoek et.al. 1995).

Once the support has been installed and is in full and effective contact with the rock, the support starts to deform elastically as shown in Figure 1-4. The maximum elastic displacement which can be accommodated by the support system is u_{sm} and the maximum support pressure p_{sm} is defined by the yield of the support system.

Depending upon the characteristics of the support system, the rock mass surrounding the tunnel and the in-situ stress level, the support system will deform elastically in response to the closure of the tunnel, as the face advances away from the point under consideration.

Rock-Support Equilibrium

Equilibrium is achieved if the support reaction curve intersects the rock mass displacement curve before either of these curves have progressed too far. If the support is installed too late (i.e. u_{so} is large in Figure 1-4), the rock mass may have already deformed to the extent that loosening of the failed material is irreversible. On the other hand, if the capacity of the support is inadequate (i.e. p_{sm} is low in Figure 1-4), then yield of the support may occur before the rock mass deformation curve is intersected. In either of these cases the support system will be ineffective, since the equilibrium condition, illustrated in Figure 1-4, will not have been achieved.

Support Characteristics

In *RocSupport*, the stiffness and capacity of support is expressed in terms of Maximum Average Strain and Maximum Support Pressure. In this form it is incorporated directly into the rock support interaction analysis.

Note that since the support capacity is simply modeled as an equivalent internal pressure, the reinforcement provided by grouted rockbolts or cables cannot be properly accounted for in this simple model. However, the radius of the plastic zone calculated from the analysis, can be used as a guide for the length of bolts or cables – i.e. bolts or cables should always be anchored in unyielded rock.

The stiffness and capacity of support systems such as rockbolts, steel sets, shotcrete and of combinations of these elements can be estimated from relatively simplistic analyses published in Hoek and Brown (1980) and summarized in Hoek (1999b). These estimates have been used for the pre-defined support types available in *RocSupport*.

Support Installation

The origin of the support reaction curve in Figure 1-4 (i.e. the value of u_{so}), is the tunnel convergence which has occurred at the point of support installation. In *RocSupport*, this value can be specified in two ways:

- directly (as a convergence or wall displacement), or
- indirectly (a distance from the tunnel face is specified, which is then converted to tunnel convergence using a longitudinal tunnel deformation profile)

The default tunnel deformation profile used in *RocSupport* is shown in Figure 1-5. The equation of this curve allows the user to input a value for distance from the tunnel face and obtain a value of wall displacement. In *RocSupport*, it is also possible to create a user-defined tunnel deformation profile.

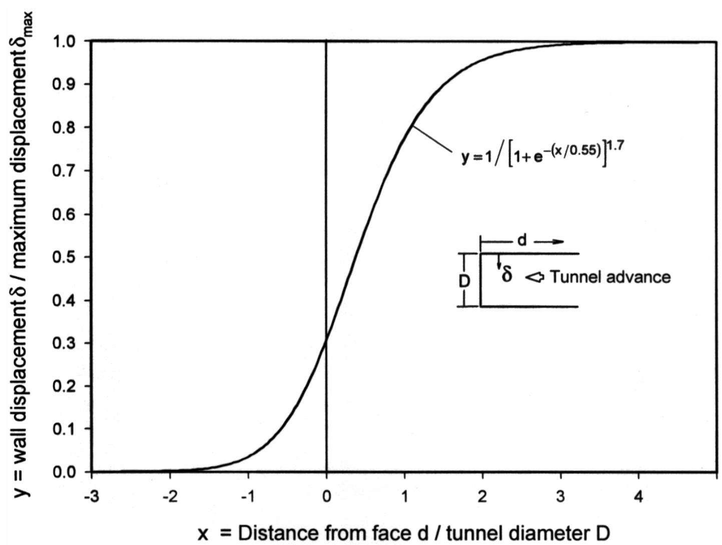


Figure 1-5: Tunnel wall displacement as a function of distance from face (Hoek, 1999a).

Determination of the tunnel wall displacement that has occurred before the support is installed is not a trivial problem, since it involves a consideration of the three-dimensional stress distribution, and propagation of failure surrounding the advancing face. Chern et. al. (1998) published a set of results obtained from three-dimensional numerical analyses and also from measurements in an advancing tunnel where instruments had been installed from a parallel tunnel before excavation. Hoek (1999a) derived the curve in Figure 1-5 by averaging the results presented by these authors.

Solution Methods

A number of derivations of the “rock support interaction” analysis method have now been published, as discussed in Hoek (1999a). All methods assume a circular tunnel in a hydrostatic stress field, and the main theoretical efforts have been devoted to the calculation of the size of the plastic zone, and the shape of the ground reaction curve, for different assumptions on how the failure of the rock mass progresses as the tunnel is advanced.

The main differences between the various methods used to calculate the ground reaction curve, are in the choice of the rock mass failure criterion, and in whether or not the rock mass dilates (changes in volume) during failure.

In *RocSupport*, two solution methods are available: the Duncan Fama method or the Carranza-Torres method.

Duncan Fama Solution

The Duncan Fama (1993) solution is based on the Mohr-Coulomb failure criterion, and allows the user to define the rock mass strength and deformation characteristics in terms of:

- Rock mass compressive strength
- Friction angle
- Young’s modulus
- Poisson’s ratio

A useful outline of this solution method, is also presented in Hoek et. al. (1995).

NOTE: although the Duncan Fama solution is based on the Mohr-Coulomb failure criterion, estimates of the rock mass compressive strength and friction angle, can be obtained from Hoek-Brown strength parameters, as discussed in Example 1.

Carranza-Torres Solution

The Carranza-Torres (2004) solution is based on the Generalized Hoek-Brown failure criterion, and allows the user to define the rock mass strength and deformation characteristics in terms of:

- Intact rock compressive strength (UCS)
- Geological Strength Index (GSI)
- Intact rock constant mi

- Dilation angle
- Disturbance Factor (D)
- Young's modulus
- Poisson's ratio

The Carranza-Torres solution can also account for residual strength, which is always specified directly in terms of the Generalized Hoek-Brown parameters mb, s and a.

Deterministic Analysis

In the toolbar or the Project Settings dialog, the user can choose either Deterministic or Probabilistic analysis types.

A Deterministic analysis simply means that all input variables are assumed to be "exactly" known (e.g. in-situ stress and rock strength parameters).

This results in a unique solution for all program output, including:

- the Ground Reaction curve
- Plastic Zone Radius
- Equilibrium pressure (if support is installed)
- Factor of Safety (for support)

Factor of Safety

A unique Factor of Safety for the support is calculated in a Deterministic analysis. The definition of the Factor of Safety in *RocSupport* is as follows:

- A Factor of Safety GREATER THAN 1 is calculated as shown in Figure 1-6. In this case the Factor of Safety is simply the ratio of the Maximum Support Pressure p_{sm} to the Equilibrium Pressure p_{eq} (the pressure at the intersection point of the Ground Reaction and Support Reaction curves).

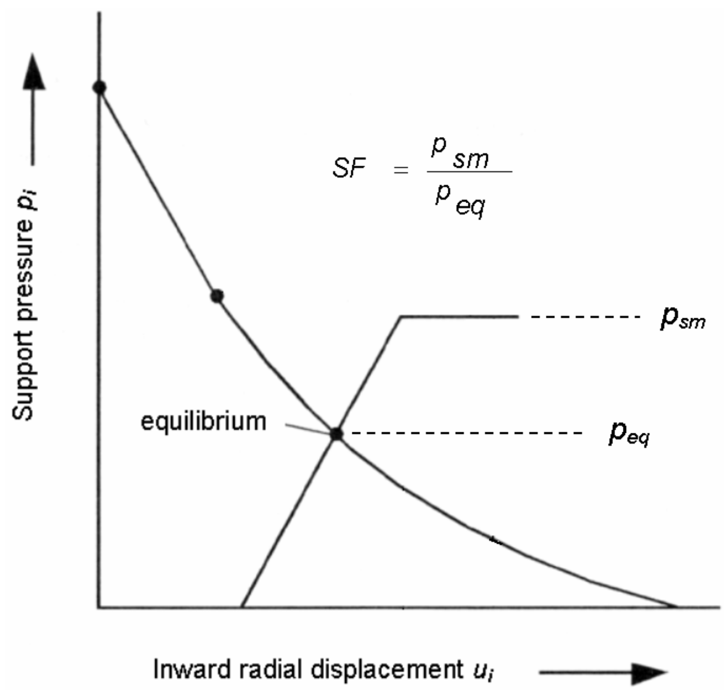


Figure 1-6: Definition of Factor of Safety > 1.

- A Factor of Safety LESS THAN 1 is calculated as shown in Figure 1-7. This occurs when the Ground Reaction curve intersects the Support Reaction curve after the elastic limit of the support has been exceeded. A "projected" equilibrium pressure p'_{eq} is calculated by projecting the elastic support reaction curve until it intersects the Ground Reaction curve, and this value is used in the denominator of the Factor of Safety equation.

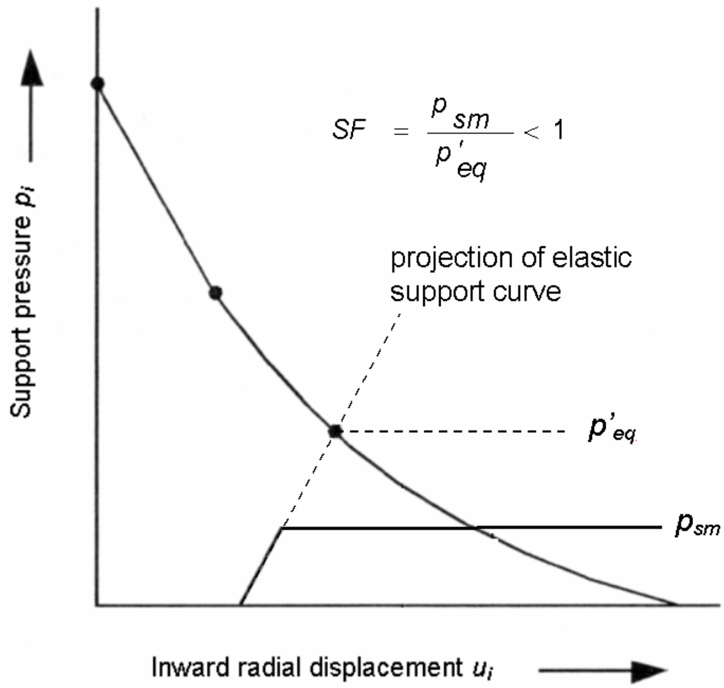


Figure 1-7: Definition of Factor of Safety < 1.

Probabilistic Analysis

In the toolbar or the Project Settings dialog, the user can choose either Deterministic or Probabilistic analysis types.

A Probabilistic analysis allows the user to input statistical distributions for:

- tunnel radius
- in-situ stress
- all rock mass parameters

Using either Monte Carlo or Latin Hypercube sampling, the program will then sample the input distributions and run the analysis for the specified Number of Samples defined by the user in the Project Settings dialog.

The user can then view statistical distributions of all output variables (e.g. plastic zone radius, wall displacement), rather than simply a single number as calculated from a Deterministic analysis.

Probability of Failure

A Probabilistic analysis results in a distribution of Safety Factor, rather than a single value. From a Safety Factor distribution, a Probability of Failure can be calculated.

The Probability of Failure in *RocSupport* is simply the number of analyses with Safety Factor less than 1, divided by the total number of analyses generated by the Probabilistic analysis.

For example, if 100 out of 1000 samples in a Probabilistic analysis resulted in a Factor of Safety less than 1, then the Probability of Failure would be 10 %.

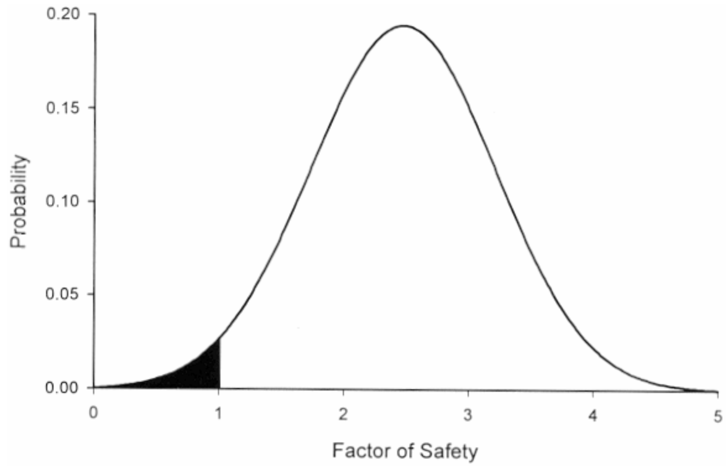
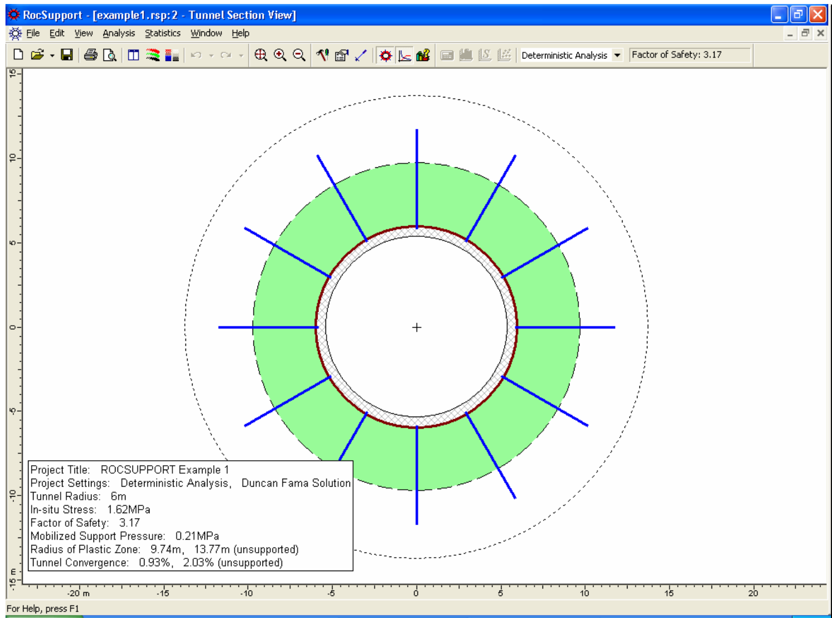


Figure 1-8: Definition of Probability of Failure.

Mathematically speaking, the Probability of Failure is the area under the Factor of Safety probability distribution to the LEFT of Factor of Safety = 1 (i.e. the black area in Figure 1-8), divided by the total area under the curve.

Example 1 – Medium Support



Example 1 will demonstrate the basic features of *RocSupport*, and will use the Duncan Fama solution method to determine the Ground Reaction Curve. The tunnel will first be analyzed without support. Then support will be added, and a factor of safety for the support determined. Analysis will be Deterministic (all parameters assumed to be exactly known).

MODEL FEATURES:

- A 12 meter diameter tunnel is to be constructed at a depth of 60 meters in a rock mass whose strength is defined by the Hoek-Brown criterion with an intact rock strength σ_{ci} = 7 MPa, constant m_i = 10 and a Geological Strength Index = 15.

NOTE: the finished product of this tutorial can be found in the **example1.rsp** data file in the EXAMPLES folder in your *RocSupport* installation folder.

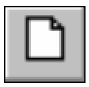
Starting a Project

If you have not already done so, start the *RocSupport* program by double-clicking on the *RocSupport* icon in your installation folder. Or from the Start menu, select Programs → Rocscience → RocSupport → RocSupport.

If the *RocSupport* application window is not already maximized, maximize it now, so that the full screen is available for viewing the model.

New File

To begin creating a new model:



Select: File → New

When a new file is created, the Ground Reaction View will initially be displayed. This will show the Ground Reaction Curve based on the default Tunnel and Rock input data.

If it is not already maximized, maximize the Ground Reaction View by selecting the Maximize button in the upper right corner of the view.

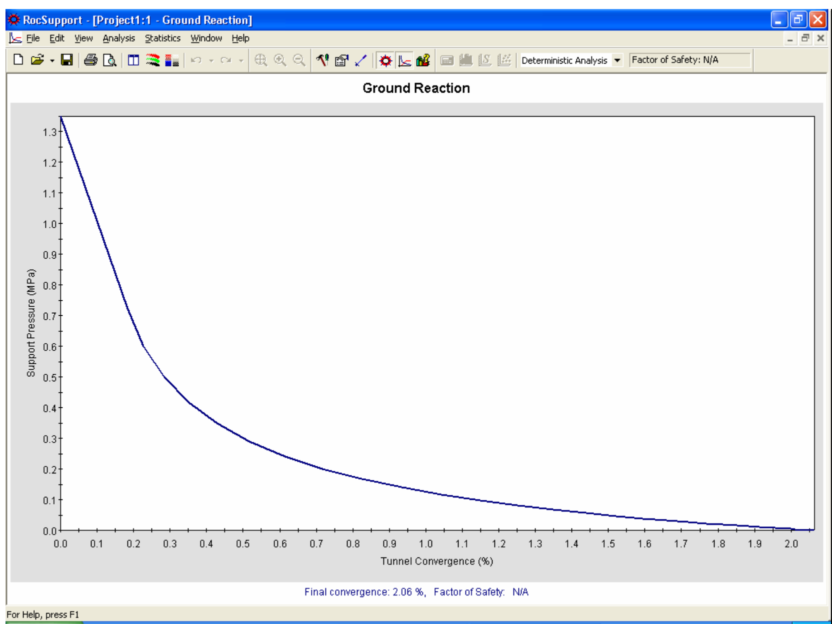
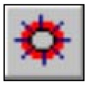


Figure 2-1: Ground reaction curve for default input data.

Tunnel Section View

To view a cross-sectional view of the model, select the Tunnel Section option from the toolbar or the Analysis menu.



Select: Analysis → Tunnel Section

The Tunnel Section View displays:

- A cross-section of the tunnel diameter, and the plastic zone (shaded region). The size of the plastic zone is drawn to scale with respect to the tunnel diameter.
- A Project Info Textbox with a summary of the main input and output parameters. The Textbox display can be toggled on or off in the right-click menu. The textbox position, colour and font can be customized by double-clicking on the textbox.
- If support is installed, this will be displayed on the Tunnel Section View and the plastic zone radius (with support) will be displayed.

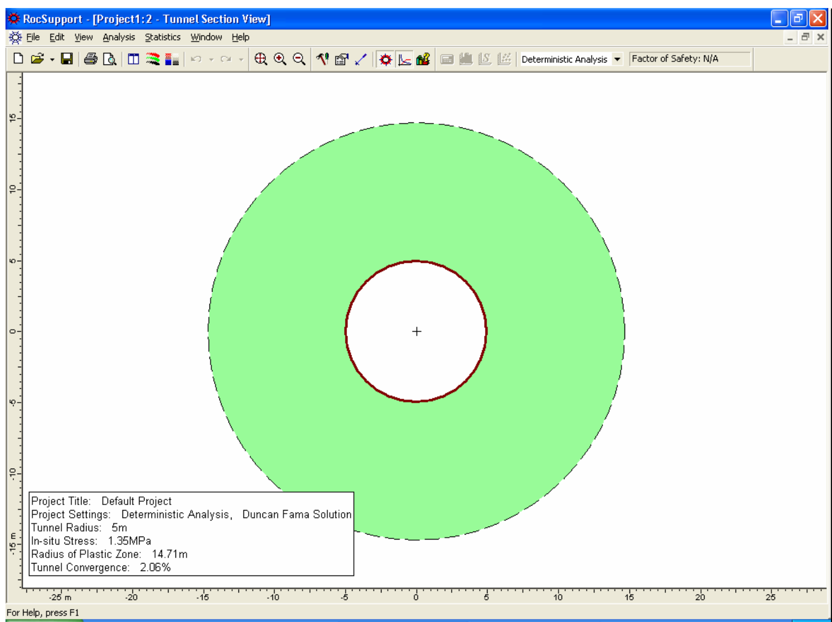
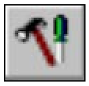


Figure 2-2: Tunnel Section View for default input data (no support).

Project Settings

Although we do not need to change any Project Settings for this example, let's take a look at the Project Settings dialog.



Select: Analysis → Project Settings

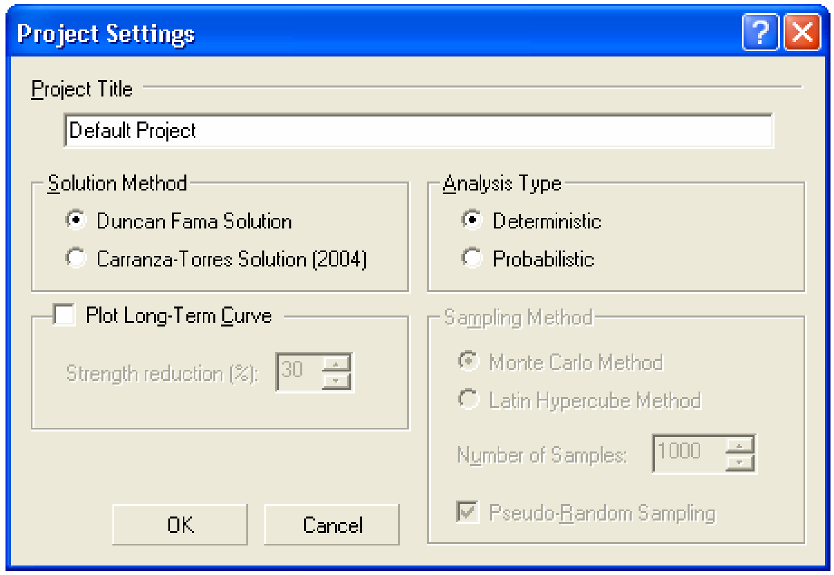


Figure 2-3: Project Settings dialog.

In the Project Settings dialog, you may enter:

- A Project Title
- Select the Solution Method and Analysis Type
- Plot the Long Term Ground Reaction Curve

See the Introduction to this manual for a discussion of the Solution Method and Analysis Type. See the last tutorial for a discussion of the Long Term Ground Reaction curve.

For this example, we will use the default Project Settings, however, you may enter a Project Title – ROCSUPPORT EXAMPLE 1. Select OK.

Tunnel and Rock Parameters

The tunnel diameter, in-situ stress and rock parameters are defined with the Tunnel Parameters option, which you may select from the toolbar or the Analysis menu.

Select: Analysis → Tunnel Parameters

For a Deterministic analysis, the Tunnel and Rock Parameters dialog will appear as shown below. Because we are using the Duncan Fama solution method, based on the Mohr-Coulomb failure criterion, the required Strength Properties are the rock mass Compressive Strength and Friction Angle.

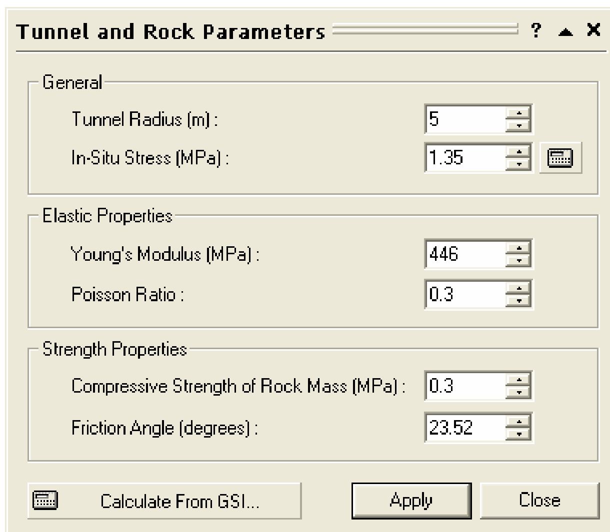


Figure 2-4: Tunnel and Rock Parameters dialog.

Tunnel Radius

NOTE that you must input the tunnel radius, and NOT the tunnel diameter, in the Tunnel and Rock Parameters dialog!

For this example, the tunnel diameter is 12 meters, so enter a tunnel radius of 6 meters.

In-Situ Stress

In the Tunnel and Rock Parameters dialog, you may input the hydrostatic in-situ stress directly, if it is known.

However, as you will discover with other input data in *RocSupport*, whenever you see a “calculator” icon in an input data dialog, this means that the required input data may be estimated from other parameters.

In the case of In-Situ Stress, this can be simply estimated from the tunnel depth and the rock unit weight.

In the Tunnel and Rock Parameters dialog, select the Calculator icon to the right of the In-Situ Stress edit box. You will see the Estimate In-Situ Stress dialog.

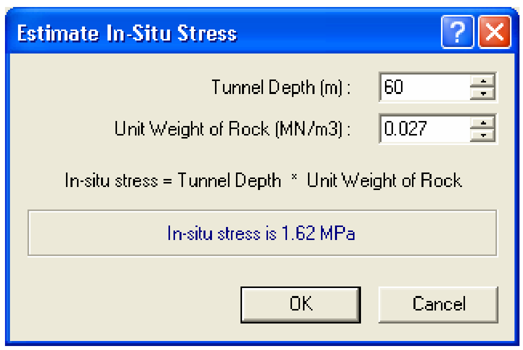


Figure 2-5: Estimate In-Situ Stress dialog.

Enter a tunnel depth of 60 meters. We will use the default value for Unit Weight of Rock (0.027 MN / m³). Note that the estimated in-situ stress (1.62 MPa) is displayed in the dialog. Select OK and the estimated value will be loaded into the Tunnel and Rock Parameters dialog.

The estimated In-Situ Stress is simply the product of the Tunnel Depth and Unit Weight (Eqn. 2.1):

$$p_o = \gamma * H \qquad \text{Eqn. 2.1}$$

where: p_o = in-situ stress

γ = rock unit weight

H = tunnel depth below ground surface

Rock Parameters

Now let's enter the elastic and strength parameters for the rock.

Remember at the beginning of this example, the rock properties were given in terms of Hoek-Brown parameters. However, the Duncan Fama solution method uses the Mohr-Coulomb failure criterion, and requires a Friction Angle.

For this purpose, the "Calculate from GSI…" option is provided in the Tunnel and Rock Parameters dialog.

If you select this button, you will see the following dialog.

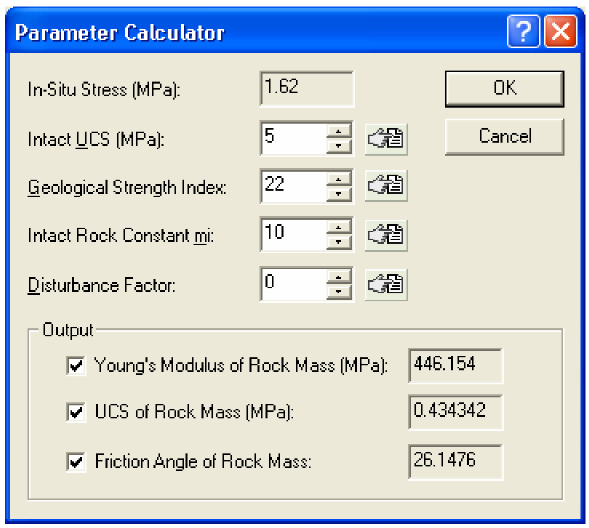


Figure 2-6: Parameter Calculator dialog.

This dialog allows you to obtain estimates of the following rock mass properties:

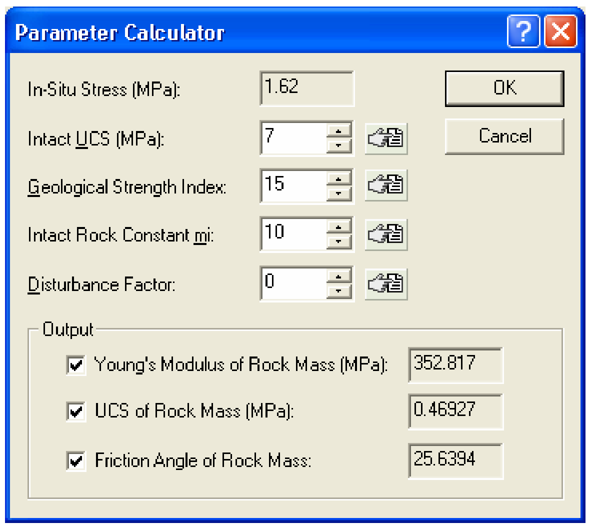
- Young's Modulus
- Compressive Strength
- Friction Angle

by entering values of the Hoek-Brown parameters GSI, mi, intact UCS and D. The ability to calculate these parameters is very useful because the rock mass modulus, compressive strength and friction angle are usually not very well known quantities, whereas GSI, intact mi, intact UCS are often more readily available parameters.

The calculations are based on the equations and methods presented in Hoek, Carranza-Torres and Corkum (2002). This paper presents the latest developments in the Hoek-Brown failure criterion, including an improved method of determining equivalent Mohr-Coulomb parameters from the Hoek-Brown failure envelope.
For full details, the paper is available from the Rocscience website at the following link:

http://www.rocscience.com/library/pdf/RL_1.pdf

In the Parameter Calculator dialog, enter the following values: Intact UCS = 7, GSI = 15, Intact mi = 10. You should see the following output values for Young's Modulus, rock mass UCS and rock mass Friction Angle.



TIP – you can use the checkboxes in the dialog to select which output variables will be calculated. This is useful if you only wish to calculate some variables, and manually enter known values for other variables.

Before you select OK, notice that beside each edit box is a "pick" button. Whenever you see this icon displayed in a *RocSupport* dialog, this means that data can be selected or estimated from a table or chart. Let's examine this now.

In the Parameter Calculator dialog, select the "pick" button beside the GSI edit box. You will see the following GSI table, allowing you to estimate a value for GSI based on the rock structure and surface conditions.

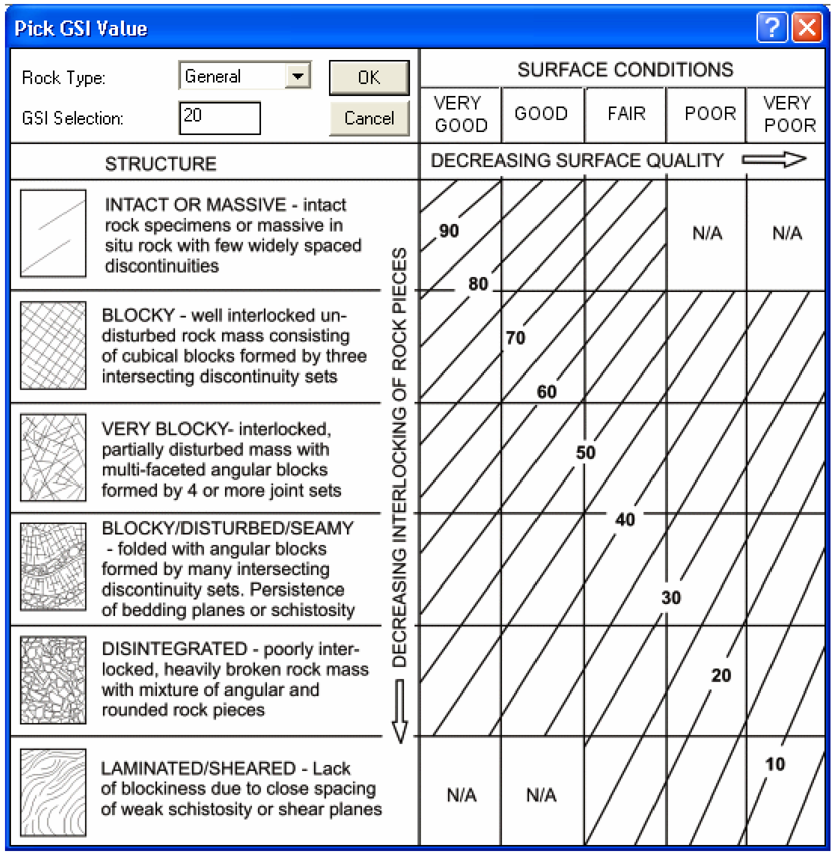


Figure 2-7: Built-in GSI table in *RocSupport*. (Hoek, 1998).

Note:

- as you move the mouse around the chart, the GSI value at that point will be displayed beside the cursor
- if you click the mouse at a point on the chart, the corresponding GSI value will be loaded into the edit box at the top of the GSI table
- you may then edit this value, if necessary

The significance and derivation of the Geological Strength Index will not be discussed in this manual. However, it should be emphasized that a parameter such as GSI should not be considered an exact value, and a range of possible values should always be considered in an analysis. For further information see Hoek et.al (1995) or Hoek (2004).

Since we have already decided on a value for GSI, select Cancel in the GSI dialog.

Now select the "pick" button beside the "Intact Rock Constant mi" edit box. You will see the following dialog, allowing you to select a value for m_i based on rock type.

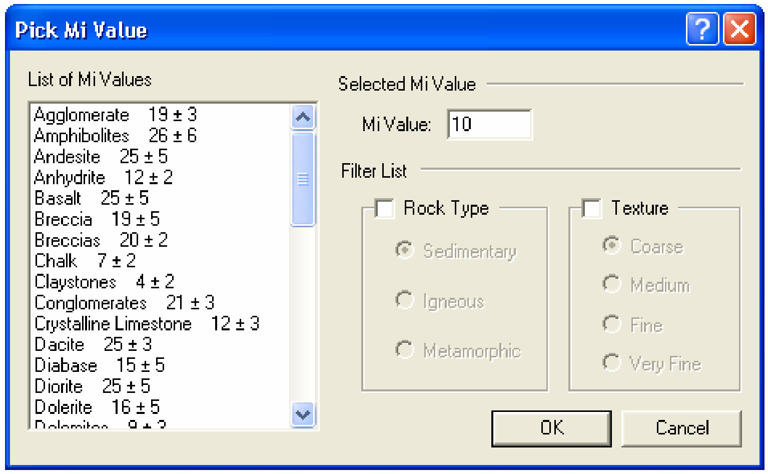


Figure 2-8: Pick Mi Value dialog.

To use this dialog:

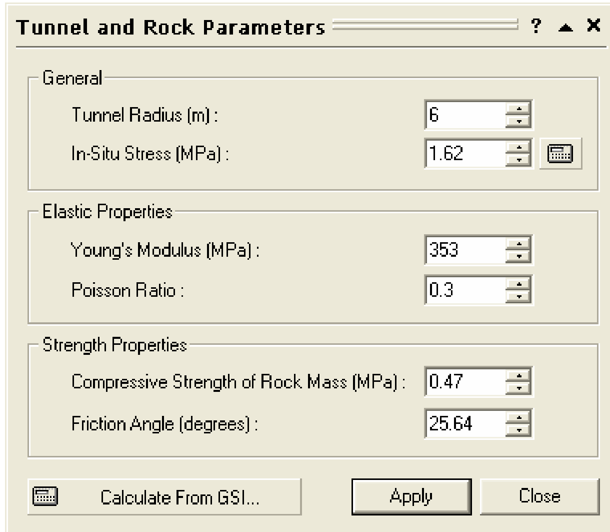
- simply select a rock type from the list at the left of the dialog, and the corresponding m_i value will be loaded into the edit box at the top of the dialog.

- you may filter the list, if desired, by selecting the Rock Type and / or Texture checkboxes, and then selecting the desired Rock Type and / or Texture. This will display only the requested subset in the list. This is left as an optional exercise for the user to experiment with.

Since we have already decided on a value for m_i*, select Cancel in the Pick Mi Value dialog.*

Select OK in the Parameter Calculator dialog, to return to the Tunnel and Rock Parameters dialog.

The computed values of modulus, compressive strength and friction angle are automatically entered in the Tunnel and Rock Parameters dialog. Notice that the number of decimal places have been rounded appropriately for each parameter (e.g. decimal places are not warranted for the rock mass Young's modulus!)



Apply

We are now finished entering all of the desired data in the Tunnel and Rock Parameters dialog.

In order to save the newly entered parameters, and re-run the analysis, you must select the Apply button.

Select Apply in the Tunnel and Rock Parameters dialog.

All analysis results in the Ground Reaction View and the Tunnel Section View will be updated with the new results.

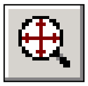
Close the dialog by selecting either the Close button, or the X in the upper right corner of the dialog.

Remember that you *must select Apply* to save the data and re-run the analysis. If you select the Close button without FIRST selecting Apply, then this will cancel all new data entered, and the previous results will remain on the screen.

Analysis Results (No Support)

If you are not already viewing it, switch to the Tunnel Section View.

Select Zoom All to maximize the model within the view (you can also use the F2 function key to Zoom All):



Select: View → Tunnel Section → Zoom All

As can be seen in the summary provided in the Project Info Textbox:

- the Plastic Zone radius (no support) = 13.8 m
- the final Tunnel Convergence = 2.0 %

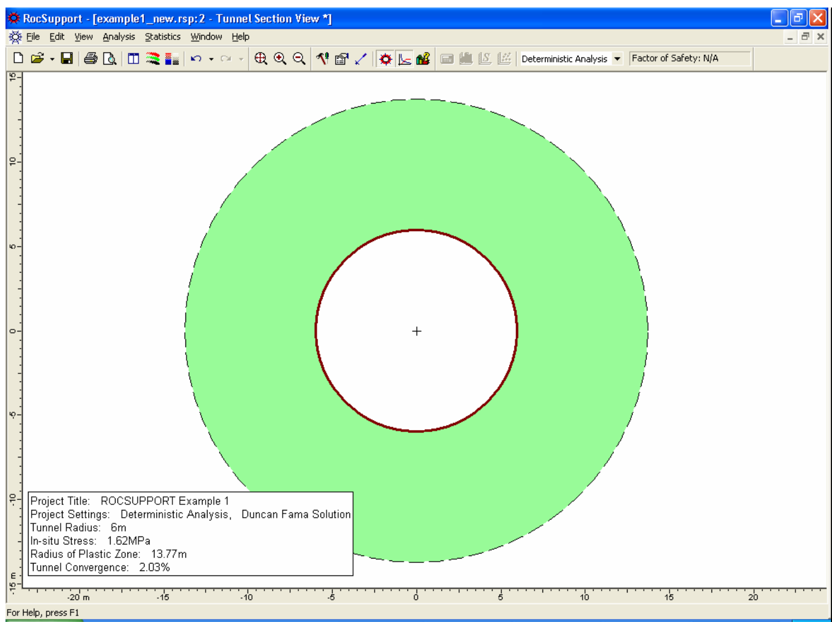


Figure 2-9: Analysis with NO support.

With an unsupported Tunnel Convergence of 2.0 %, this tunnel falls into "category B" according to the guidelines discussed in the Appendix, for a first estimate of support requirements. This indicates that appropriate support would involve rockbolts and shotcrete. See the Appendix for more information.

Ground Reaction Curve

To view the Ground Reaction Curve, select the Ground Reaction option from the toolbar or the Analysis menu.

Select: Analysis → Ground Reaction

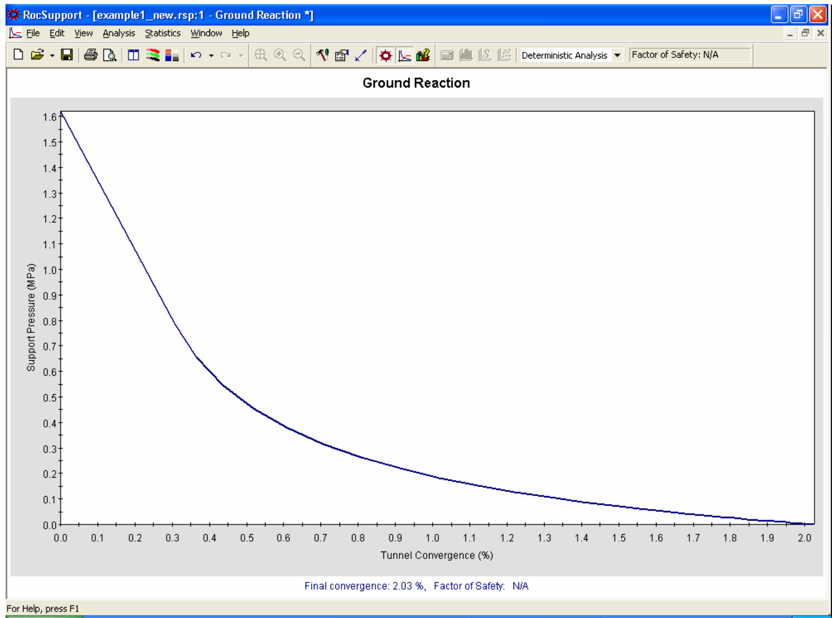


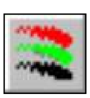
Figure 2-10: Ground reaction curve for Example 1.

By default, the X-axis of the Ground Reaction Curve is expressed as Tunnel Convergence (%). The X-axis can also be displayed as Wall Displacement, using a convenient right-click shortcut.

Right-click on the view and select Horizontal Axis > Wall Displacement from the popup menu.

The X-axis of the Ground Reaction plot is now in terms of Wall Displacement rather than Tunnel Convergence.

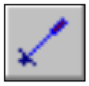
Right-click again on the view and select Horizontal Axis > Tunnel Convergence to reset the X-axis to Tunnel Convergence.



Note: the horizontal axis of the Ground Reaction View can also be changed in the Display Options dialog.

Adding Support

Now let's add some rockbolt support, and see the effect on the tunnel behaviour. To add support, select the Support Parameters option from the toolbar or the Analysis menu.



Select: Analysis → Support Parameters

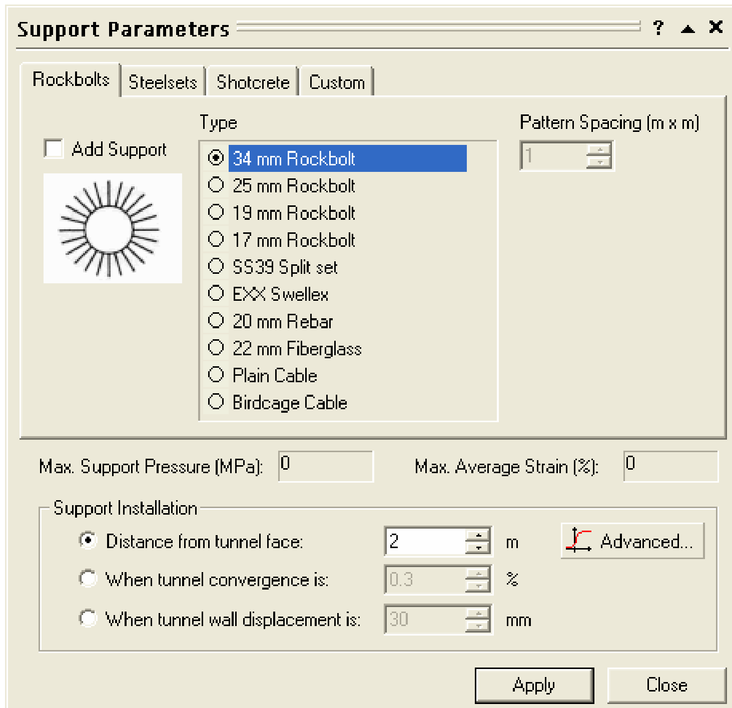


Figure 2-11: Support Parameters dialog.

Based on the unsupported analysis results, what type of support would be appropriate for this problem?

As described in the Appendix, this example problem, with an unsupported Tunnel Convergence of 2.0 %, falls into a category of tunneling problems, which can be stabilized with relatively modest support (e.g. rockbolts and shotcrete).

For this example, we will start by adding 34 mm rockbolt support, at 1 x 1 m pattern spacing. Support will be installed at a distance of 3 m from the face.

To add the rockbolt support:

1. Select the Add Support checkbox under the Rockbolts tab. Notice that a green checkmark now appears beside the Rockbolts tab, to indicate that rockbolt support will be in effect.

2. We will use 34 mm rockbolts, which is already selected by default in the Type list.

3. We will use the default Pattern Spacing = 1 x 1 meters.

4. Enter Distance from Tunnel Face = 3.

The dialog should appear as follows:

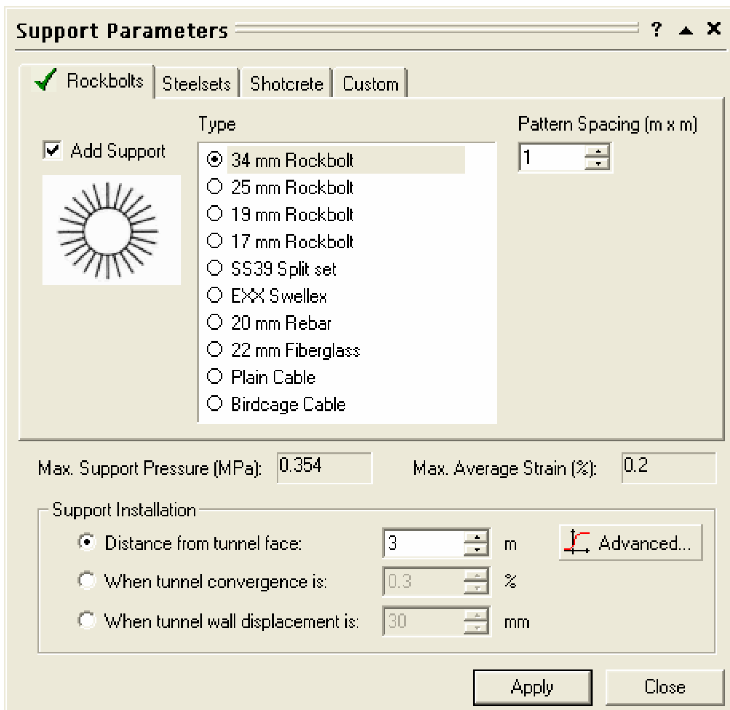


Figure 2-12: Rockbolt support parameters for Example 1.

5. Select the Apply button. This will save the support parameters you have entered, and re-run the analysis. All open views of the current document, will be updated with the latest analysis results.

Maximum Support Pressure and Strain

Before we close the Support Parameters dialog, we will comment on the Maximum Support Pressure and Maximum Average Strain, which are displayed in the dialog. Note:

- These values CANNOT be edited; they are pre-defined, calculated values (Hoek, 1999b) based on the support parameters you have selected.

- For a given tunnel diameter, the Maximum Support Pressure depends on the type of support you have added, as well as the Out of Plane Spacing (for steel sets) or the Pattern Spacing (for rockbolts)

- The Maximum Average Strain depends only on the support type you have selected, and is not affected by Out of Plane Spacing or Pattern Spacing.

- If none of the pre-defined support types (Rockbolts, Steel Sets or Shotcrete), provide the required Support Pressure and Average Strain, then the user can simply define a Custom support type in the Support Parameters dialog. See the *RocSupport* Help system for details about defining Custom support.

- Different support types (e.g. Rockbolts and Shotcrete) can be combined in the same analysis. This is discussed later in this tutorial.

In this example, for the support parameters we have entered, Maximum Support Pressure = .354 MPa and Maximum Average Strain = 0.2 %.

Now close the Support Parameters dialog (make sure you have selected Apply before you select Close), and we will discuss the results of the analysis with support.

Analysis Results (With Support)

If the Tunnel Section View is not currently active, then select the Tunnel Section option from the toolbar or the Analysis menu, to view the Tunnel Section and analysis summary.

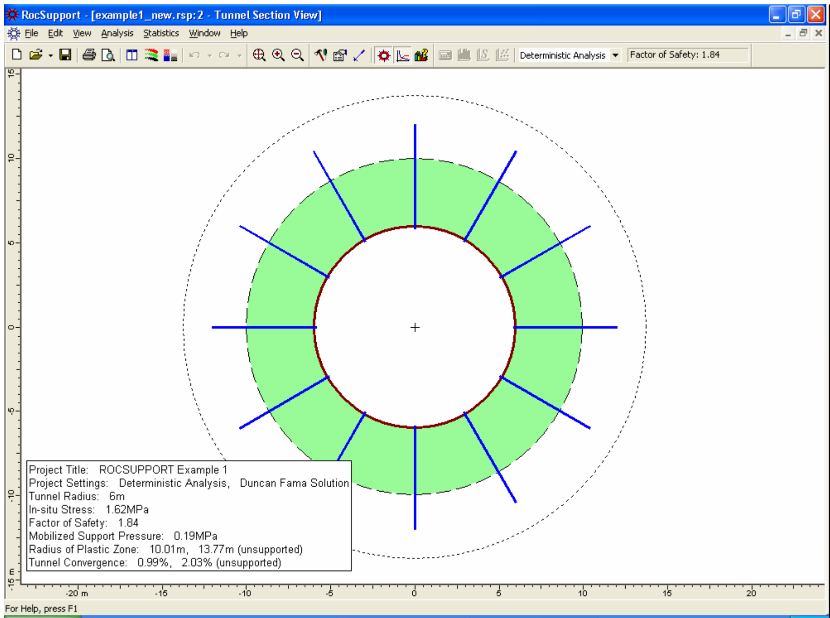


Figure 2-13: Analysis with rockbolt support.

Notice that there are now two plastic zone radius boundaries displayed (dotted lines). The interior boundary shows the extents of the plastic zone (shaded region) around the tunnel when support is installed. The outer boundary depicts the plastic zone when the problem is analyzed without support.

When you place the mouse pointer in the shaded region, a tool tip appears that reads “Plastic zone: 10.01 m”. When you move the pointer to the outer boundary the tip changes to “Unsupported plastic zone: 13.77 m”.

The analysis summary in the Project Info textbox provides values of:

- Factor of Safety
- Mobilized Support Pressure
- Plastic Zone Radius (decreased from 13.8 meters to 10.0 meters with support)

- Tunnel Convergence (decreased from 2.0 % to 0.99 % with support)

Factor of Safety

The factor of safety for the rockbolts is 1.84. See the Introduction to this manual for a definition of the Factor of Safety in *RocSupport*.

Although this would be considered an adequate Factor of Safety in other types of analyses (e.g. limit equilibrium slope stability), in a rock support interaction analysis this may not be the case, due to the assumptions inherent in the analysis. See the Introduction for more information.

Mobilized Support Pressure

The Mobilized Support Pressure listed in the Project Info Textbox is the Support Pressure determined from the intersection of the Ground Reaction and Support Reaction Curves, as shown in Figure 2-14 in the next section.

When the Factor of Safety is greater than 1, this value will always be LESS than the Maximum (Available) Support Pressure.

Plastic Zone Radius

The rockbolt support has reduced the radius of the plastic zone from 13.8 meters to 10.0 meters.

Note about Bolt Length

Although bolt length does not enter into a *RocSupport* analysis (since support is modeled as an equivalent uniform internal pressure), the Plastic Zone Radius gives an indication of the required bolt lengths for effective support. For bolts to be effective, they must be anchored in unyielded rock. This means that they have to extend beyond the plastic zone.

By default, *RocSupport* extends bolts 2.0 m beyond the plastic zone, when drawing the bolts on the screen. For the current example, this makes the rockbolt support approximately 6 meters in length. The default value of 2.0 m can be changed in the Section View tab of the Display Options dialog.

Ground Reaction and Support Reaction

Now select the Ground Reaction view, which will display the Ground Reaction and Support Reaction curves on the same plot.

Select: Analysis → Ground Reaction

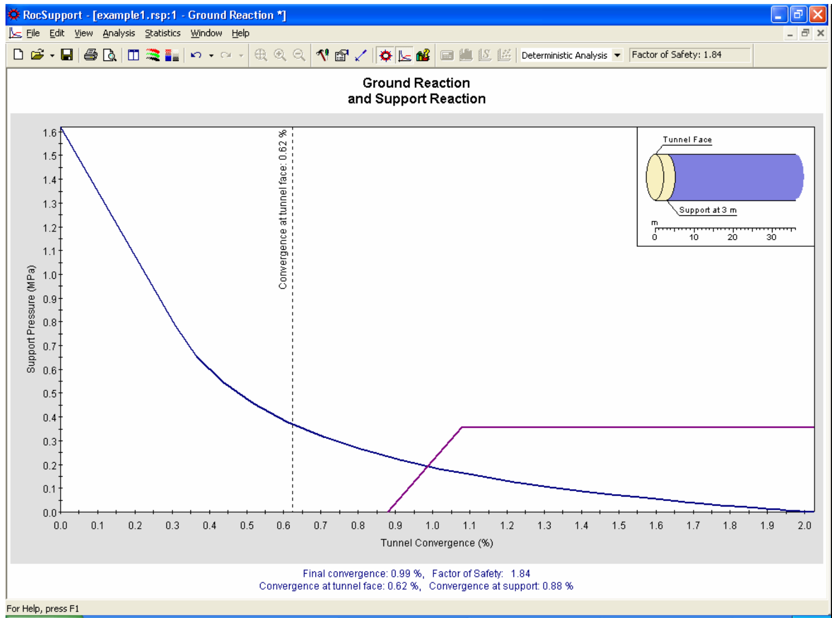


Figure 2-14: Ground reaction and support reaction curves.

As discussed in the Introduction, note the following about the Support Reaction Curve:

- The origin of the Support Reaction Curve, on the horizontal (Tunnel Convergence) axis, is determined from the Distance from Tunnel Face entered in the Support Parameters dialog. See the Introduction to this manual for details about how this value is determined.
- The slope of the elastic portion of the Support Reaction curve, is equal to the Maximum Support Pressure divided by the Maximum Average Strain.
- The intersection of the Support Reaction with the Ground Reaction, determines the mobilized support pressure, final tunnel convergence (with support) and plastic zone radius, listed in the Tunnel Section View.

If the Ground Reaction Curve intersects the Support Reaction Curve in the elastic region, as in this example, then the mobilized Support Pressure and Tunnel Convergence are considered EQUILIBRIUM values.

Combining Support Types

As mentioned earlier in this tutorial, the Support Parameters dialog allows multiple support types to be added for a given model.

For example, Rockbolts and Shotcrete could be added to the same model, simply by selecting the Add Support checkbox for both Rockbolts and Shotcrete, and entering the desired parameters for each.

When multiple support types are used for a single model, the following rules apply to the Maximum Support Pressure and Average Strain:

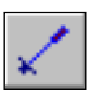
- The Maximum Support Pressure is cumulative, and is ADDED for all applied support types.
- The Maximum Average Strain is AVERAGED for all applied support types.

These simplistic assumptions are of course not intended to model the actual, complex interaction of multiple support systems, but are an idealized approximation.

For our current example, also remember that:

- The guidelines described in the Appendix suggest that rockbolts and shotcrete together, would be appropriate support for this tunnel.

So, let's add some shotcrete support to the rockbolt support, and see the effect on the analysis results.



Select: Analysis → Support Parameters

In the Support Parameters dialog:

1. Select the Shotcrete tab.
2. Select the Add Support checkbox.
3. Notice that green checkmarks now appear on BOTH the Rockbolts tab and the Shotcrete tab, indicating that both rockbolt and shotcrete support will be in effect.

4. Select the 50 mm thickness, 28-day age shotcrete type from the Properties list.

The dialog should appear as follows:

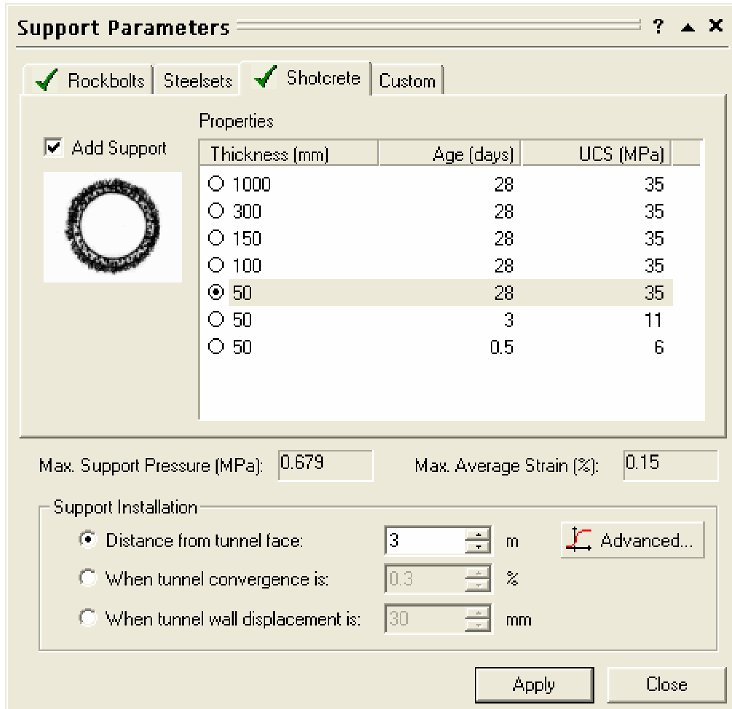


Figure 2-15: Shotcrete added in Support Parameters dialog.

5. Select the Apply button, to save the shotcrete parameters and re-run the analysis. All open views of the current document, will be updated with the latest analysis results.

Before we close the Support Parameters dialog, notice the Maximum Support Pressure and Maximum Average Strain values listed in the dialog. These are now the COMBINED values, for the rockbolts AND shotcrete.

As discussed above:

- the (combined) Maximum Support Pressure is the SUM of the 34 mm rockbolt support pressure and the 50 mm shotcrete support pressure (.354 + .325 = .679)

- the (combined) Maximum Average Strain is the AVERAGE of the rockbolt and shotcrete maximum strain values (.200 + .100) / 2.

Now close the dialog and observe the new analysis results.

Note that the thickness of shotcrete (or steel set) support is not drawn to scale in the Tunnel Section View. If desired, it can be drawn either with a specified thickness in mm or as a percentage of tunnel radius, as selected in the Display Options dialog (use the Thickness of Support Layer option in the Section View tab of the Display Options dialog). This is left as an optional exercise for the user to experiment with.

Analysis Results (With Combined Support)

As we did after adding rockbolt support, examine the information in the Tunnel Section View and the Ground Reaction / Support Reaction View. The following table summarizes the results with No Support, Rockbolt Support, and Combined Rockbolt / Shotcrete Support.

	No Support	**Rockbolts**	**Rockbolts + Shotcrete**
Factor of safety	n / a	1.8	3.2
Mobilized support pressure (MPa)	n / a	.19	.21
Plastic zone radius (m)	13.8	10.0	9.7
Tunnel convergence (%)	2.0	1.0	0.9

Table 2-1: Summary of Example 1 analysis results.

It can be seen that the addition of shotcrete support did not have a great effect on the plastic zone radius, tunnel convergence or mobilized support pressure, compared to the rockbolt support alone.

This is because the additional support capacity, in this case, has not significantly changed the intersection point of the Ground Reaction and Support Reaction curves, which determines these values. Compare Figures 2-14 and 2-16.

However, the Factor of Safety for the combined support has been significantly increased, from 1.8 to 3.2. This might now be considered an adequate safety factor for the support system.

Keep in mind that we used the 28-day shotcrete strength. The support pressure provided by the shotcrete at early ages is much less than the 28-day strength, and this must be taken into consideration when considering the actual combined safety factor, at different stages of the shotcrete curing.

(Note that 3-day and 0.5-day 50 mm shotcrete support, is also available in the Support Parameters dialog).

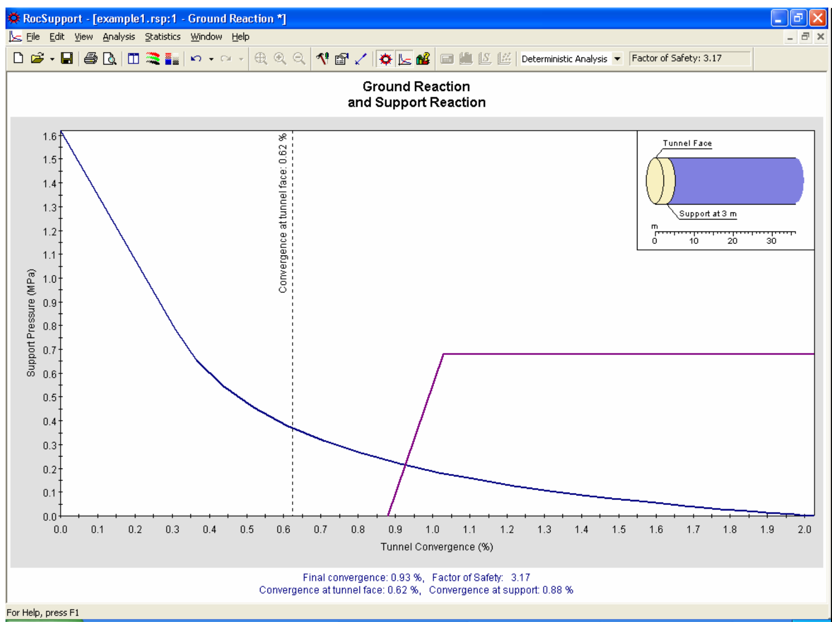


Figure 2-16: Ground reaction and combined rockbolt / shotcrete support reaction curves.

Info Viewer

Finally, let's look at the Info Viewer option. The Info Viewer option provides a well-formatted summary of all input and output data.

Select: Analysis → Info Viewer

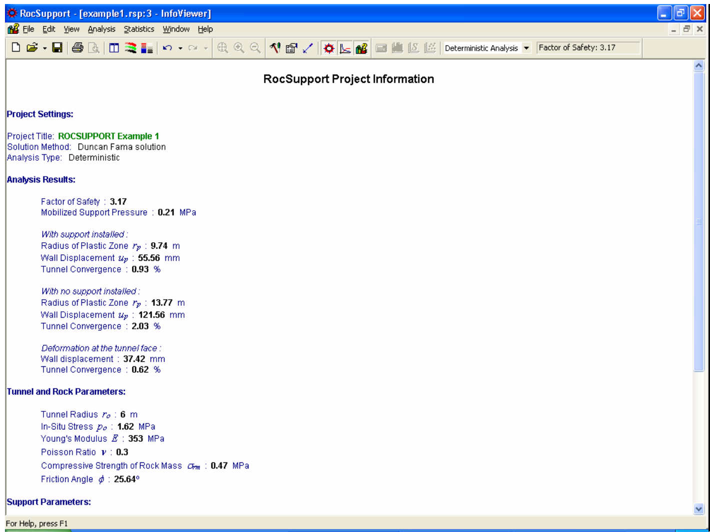


Figure 2-17: Info Viewer display.

If necessary, scroll down to view all of the information in the Info Viewer. The font size can be changed in the View menu.

Notice that the Support Parameters information lists the Total Combined (Maximum Support Pressure and Maximum Average Strain), as well as the contributions from each individual support type used in the model (in this case, rockbolts and shotcrete).

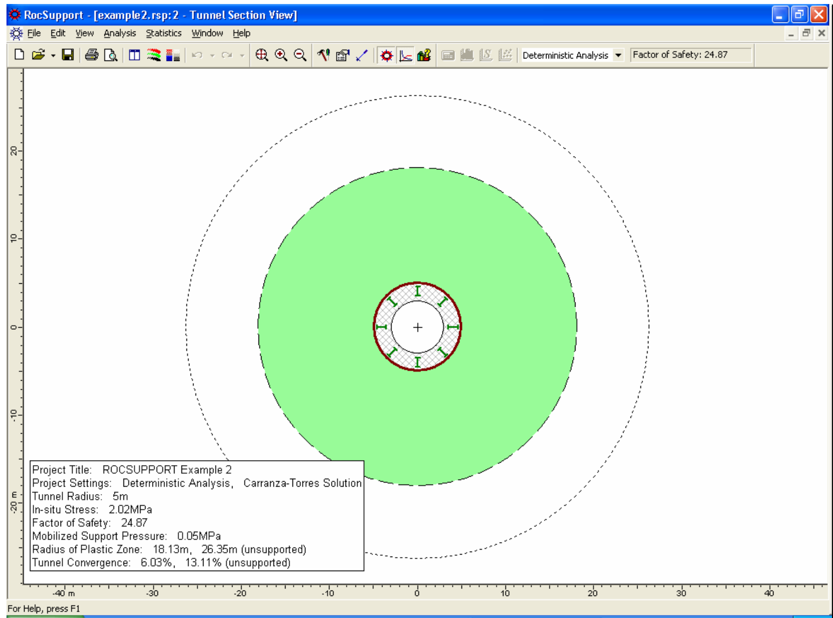
The Info Viewer text can be copied to the Windows clipboard, by selecting the Copy option from the Edit menu or the toolbar, or by right-clicking in the Info Viewer and selecting Copy. From the Windows clipboard, the text can be pasted into other applications for report writing, presentations, etc.

The Info Viewer text can also be saved to a file, by right-clicking in the view and selecting Save As .rtf file or Save As .txt file. A Rich Text Format file (.rtf file) preserves the formatting of the text, as it is displayed in the Info Viewer. A plain text file (.txt file) saves the text only, with no formatting.

That concludes this tutorial. To exit the program:

Select: File → Exit

Example 2 – Heavy Support



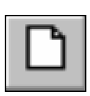
Example 2 will model a tunnel with much more serious stability problems than Example 1, requiring heavier support. The Carranza-Torres solution method will be used to determine the Ground Reaction Curve. Analysis will be Deterministic (all parameters assumed to be exactly known).

MODEL FEATURES:

- A 10 meter diameter tunnel is to be constructed at a depth of 75 meters in a rock mass whose strength is defined by the Hoek-Brown criterion with an intact rock strength σ_{ci} = 4 Mpa, constant m_i = 12 and a Geological Strength Index = 17.

NOTE: the finished product of this tutorial can be found in the **example2.rsp** data file in the EXAMPLES folder in your *RocSupport* installation folder.

If you have not already done so, start the *RocSupport* program, and create a new file to begin working with.

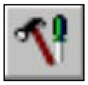


Select: File → New

If necessary, maximize the application window and the Ground Reaction View.

Project Settings

For this example, we will use the Carranza-Torres solution method, which must be selected in the Project Settings dialog.



Select: Analysis → Project Settings

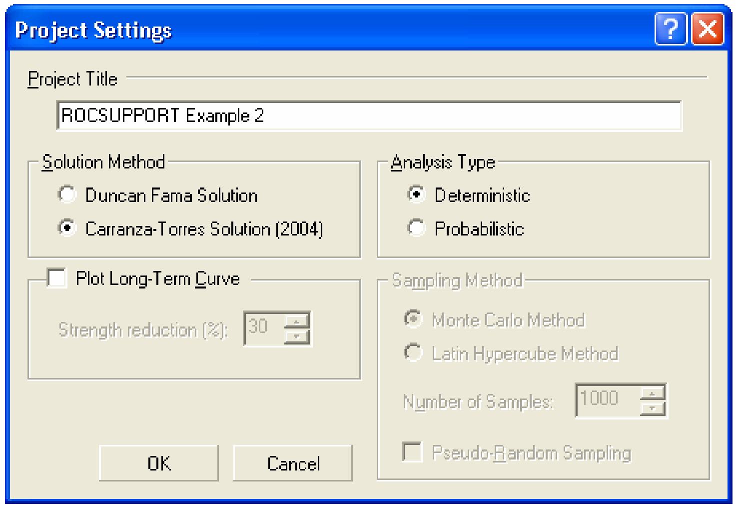


Figure 3-1: Project Settings dialog.

In the Project Settings dialog, select the Carranza-Torres Solution Method. Enter a Project Title – ROCSUPPORT Example 2. Select OK.

Immediately, the Tunnel and Rock Parameters dialog comes up. Anytime you change from one solution method to the other this dialog is automatically invoked. This is because the input rock parameters for the two methods differ, making it necessary for you to verify that you are using the right values for analysis.

Remember that:

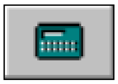
- The Carranza-Torres (2004) solution method uses the Hoek-Brown failure criterion, to determine the Ground Reaction Curve and plastic zone radius.
- The Duncan Fama (1993) solution method uses the Mohr-Coulomb failure criterion, to determine the Ground Reaction Curve and plastic zone radius.

Tunnel and Rock Parameters

Our tunnel diameter is 10 meters, so the default Tunnel Radius of 5 meters is already correct and does not need to be changed.

In-Situ Stress

The In-Situ Stress can be estimated from the Tunnel Depth.



1. Select the Estimate button beside the In-Situ Stress edit box.
2. Enter Tunnel Depth = 75 meters. Select OK in the Estimate In-Situ Stress dialog.
3. The estimated In-Situ Stress is 2.02 MPa.

Rock Parameters

Enter the following Rock Parameters:

Intact Rock Constant m_i *= 12,* GSI = *17 and Compressive Strength of Intact Rock* σ_{ci} *= 4.*

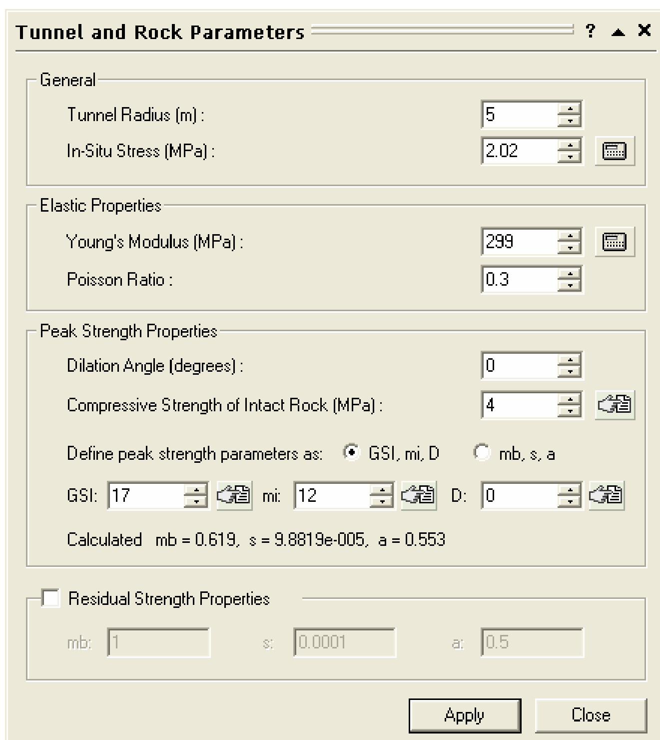


Figure 3-2: Tunnel and Rock Parameters for Example 2.

NOTE: built-in tables for selection of appropriate m_i , GSI, intact UCS and D can be accessed by selecting the “pick” buttons in the Tunnel and Rock Parameters dialog. This is left as an optional exercise for the user to explore. See the previous tutorial for a discussion of these tables.

Young’s Modulus

You will notice that there is a calculator button beside the Young’s Modulus edit box.

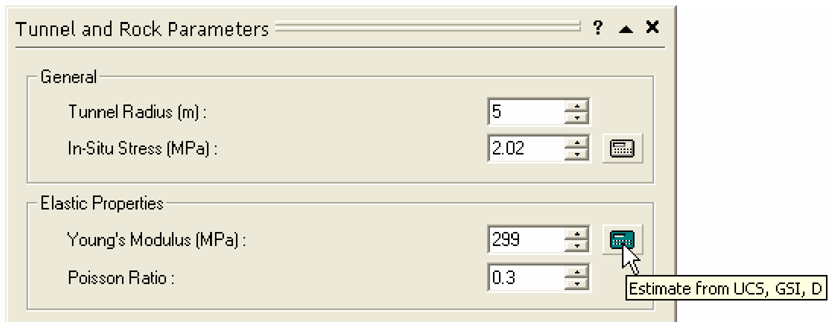


Figure 3-3: Estimation of Young’s Modulus from strength parameters.

If you select this button, the rock mass Young’s Modulus will be automatically calculated from the current values of GSI, intact UCS and Disturbance Factor. The equation used to calculate Young’s Modulus can be found in Hoek, Carranza-Torres and Corkum (2002).

For this example, the rock mass Young’s Modulus is calculated to be 299 MPa.

Apply

Now select Apply to save the Tunnel and Rock Parameters you have entered, and run the analysis with the new parameters. Then select Close.

Analysis Results (No Support)

The Ground Reaction curve should appear as follows.

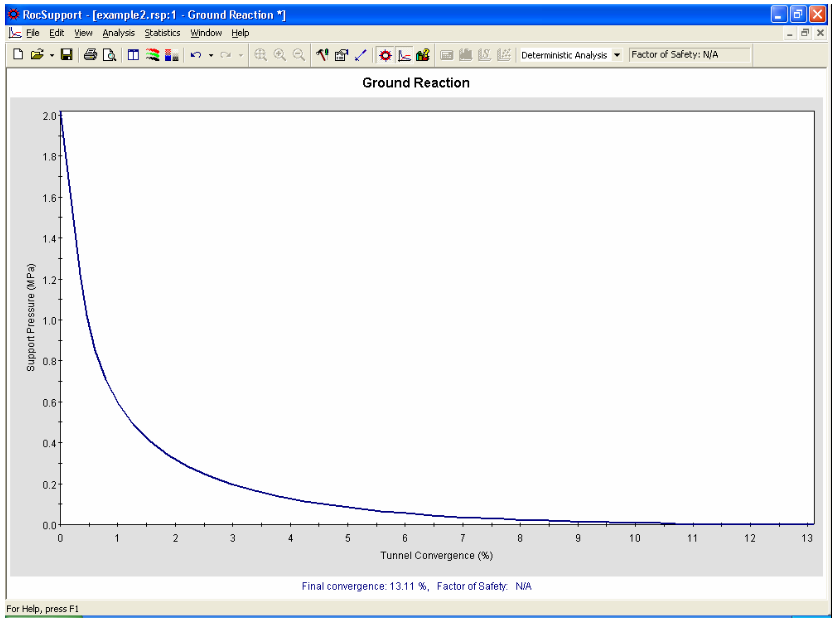
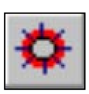


Figure 3-4: Ground Reaction curve, no support, Example 2.

The final Tunnel Convergence = 13.1 %

This is a very high value of Tunnel Convergence. As discussed in the Appendix, a tunnel with these input parameters would have very serious stability problems. Very heavy support, installed as close as possible to the advancing face, would be necessary.

Select the Tunnel Section View.



Select: Analysis → Tunnel Section

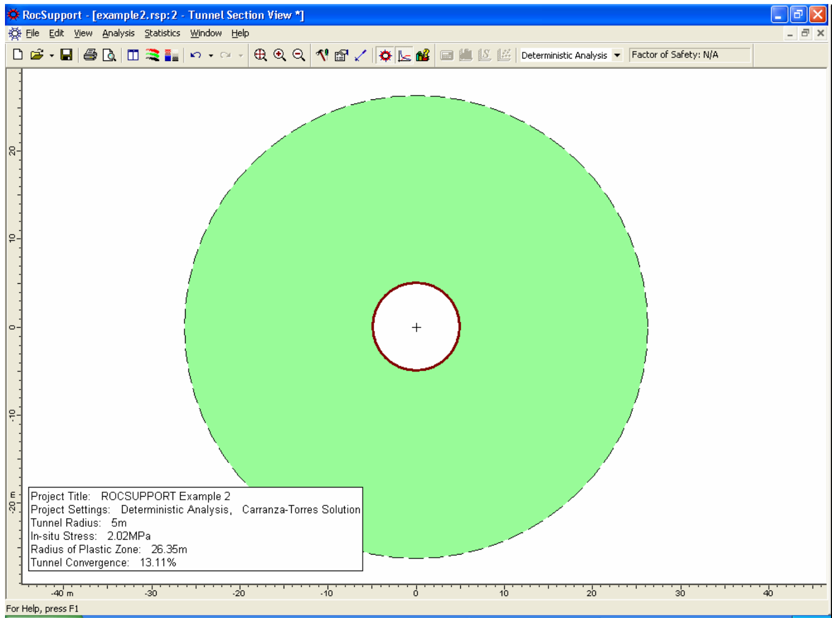
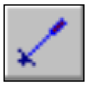


Figure 3-5: Tunnel section view, no support, Example 2.

Notice the very large plastic zone radius (26.3 m) around the unsupported tunnel.

Adding Support

For support, let's start with I section steel sets (254 mm depth, 203 mm width, weighing 82 kg / m), spaced at 1.5 m, and installed at a distance of 3 m from the face.



Select: Analysis → Support Parameters

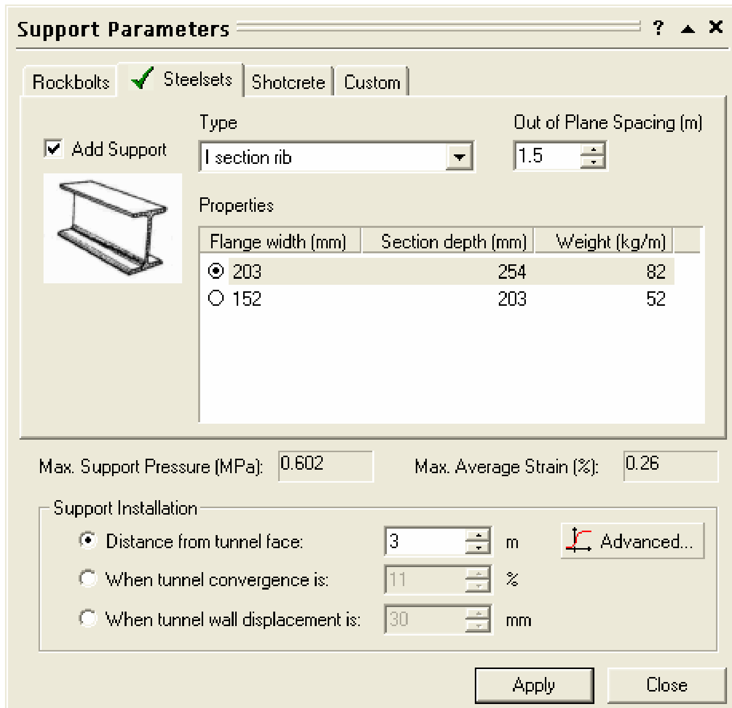


Figure 3-6: Steel set support parameters.

In the Support Parameters dialog:

1. Select the Steel Sets tab, and select the Add Support checkbox.
2. Select I section rib from the Type drop-down list. We will use the default selection 203 mm Flange Width.
3. Enter Out of Plane spacing = 1.5, and Distance from Tunnel Face = 3.
4. Select Apply to save the support parameters you have entered and re-run the analysis. Select Close.

Analysis Results (With Support)

Select the Ground Reaction view. The Ground Reaction and Support Reaction should appear as follows:

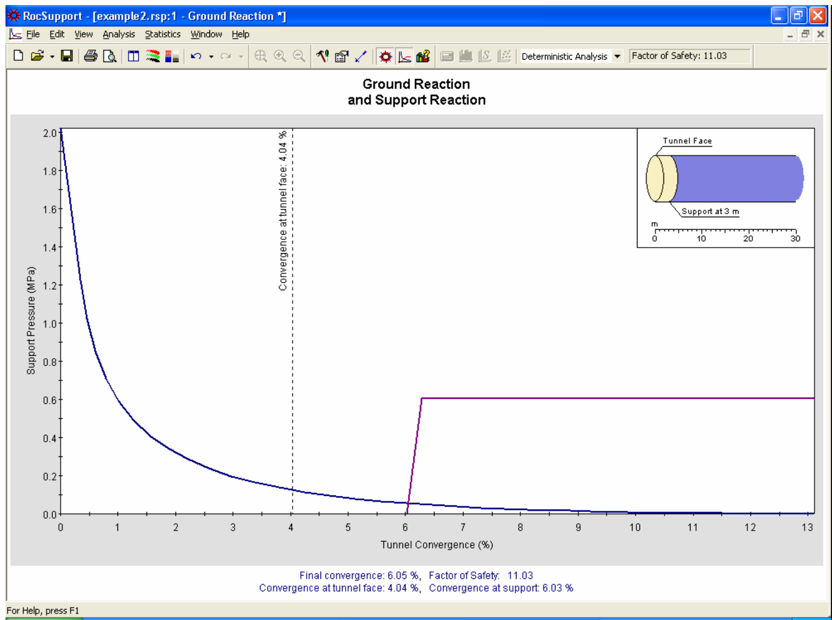
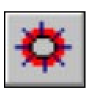


Figure 3-7: Ground reaction and support reaction.

Select the Tunnel Section view, and view the analysis summary in the Project Info Textbox.



Select: Analysis → Tunnel Section

Compared to the unsupported results, the Steel Set support has:

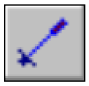
- decreased the plastic zone radius (26.3 to 18.2 m)
- decreased the final Tunnel Convergence (13.1 to 6.0 %)
- Factor of safety for the support is 11.0

Note:

Even with support, the tunnel is still surrounded by a large plastic zone radius, and final convergence is still high. However, the Factor of Safety for the Steel Sets indicates that the loading is well within the support capacity.

Additional Support

Let's now see the effect of adding a layer of shotcrete in addition to the steel set support.



Select: Analysis → Support Parameters

In the Support Parameters dialog, select the Shotcrete tab, select the Add Support checkbox, and select 100 mm thickness shotcrete. Note the combined Maximum Support Pressure (1.366) and Maximum Average Strain (0.18 %), of the shotcrete and the steel sets.

Select Apply.

NOTE:

- The safety factor of the combined support system has more than doubled (11.0 to 24.9).

- However, this has not significantly reduced the final Tunnel Convergence (which remains at 6.0 %) or the Plastic Zone Radius.

Let's look at the Ground Reaction / Support Reaction plot, to examine why the shotcrete support has not affected the final convergence or Plastic Zone Radius.

Select: Analysis → Ground Reaction

If we compare the combined Support Reaction curve, to the curve for the Steel Sets alone (Figure 3-7), you will note the following:

- the additional shotcrete support, has approximately doubled the Maximum Support Pressure, hence the Factor of Safety increase from 11.0 to 24.9.

- However, the intersection point of the Ground Reaction and Support Reaction curve, has not changed significantly, hence there is no significant change in the final Tunnel Convergence or Plastic Zone radius.

In this example, the intersection of the Ground Reaction and Support Reaction is affected primarily by the Distance From Face (entered in the Support Parameters dialog). We did not change this value when we added the shotcrete support.

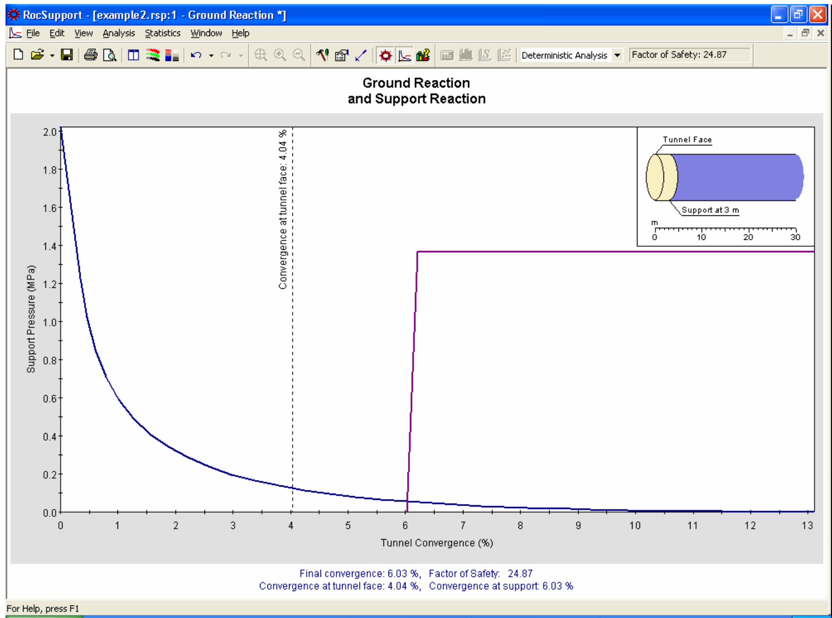


Figure 3-8: Combined support reaction, steel sets and shotcrete.

Support Installation

As a final exercise, enter different values for the Distance from Face in the Support Parameters dialog (e.g. 2 meters, 1 meter etc), and select Apply to re-calculate and view the results.

Notice that changing the Distance from Face shifts the origin of the Support Reaction curve. This DOES have an effect on final Tunnel Convergence, Plastic Zone Radius, and Factor of Safety for the Support. The Factor of Safety decreases as the Distance From Face decreases, because the Support takes a greater load as it is installed closer to the face.

Note: support installation can also be specified directly as a value of tunnel convergence or wall displacement. In this case, the longitudinal deformation profile function is not used.

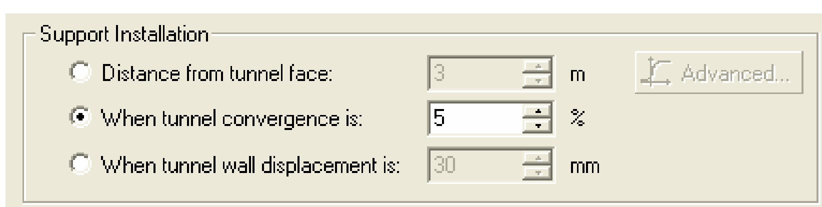


Figure 3-9: Specifying support installation by tunnel convergence.

The user is encouraged to experiment with the Support Parameters dialog. Parametric analysis can be performed very quickly, by adding or removing support, changing support parameters, and selecting Apply to re-calculate the results. Observe the effects on the Support Reaction Curve.

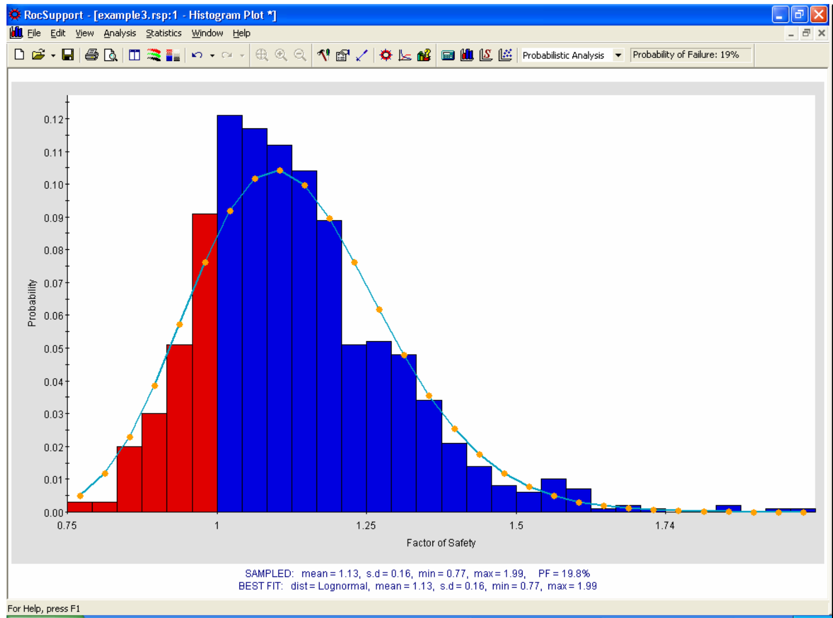
Comment on Example 2

A tunnel with the input parameters used for this example, would certainly require very detailed final support design, which would include numerical analysis such as finite element.

A rock-support interaction analysis of such a tunnel, as demonstrated here using *RocSupport*, would not be adequate for final design purposes. See the guidelines in the Appendix (“category E ”), for the expected support design issues for this tunnel.

Nonetheless, valuable insight into the tunnel behaviour can be gained from the use of *RocSupport* even in such cases. Quick parametric analysis is very easy to perform in *RocSupport*, allowing the user to vary all input parameters, and view the effect on the results.

Example 3 – Probabilistic Analysis



This tutorial will demonstrate how to carry out a Probabilistic analysis with *RocSupport*.

For a given tunneling problem, many of the input parameters are not known with accuracy, particularly those describing the rock mass characteristics. Therefore it is very useful to be able to input statistical distributions for input parameters, in order to obtain statistical distributions of the analysis results.

MODEL FEATURES:

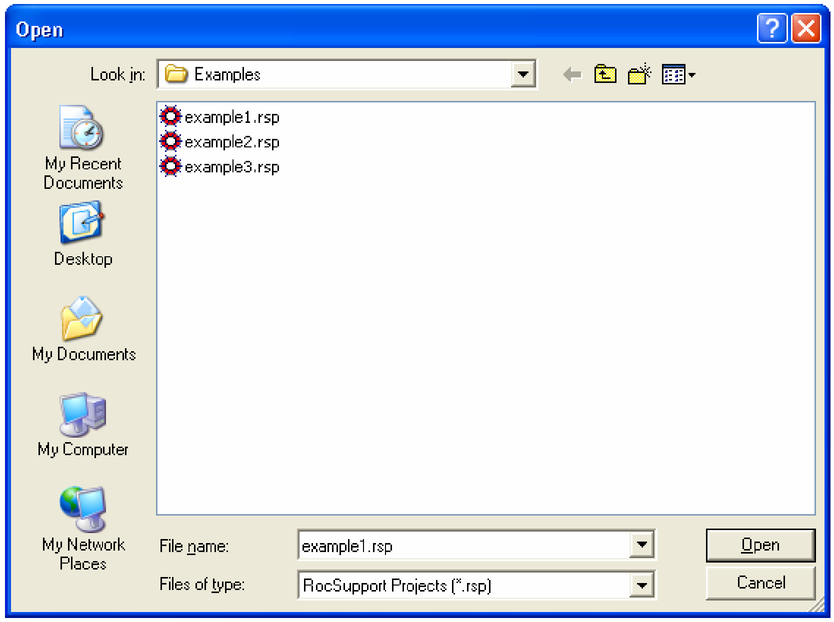
This example will be based on the Example 1 problem, with statistical distributions entered for some of the input variables.

NOTE: the finished product of this tutorial can be found in the **example3.rsp** data file in the EXAMPLES folder in your *RocSupport* installation folder.

Open File

Open the Example 1 file.

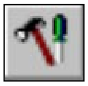
Select: File → Open



Navigate to your RocSupport *installation folder, and open the Example1.rsp file. Note that* RocSupport *files have a .RSP filename extension.*

Project Settings

First we need to change the Analysis Type in the Project Settings dialog from Deterministic to Probabilistic.



Select: Analysis → Project Settings

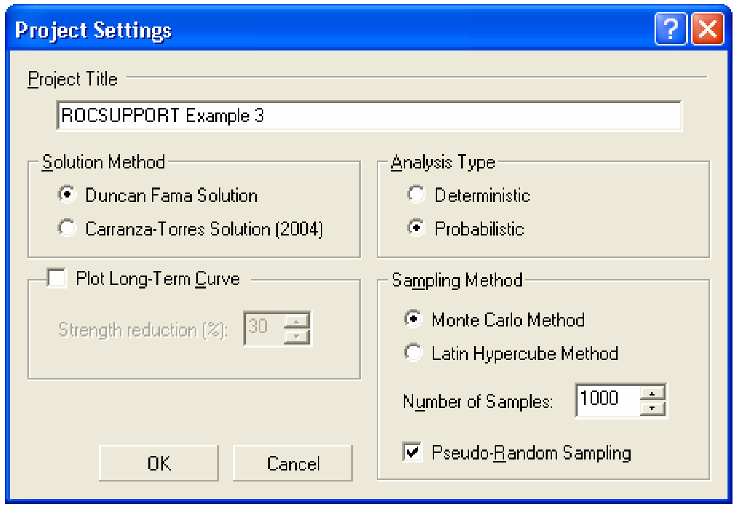


Figure 4-1: Project Settings dialog, Example 3.

In the Project Settings dialog, change the Analysis Type to Probabilistic, and change the Project Title to ROCSUPPORT Example 3. Select the Pseudo-Random Sampling option and click OK.

We will examine the Pseudo-Random sampling option and its purpose later on in the tutorial.

NOTE: the Analysis Type (Probabilistic or Deterministic) can also be selected from the toolbar, as shown below.

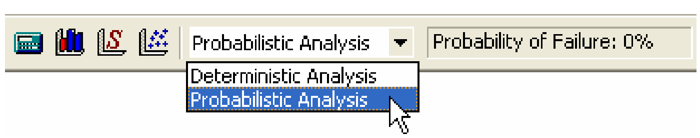


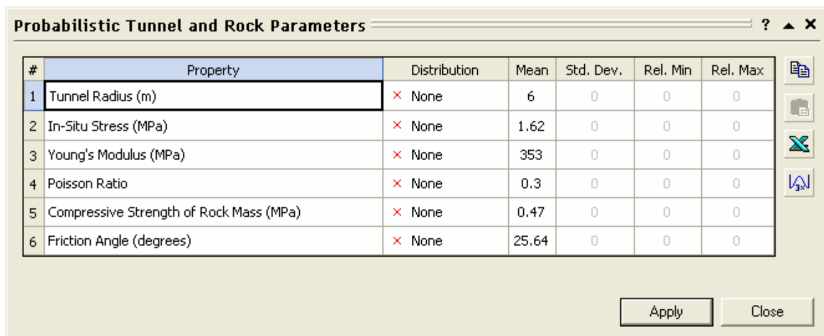
Figure 4-2: Selecting the Analysis Type in the toolbar.

Tunnel and Rock Parameters

Now select Tunnel Parameters from the toolbar or the Analysis menu.

Select: Analysis → Tunnel Parameters

Notice that the Tunnel and Rock Parameters dialog is presented in a grid format for a Probabilistic analysis. This simplifies the input of statistical parameters, and allows you to easily define random variables and keep track of which variables have been assigned statistical distributions.



#	Property	Distribution	Mean	Std. Dev.	Rel. Min	Rel. Max
1	Tunnel Radius (m)	None	6	0	0	0
2	In-Situ Stress (MPa)	None	1.62	0	0	0
3	Young's Modulus (MPa)	None	353	0	0	0
4	Poisson Ratio	None	0.3	0	0	0
5	Compressive Strength of Rock Mass (MPa)	None	0.47	0	0	0
6	Friction Angle (degrees)	None	25.64	0	0	0

Figure 4-3: Tunnel and rock parameters dialog, probabilistic analysis.

Random Variables

To define a random variable, first select a statistical distribution for the variable (e.g. Normal) in the Tunnel and Rock Parameters dialog. Then enter the mean, standard deviation and *relative* minimum and maximum values, which define the statistical distribution for the variable.

- It is important to note that the Minimum and Maximum values are specified as RELATIVE distances from the mean, rather than as absolute values. This simplifies the data input of these values.

  For example: if the mean Friction Angle = 25 degrees, and the minimum = 20 and maximum = 30, then the relative minimum = 5 degrees and the relative maximum = 5 degrees.

- See the *RocSupport* Help system for details about the various statistical distributions that are available in *RocSupport*, and the significance of the input parameters for each distribution.

For this example, we will define the following variables as random:

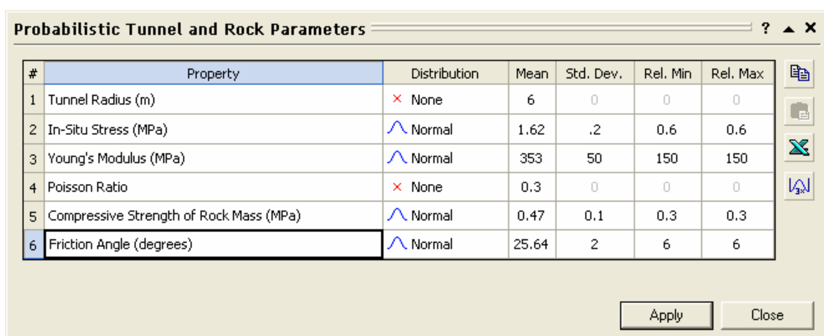
- In-Situ stress
- Young's Modulus
- Compressive Strength
- Friction Angle

Enter the following data:

Property	Distribution	Mean	Std.Dev.	Rel. Min.	Rel. Max.
In-Situ Stress	Normal	1.62	.2	.6	.6
Young's Modulus	Normal	353	50	150	150
Compressive Strength	Normal	0.47	.1	.3	.3
Friction Angle	Normal	25.64	2	6	6

Table 4-1: Statistical input for random variables, example 3.

The Tunnel and Rock Parameters dialog should appear as follows.



#	Property	Distribution	Mean	Std. Dev.	Rel. Min	Rel. Max
1	Tunnel Radius (m)	None	6	0	0	0
2	In-Situ Stress (MPa)	Normal	1.62	.2	0.6	0.6
3	Young's Modulus (MPa)	Normal	353	50	150	150
4	Poisson Ratio	None	0.3	0	0	0
5	Compressive Strength of Rock Mass (MPa)	Normal	0.47	0.1	0.3	0.3
6	Friction Angle (degrees)	Normal	25.64	2	6	6

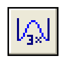
Figure 4-4: Tunnel and Rock parameters, example 3.

Automatic Minimum and Maximum Values

You may have noticed that the relative minimum and maximum value we entered for each variable, was 3 times the standard deviation. For a Normal distribution, this ensures that a complete (non-truncated) distribution is defined (i.e. since 99.7% of all samples fall within 3 standard deviations of the mean, for a normally distributed random variable).

In the Tunnel and Rock Parameters dialog, the following shortcut can be used for this purpose (this is left as an optional exercise to experiment with, after completing this tutorial):

1. Enter the standard deviation for a random variable.

2. Select the  button in the dialog, and the relative minimum and relative maximum for the variable will be automatically set to 3 times the standard deviation.

You can use this shortcut for multiple variables simultaneously – just use the mouse to first select all of the desired variables in the dialog, and then select the 3x button.

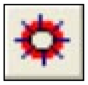
Apply

Now select Apply. This will save the parameters you have just entered, and run the *RocSupport* Probabilistic analysis. The analysis should only take a few seconds or less (remember that we used the default Number of Samples = 1000 in the Project Settings dialog). Close the Tunnel and Rock Parameters dialog, and we will view the analysis results.

NOTE: because we selected Pseudo-Random sampling, the Probabilistic analysis will always generate exactly the same results, for a given set of input parameters. To generate true random sampling, we can turn OFF the Pseudo-Random Sampling option, as described later in this example.

Tunnel Section View

Select the Tunnel Section View.



Select: Analysis → Tunnel Section

The Tunnel Section View, for a Probabilistic analysis, appears the same as for a Deterministic analysis. However, in the analysis summary provided in the Project Info Textbox, note that:

- The results are the MEAN values from the statistical analysis. In general, these MEAN values will NOT NECESSARILY be the same as the Deterministic analysis results, based on the mean input data.

- A Probability of Failure, for the support, is listed, as well as the MEAN safety factor. The Probability of Failure represents the number of analyses, in which the Factor of Safety for the support was less than 1, divided by the total number of analyses (1000 in this case).

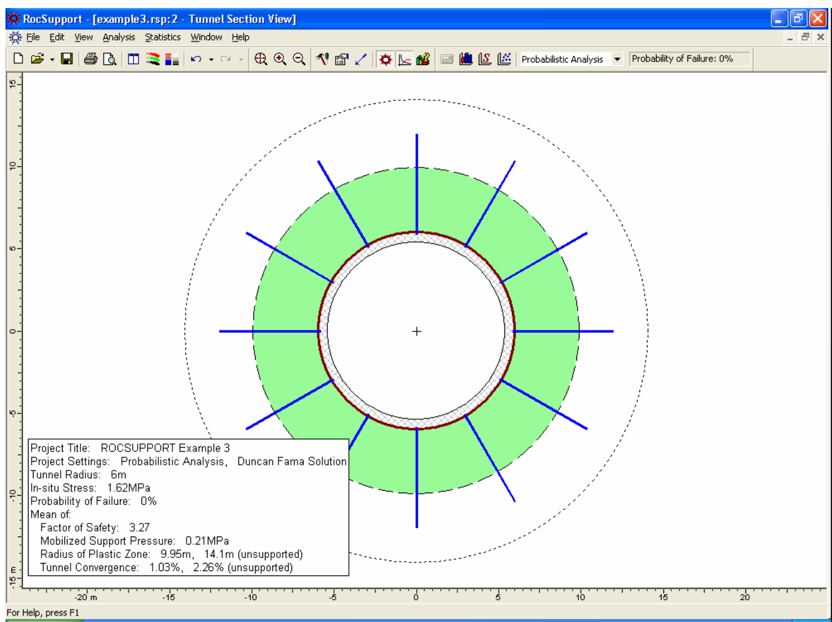


Figure 4-5: Tunnel Section view, probabilistic analysis.

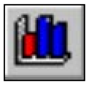
The Probability of Failure is currently zero (i.e. Factor of Safety is greater than 1 for all cases analyzed).

Statistics

After a Probabilistic analysis, the user can plot the results in the form of Histograms, Cumulative Distributions or Scatter Plots of input and output variables.

Histogram Plots

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



Select: Statistics → Histogram Plot

(Alternatively, you can also activate the Histogram Plot dialog by pressing F7.)

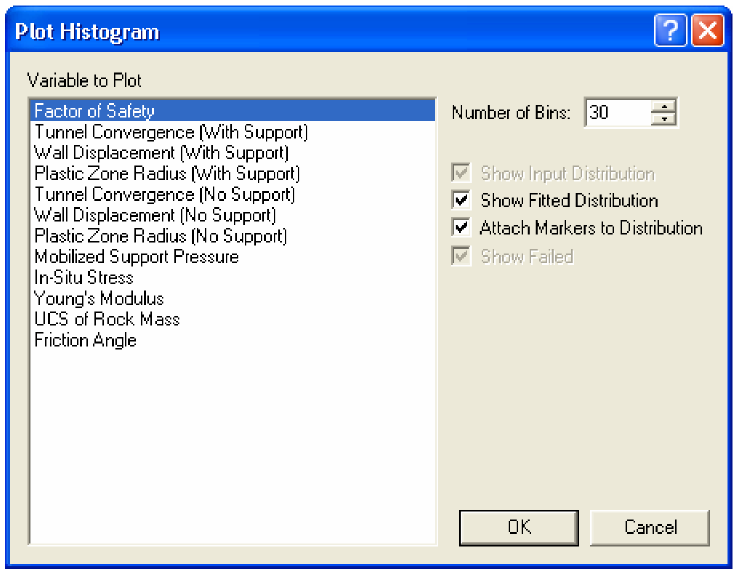


Figure 4-6: Plot Histogram dialog.

Note that both input and output variables are listed in the Variable to Plot list.

- The output variables will always include Factor of Safety, Tunnel Convergence, Wall Displacement and Plastic Zone Radius.
- The input variables listed, will only be those for which you have entered a statistical distribution, in the Tunnel and Rock Parameters dialog. For our current example, this includes In-Situ Stress, Young's Modulus, UCS of Rock Mass and Friction Angle.

Let's plot a histogram of Factor of Safety. Since this is the default selection in the Plot Histogram dialog, just select OK to generate the plot.

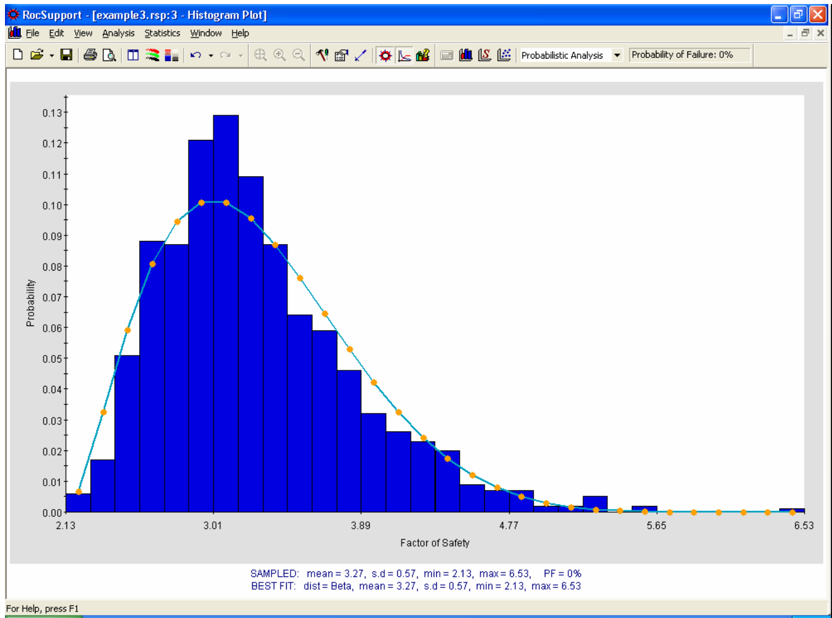


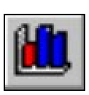
Figure 4-7: Factor of safety histogram.

As you can see in this plot, there were no analyses with a Factor of Safety less than 1. The Probability of Failure is therefore zero.

For calculated output variables such as Factor of Safety, a FITTED distribution can be displayed on a histogram, as shown in the above figure. The fitted distribution can be toggled on or off in the right-click menu, the Statistics menu or in the Plot Histogram dialog (select the Show Fitted Distribution option).

The Fitted Distribution represents a best-fit distribution for the output variable, and is automatically determined by *RocSupport*. Note that the Fitted Distribution can be any one of the statistical distributions used in *RocSupport* (i.e. normal, uniform, triangular, beta, exponential, lognormal or gamma).

Now let's generate a histogram of one of our input variables, for example, In-Situ Stress.



Select: Statistics → Histogram Plot

In the Plot Histogram dialog, select In-Situ Stress from the Variable to Plot list. Select OK.

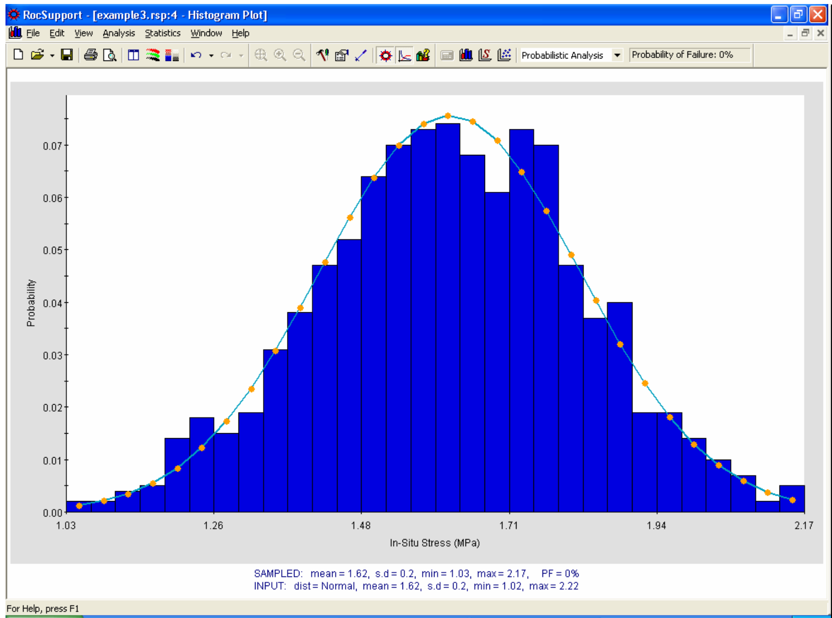


Figure 4-8: In-Situ stress histogram.

For input variables, the Input Distribution can be displayed on the Histogram plot, as shown in the above figure for In-Situ Stress. Also a statistical summary of the simulated values, and the parameters of the Input Distribution are provided at the bottom of the plot.

- The Input Distribution is the distribution defined by the input data you have entered in the Tunnel and Rock Parameters dialog.
- The Sampled data statistics are derived from the raw data generated by the statistical sampling (Monte Carlo method in this case) of the Input Distribution you have defined.

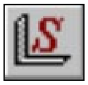
This explains why the SAMPLED and INPUT statistical parameters listed at the bottom of an input variable histogram, will in general differ slightly, especially if the Number of Samples is small.

(Note: if you use Latin Hypercube sampling, and a large number of samples, the Sampled and Input statistical parameters should be equal, or very nearly equal. This is because the Latin Hypercube method samples the input data distributions more uniformly than Monte Carlo sampling. This is left as an optional exercise to explore, after completing this tutorial).

Cumulative Plots

A cumulative distribution is, mathematically speaking, the integral of the normalized probability density function. Practically speaking, a point on a cumulative distribution gives the probability that a random variable will be LESS THAN OR EQUAL TO a specified value.

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



Select: Statistics → Cumulative Plot

Note that the list of Variables to Plot, is exactly the same in both the Plot Histogram and Plot Cumulative dialogs.

Let's plot the Factor of Safety cumulative distribution. Since this is the default selection in the Plot Cumulative dialog, just select OK to generate the plot.

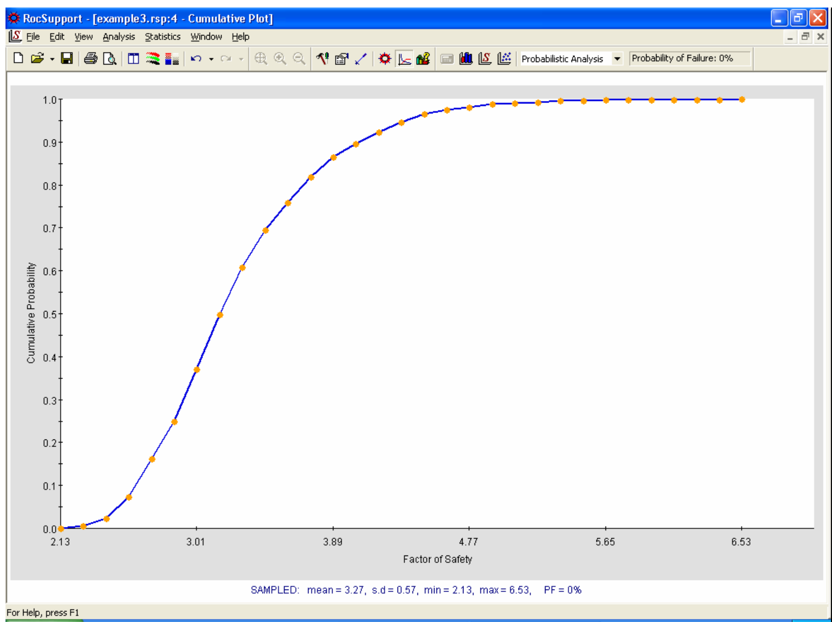
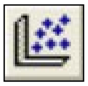


Figure 4-9: Cumulative plot of Factor of Safety.

It is worthwhile noting that for the cumulative distribution of Factor of Safety, the cumulative probability at Factor of Safety = 1, is equal to the Probability of Failure. In this example, the Factor of Safety is greater than 1 for all cases, therefore the Probability of Failure = 0.

Scatter Plots

Scatter plots can also be generated after a probabilistic analysis. Scatter plots allow you to plot any two random variables against each other, to view the correlation (or lack of correlation) between the two variables.



Select: Statistics → Scatter Plot

In the Scatter plot dialog, select Factor of Safety versus UCS of Rock Mass.

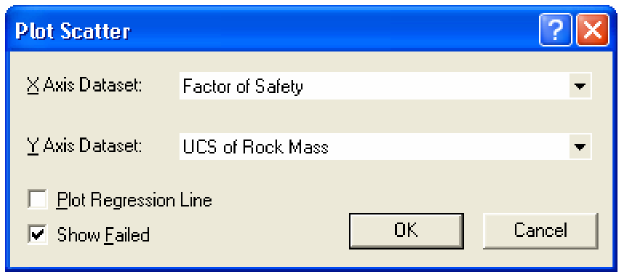


Figure 4-10: Scatter plot dialog.

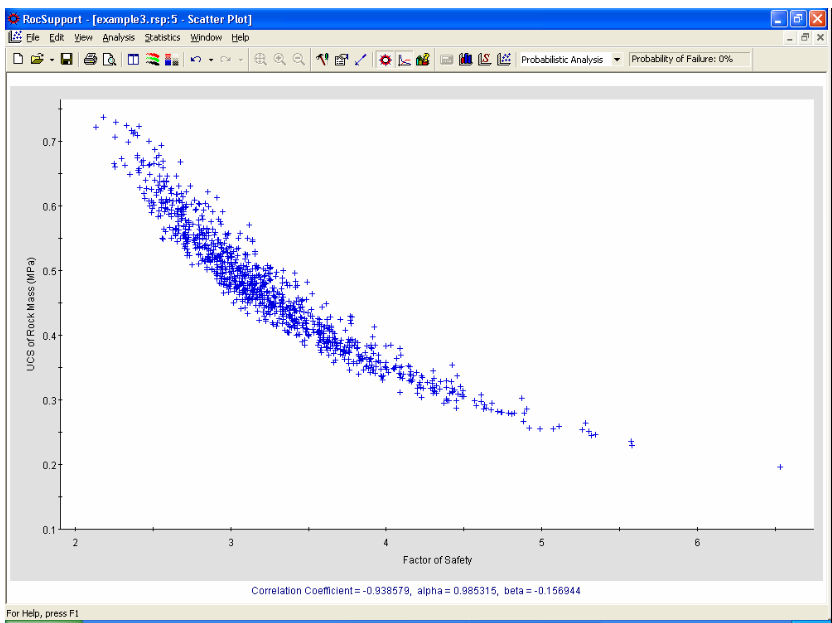


Figure 4-11: Scatter plot of Factor of Safety versus rock mass UCS.

It can be seen that there is a strong correlation between the input variable UCS of Rock Mass, and the Factor of Safety for the support. The best fit linear regression line can be displayed using the right-click menu shortcut, if desired.

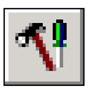
Computing the Analysis using True Random Sampling

For this tutorial, we selected the Pseudo-Random Sampling option in Project Settings. Therefore, when the Apply button is clicked in the Tunnel Parameters or Support Parameters dialogs, *RocSupport* uses PSEUDO-RANDOM numbers to generate the statistical sampling of the input variable distributions. Pseudo-random sampling generates the SAME RESULTS each time the analysis is run. This allows the user to obtain reproducible results for a Probabilistic analysis.

To run a Probabilistic analysis using TRUE RANDOM sampling, then you must de-select the Pseudo-Random sampling checkbox in the Project Settings dialog.

With Pseudo-Random Sampling turned OFF, different random numbers are used to generate each sampling of the input variable distributions. This means that EACH TIME COMPUTE or APPLY is selected, different results will be generated.

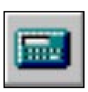
We will re-run our example using true random sampling and observe the results.



Select: Analysis → Project Settings

De-select the Pseudo-Random Sampling option and click OK. The analysis is immediately recomputed, and results different from the previous ones are displayed.

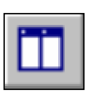
To observe the effect on the Scatter Plot, select the Compute button several times.



Select: Statistics → Compute

The graph is updated after each Compute, to reflect the latest results.

To further illustrate the results of using Compute with true random sampling, let's tile the views.



Select: Window → Tile Vertically

If you have followed the steps in this tutorial, and did not have any other *RocSupport* files open, you should have six views open. Close two of the views (for example, close the Ground Reaction View and the Tunnel Section View, so that only the statistical plot views are open).

Select the Tile option again, and your screen should look similar to the figure below.

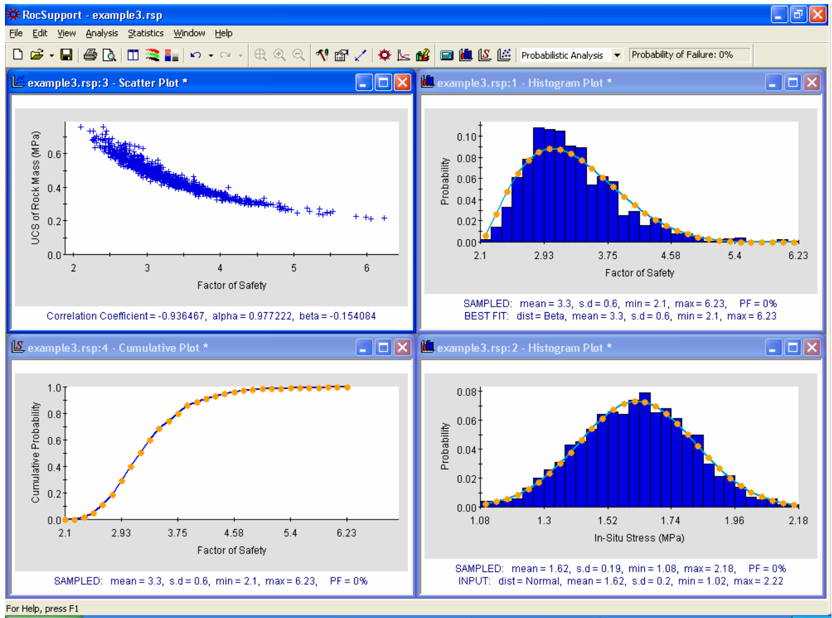


Figure 4-12: Tiled views, Example 3.

Now again re-select Compute several times. Notice that all views are updated to reflect the latest results.

Additional Exercise

Although we demonstrated the Probabilistic analysis features of *RocSupport* in this Example, the Probability of Failure was zero!

As a final suggested exercise, we will create an example with a Probability of Failure greater than zero, in order to demonstrate some additional graphing features of *RocSupport*.

1. In the Support Parameters dialog:

   - remove the Shotcrete support completely, by clearing the Shotcrete checkbox

   - change the Rockbolt type to 19 mm rockbolt. Select Apply and Close.

2. View the Safety Factor Histogram. Notice that all bars with a Factor of Safety less than 1, are now highlighted in RED.

3. View the In-Situ Stress Histogram.

4. Select Show Failed Bars from the Statistics menu (or the right-click menu). The percentage of each bar of the histogram, corresponding to analyses with Factor of Safety less than 1, is now highlighted in RED.

5. Repeat steps 3 and 4 for other input or output variables. Notice the distribution of failed analyses, with respect to the overall distribution of the variable.

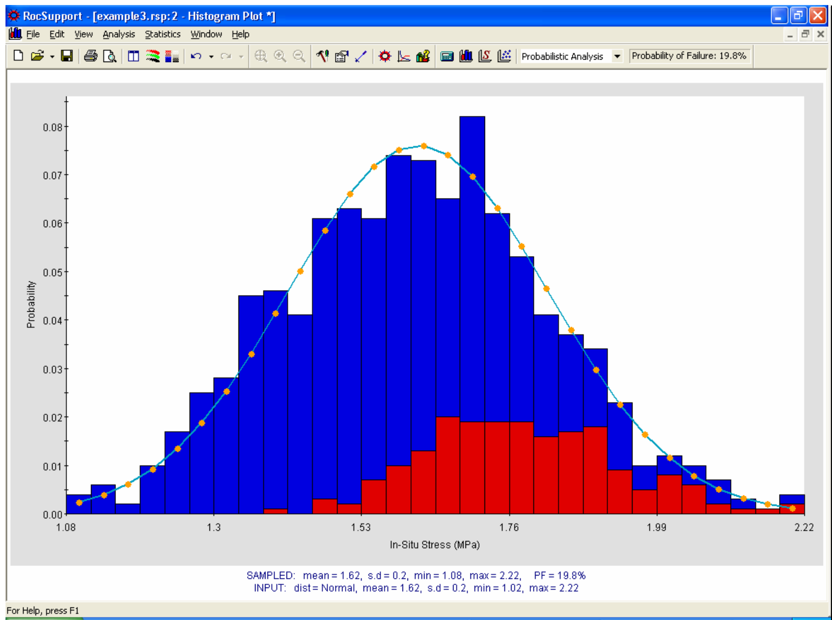


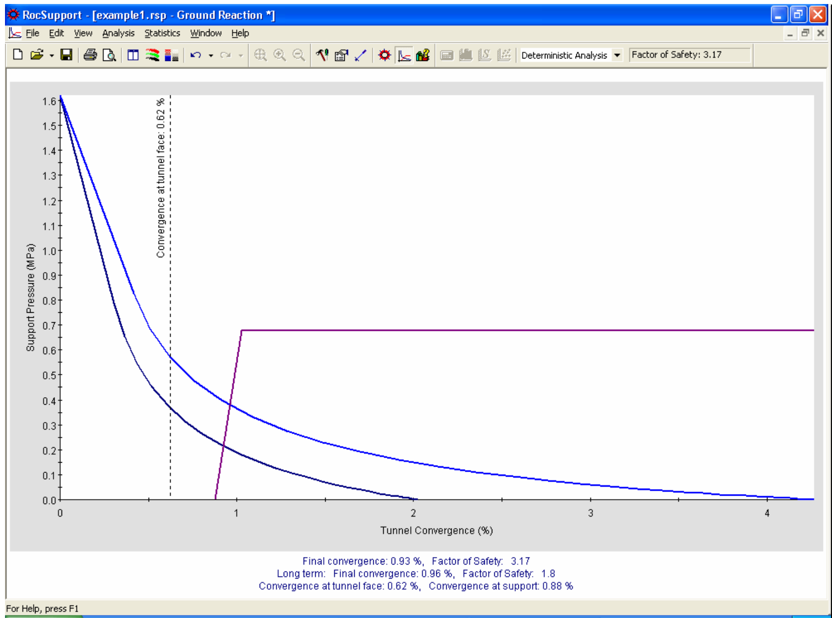
Figure 4-13: Failed results highlighted on in-situ stress histogram.

The Show Failed Bars option allows the user to examine the relationship of any given input or output variable, to the failure of the support system.

That concludes this tutorial. To exit the program:

Select: File → Exit

Long Term Ground Reaction



The long-term behavior of a tunnel and support system is a very important aspect of tunnel design.

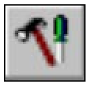
It is often assumed that the long-term properties of the rock mass surrounding a tunnel, deteriorate over time, to some extent. This may be due to rock mass property deterioration, re-establishment of groundwater regimes, creep and similar phenomena (Hoek, 2003).

In *RocSupport*, this can be accounted for by plotting a Long Term Ground Reaction curve, as selected in the Project Settings dialog.

For this example, let's first read in the Example 1 file, from the Examples subfolder in your *RocSupport* installation folder.

Strength Reduction Factor

The Long Term Ground Reaction option is selected in the Project Settings dialog.



Select: Analysis → Project Settings

Select the "Plot Long-Term Curve" checkbox.

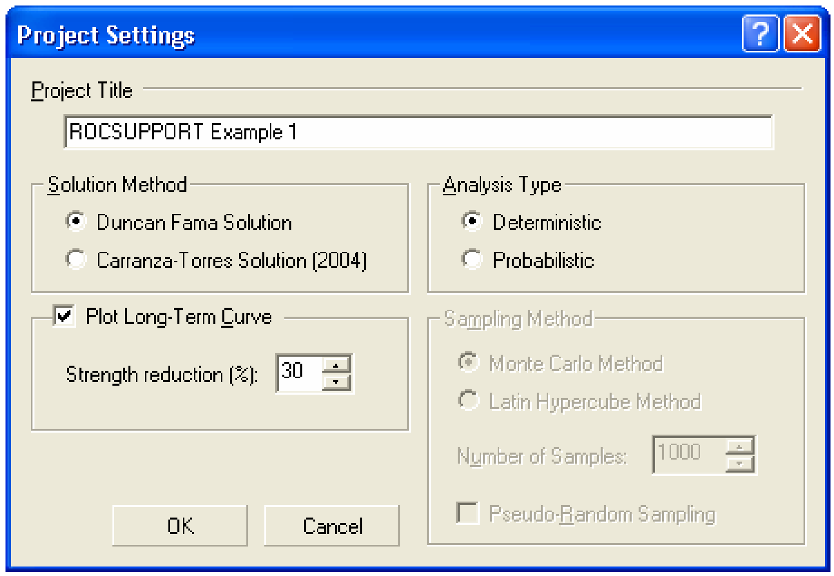


Figure 5-1: Long term ground reaction option in Project Settings.

You can now enter a "strength reduction" factor (percent). This is the percentage by which the following rock mass properties will be *reduced*, in order to determine the properties for the long term ground reaction curve:

- For the Duncan Fama solution method, the reduction factor is applied to the Compressive Strength of the *rock mass*, and to the Young's Modulus.
- For the Carranza-Torres solution method, the reduction factor is applied to the Compressive Strength of the *intact rock*, and to the Young's modulus.

For this example, we will use the default reduction factor of 30%. Select OK in the Project Settings dialog.

Long Term and Short Term Ground Reaction Curves

In the Ground Reaction view, you will now see two Ground Reaction curves plotted:

- The original Ground Reaction curve is the lower curve, and is based on the original (un-reduced) material properties entered in the Tunnel and Rock Parameters dialog. This can be referred to as the Short Term ground reaction curve.
- The Long Term Ground Reaction curve is the upper curve, and is based on the reduction of material properties, as described in the previous section.

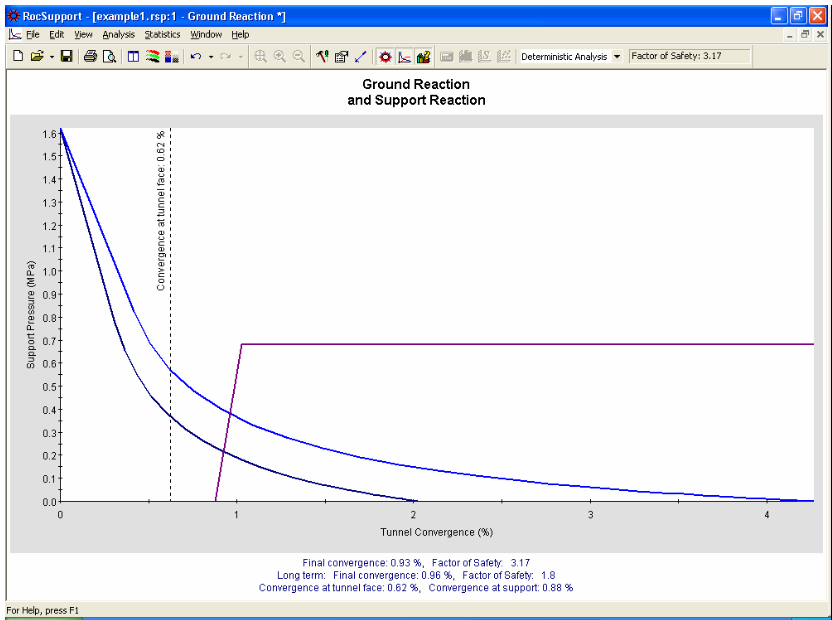


Figure 5-2: Long term and short term ground reaction curves.

As you can see in the above figure, the intersection point of the ground reaction curve with the support reaction curve, is different for the long term and the short term ground reaction.

This will result in differing values of Final Tunnel Convergence and Factor of Safety. In this example:

- The final tunnel convergence is increased slightly from .93% (short term) to .96% (long term)

- The greatest difference is in the Factor of Safety, which is reduced from 3.17 (short term) to 1.8 long term. This is the most significant result of using the long term ground reaction curve – the reduction of Factor of Safety for the support system, due to the greater mobilized support pressure which is carried by the support over the long term.

Info Viewer

For a summary of all available results for both the short term and long term ground reaction curves, check the Info Viewer.

Select: Analysis → Info Viewer

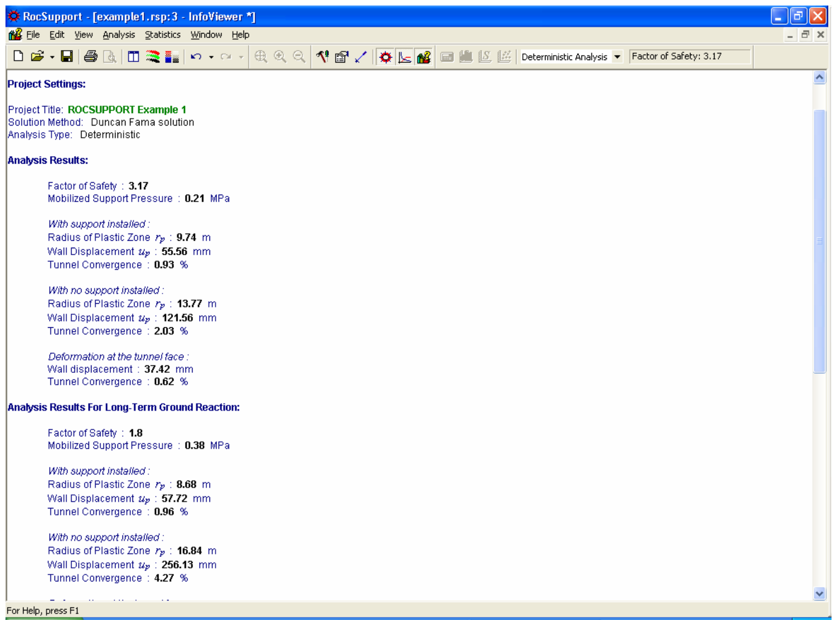


Figure 5-3: Summary of long term and short term results in Info Viewer.

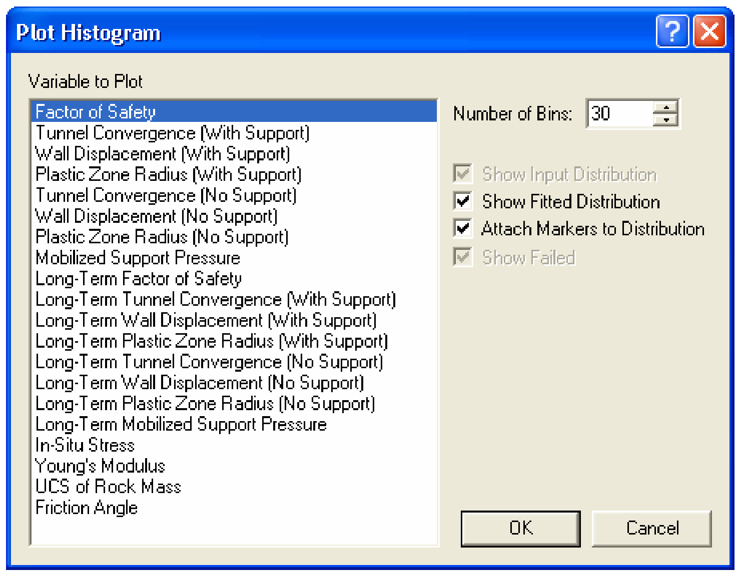
Probabilistic Results for Long Term Curve

If you have are carrying out a Probabilistic Analysis in *RocSupport*, then all of the probabilistic analysis output will be available for both the short and long term ground reaction curves. Try the following:

1. Read in the Example 3 file, from the Examples subfolder in your *RocSupport* installation folder.

2. Select Project Settings and turn on the "Plot Long Term Curve" checkbox.

3. Select the Plot Histogram option. Notice that the list of variables to plot, now includes all of the analysis output for the long term curve, as shown in the dialog below.



4. In the Plot Histogram dialog, select Long-Term Factor of Safety, and select OK. You should see the following plot.

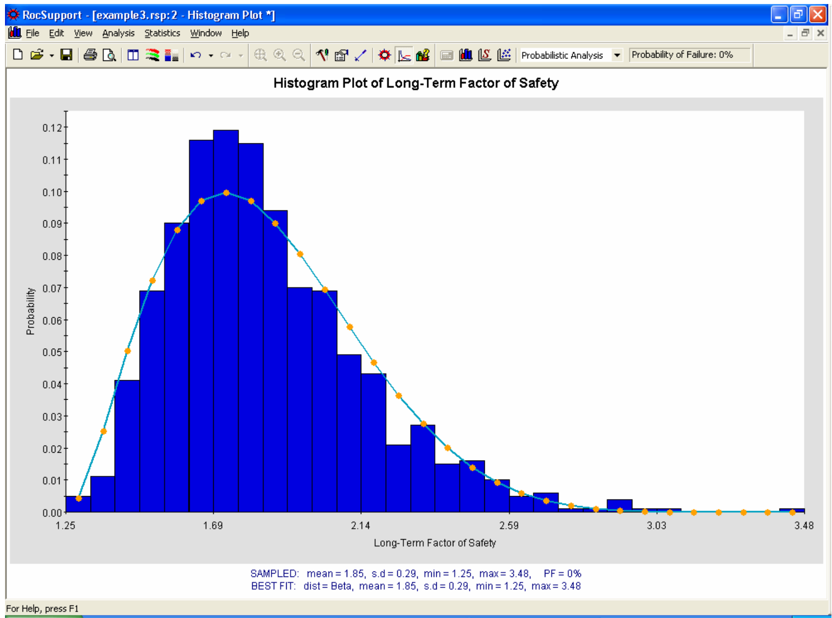


Figure 5-4: Histogram of Long Term Safety Factor.

Cumulative plots and Scatter Plots can also be created using the Long Term probabilistic analysis results. This is left as an optional exercise.

Conclusion

The plotting of the Long Term Ground Reaction curve in *RocSupport*, can be a useful option for estimating the long term performance of the tunnel and support system.

However, the long term analysis as implemented in *RocSupport*, is based on very simplistic assumptions, and should be used with caution. The value which is entered for the Strength Reduction factor will not be a well known parameter. And furthermore, the application of the reduction factor to the rock mass material properties, is a subject which requires further research and investigation.

Appendix – First estimate of support requirements

It has been demonstrated that the stability of tunnels in weak rock, is controlled by the ratio of the uniaxial compressive strength of the rock mass to the maximum in-situ stress. This ratio provides a guide to the first estimate of support requirements (Hoek, 1998).
The results of the latest studies (Hoek and Marinos, 2000) are summarized in the following graph and corresponding table. Although the categories A to E are somewhat arbitrary, they are based on considerable experience, and are considered adequate as a first indication of tunneling difficulty.

Note that this relationship is for an unsupported tunnel. Strain is defined as 100 x the ratio of tunnel closure to tunnel diameter.

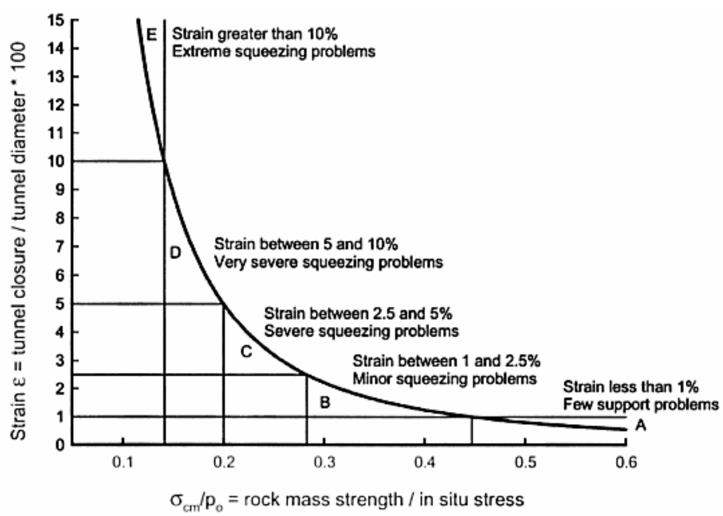


Figure A-1: Approximate relationship between strain and tunneling issues in squeezing rock.

	Strain ε %	Geotechnical issues	Support types
A	Less than 1	Few stability problems and very simple tunnel support design methods can be used. Tunnel support recommendations based upon rock mass classifications provide an adequate basis for design.	Very simple tunneling conditions, with rockbolts and shotcrete typically used for support.
B	1 to 2.5	Convergence confinement methods are used to predict the formation of a 'plastic' zone in the rock mass surrounding a tunnel and of the interaction between the progressive development of this zone and different types of support.	Minor squeezing problems which are generally dealt with by rockbolts and shotcrete; sometimes light steel sets or lattice girders are added for additional security.
C	2.5 to 5	Two-dimensional finite element analysis, incorporating support elements and excavation sequence, are normally used for this type of problem. Face stability is generally not a major problem.	Severe squeezing problems requiring rapid installation of support and careful control of construction quality. Heavy steel sets embedded in shotcrete are generally required.
D	5 to 10	The design of the tunnel is dominated by face stability issues and, while two-dimensional finite analyses are generally carried out, some estimates of the effects of forepoling and face reinforcement are required.	Very severe squeezing and face stability problems. Forepoling and face reinforcement with steel sets embedded in shotcrete are usually necessary.
E	More than 10	Severe face instability as well as squeezing of the tunnel make this an extremely difficult three-dimensional problem for which no effective design methods are currently available. Most solutions are based on experience	Extreme squeezing problems. Forepoling, face reinforcement are usually applied and yielding support may be required in extreme cases.

Table A-1: Approximate relationship between strain and tunneling issues.

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