

RocLab

Rock mass strength analysis using
the Hoek-Brown failure criterion

User's Guide

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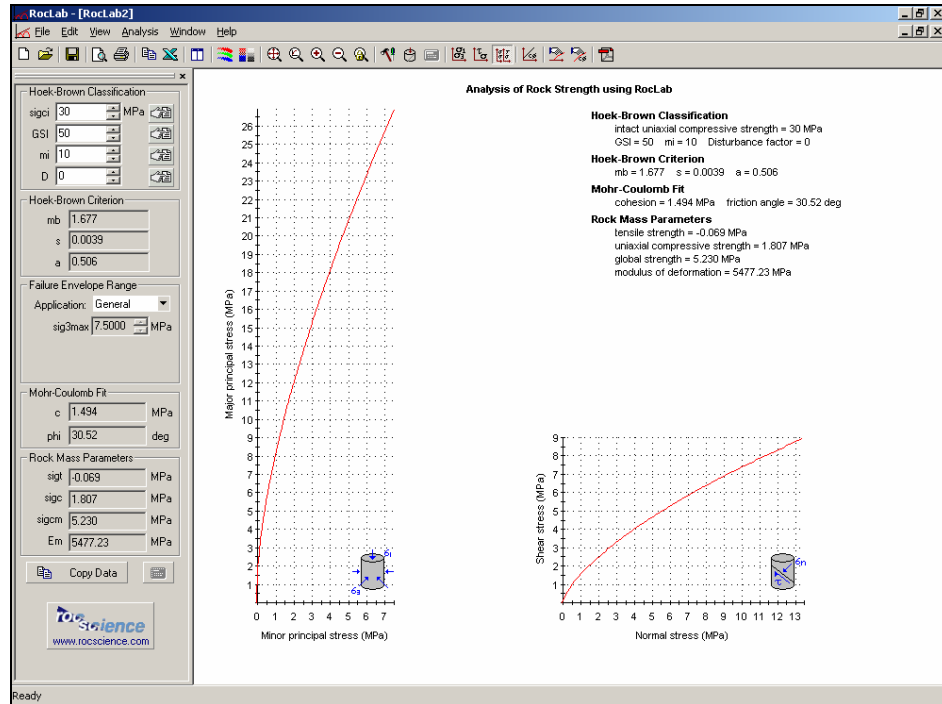
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Welcome to RocLab!

RocLab is a software program for determining rock mass strength parameters, based on the generalized Hoek-Brown failure criterion.

RocLab is a product of Rocscience Inc. It is a free software program.



Rocscience produces many other software products for geotechnical, mining and civil engineering applications. Visit www.rocscience.com to find out about the many other software products available from Rocscience.

Introduction

One of the major obstacles which is encountered in the field of numerical modeling for rock mechanics, is the problem of data input for rock mass properties.

The usefulness of elaborate constitutive models, and powerful numerical analysis programs, is greatly limited, if the analyst does not have reliable input data for rock mass properties.

The latest version of the Hoek-Brown failure criterion (Ref.1), in conjunction with its implementation in the software program **RocLab**, goes a long way toward remedying this situation.

Some formerly troublesome issues with the failure criterion have now been resolved, including:

- the applicability of the criterion to very weak rock masses, and
- the calculation of equivalent Mohr-Coulomb parameters, from the Hoek-Brown failure envelope

The program **RocLab** provides a simple and intuitive implementation of the Hoek-Brown failure criterion, allowing users to easily obtain reliable estimates of rock mass properties, and to visualize the effects of changing rock mass parameters, on the failure envelopes.

The task of determining rock mass properties is not usually an end in itself. It is carried out in order to provide input for numerical analysis programs, which require material properties in order to perform a stability or stress analysis.

The rock mass properties determined by **RocLab** can be used as input for numerical analysis programs such as **Phase2** (finite element stress analysis and support design for excavations) or **Slide** (limit equilibrium slope stability analysis). **Phase2** and **Slide** are also available from Rocscience.

Documentation

The calculations in the **RocLab** program, are based on the latest version of the Generalized Hoek-Brown failure criterion, as detailed in the following paper (Ref. 1):

Hoek, E., Carranza-Torres, C.T., and Corkum, B. (2002), Hoek-Brown failure criterion – 2002 edition. *Proc. North American Rock Mechanics Society meeting in Toronto in July 2002*

The program **RocLab** incorporates all of the latest developments described in this paper.

The paper should be read by all users of **RocLab!!!** The definitions and equations for all input and output parameters in **RocLab**, can be found in this paper, which is available as a PDF document.

Another useful document is the following (Ref. 2):

“A Brief History of the Hoek-Brown Failure Criterion”, by Evert Hoek.

This paper provides a brief chronological overview of the evolution of the Hoek-Brown failure criterion, and provides references to all of the significant papers which have been published. This is also recommended reading for all users of RocLab. The paper is available as a PDF document.

Finally, a set of notes by Dr. Evert Hoek, *Practical Rock Engineering*, (Ref. 3) is available on the Rocscience website, www.rocscience.com, in the form of a series of PDF documents. *Practical Rock Engineering* is recommended reading for all students of rock mechanics. Chapter 11 (Rock mass properties) should also be read by users of RocLab. Note that the version of the Hoek-Brown failure criterion which is presented in the current version of *Practical Rock Engineering*, has been superceded by the latest version of the criterion (Ref. 1). However, the conceptual information is still relevant, and gives further insight into the development of the Hoek-Brown criterion.

How Can I Use RocLab?

The following tasks can be accomplished with RocLab.

Determine Strength Parameters

Determine the Generalized Hoek-Brown strength parameters of a rock mass (**mb**, **s** and **a**), based on the following input data:

- unconfined compressive strength of intact rock **sigci**
- the intact rock parameter **mi**
- the geological strength index **GSI**
- the disturbance factor **D**

Plot Failure Envelopes

Plot the Hoek-Brown failure envelope in principal and / or shear-normal stress space.

- Interactively change **sigci**, **GSI**, **mi**, **D**, to see how the failure envelope changes with each parameter

Estimation of Input Parameters

Each of the above 4 input parameters (**sigci**, **mi**, **GSI** and **D**), can be conveniently estimated from built-in charts and tables, based on rock type, geological conditions, etc.

Triaxial Lab Test Data

Triaxial lab tests on intact rock, can be used to determine **sigci** and **mi** using the Marquardt-Levenberg fitting technique.

- the triaxial data can be imported from Microsoft Excel through the clipboard, tab-delimited or comma separated value text files, RocData or other RocLab files.
- the data can also be entered in the program using a built-in spreadsheet.

Equivalent Mohr-Coulomb Parameters

Calculation of equivalent Mohr-Coulomb strength parameters (cohesion and friction angle).

- The best-fit Mohr-Coulomb strength envelope is determined over a stress range that you can define based on your application (i.e. tunneling or slope stability).
- Plot the equivalent Mohr-Coulomb failure envelope in principal and / or shear-normal stress space

Stress Sampler

Graphically sample the Hoek-Brown or Mohr-Coulomb failure envelope to determine strength for any discrete value of stress (principal, shear or normal stress).

Instantaneous MC Sampler

Graphically determine the instantaneous Mohr-Coulomb parameters at any point along the Hoek-Brown failure envelopes.

Other Rock Mass Parameters

The program also calculates rock-mass parameters such as tensile strength, uniaxial compressive strength and deformation modulus.

Units

A RocLab analysis can be carried out using either Metric or Imperial units. In Metric, the stress units are Megapascals (MPa). In Imperial, the stress units may be either Kilopounds per square foot (ksf) or Kilopounds per square inch (ksi). The unit system is selected in the Project Settings dialog.

Export Data / Images

Export data for further analysis or report writing:

- Copy the data and / or plots to the clipboard for easy import into Microsoft Word or your favorite word processor or image editing program.
- Copy the data and / or plots directly into Microsoft Excel.
- Save the plots to a JPEG or BMP image file.
- Print and Print Preview capabilities.

Display Options

Numerous Display Options to customize the appearance of your plots:

- Change colors, fonts, line thickness.
- Grid overlay.
- Add plot title and show input data directly on plots.
- Zooming.
- Plot Mogi's line (transition from brittle to ductile failure).
- Grayscale for output to black and white printers

Quick Tour of RocLab

The following “quick tour” of RocLab will familiarize the user with the features of the program.

Entering Input Data

The primary means of user interaction with **RocLab**, is with the sidebar data input area, shown below. The sidebar is used for data input, and also for display of calculated output parameters.


The screenshot shows the RocLab sidebar with the following sections and values:

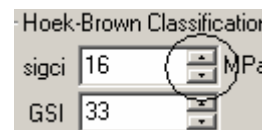
- Hoek-Brown Classification:**
 - sigci: 30 MPa
 - GSI: 50
 - mi: 10
 - D: 0
- Hoek-Brown Criterion:**
 - mb: 1.677
 - s: 0.0039
 - a: 0.506
- Failure Envelope Range:**
 - Application: General
 - sig3max: 7.5000 MPa
- Mohr-Coulomb Fit:**
 - c: 1.494 MPa
 - phi: 30.52 deg
- Rock Mass Parameters:**
 - sigt: -0.069 MPa
 - sigc: 1.807 MPa
 - sigcm: 5.230 MPa
 - Em: 5477.23 MPa

At the bottom, there is a "Copy Data" button and the Rocscience logo with the website address www.rocscience.com.

There are various methods of entering the input data for RocLab:


Interactive Data Input

- If you click on the  arrows with the mouse, to change the input data, the **RocLab** calculations are instantly performed. All output data is immediately recalculated, and the failure envelope plots are redrawn, each time the mouse is clicked on either the up or the down arrow.



This allows you to interactively observe the effect of parameter changes, on the shape of the failure envelopes, and the output values.

Pick Dialogs

- You may also enter input parameters using the “Pick” dialogs. When you select a Pick button,  you will be presented with another dialog, in the form of a chart or table, which allows you to

estimate a value of the input parameter. When you select OK in

the Pick dialog, the selected value of the parameter will be loaded into the sidebar data input area, the **RocLab** calculation will automatically be carried out, and all output data and failure envelopes will be updated.

Keyboard Entry



- If you type the numbers in the sidebar edit boxes with the keyboard, then the calculations are NOT automatically carried out. In this case, you must select the **Compute** option (available in the sidebar, the toolbar, or the Analysis menu), in order to re-compute the rock mass parameters and failure envelopes.

Triaxial Lab Test Data



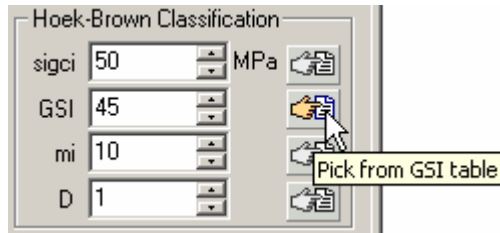
- You may also determine values of **sigci** and **mi**, from triaxial lab test data for intact rock. This is done with the **Use Lab Data** option, as described in a later section. When you select Apply or OK in the “Calculate sigci, mi from Lab Data” dialog, the **RocLab** calculation is carried out, and all output values and failure envelopes are updated.

Estimating Input Parameters

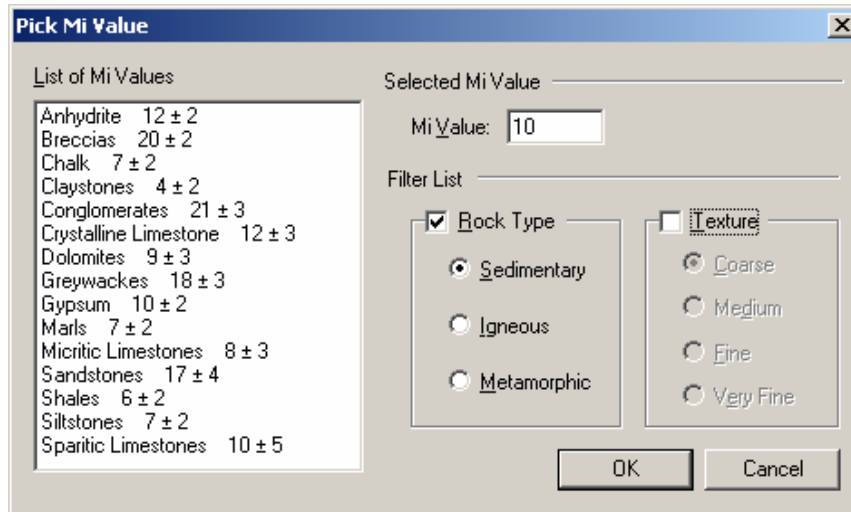
Each of the parameters used as input for the Hoek-Brown criterion – **sigci**, **mi**, **GSI** and **D** – can be estimated using convenient charts and tables built into *RocLab*.



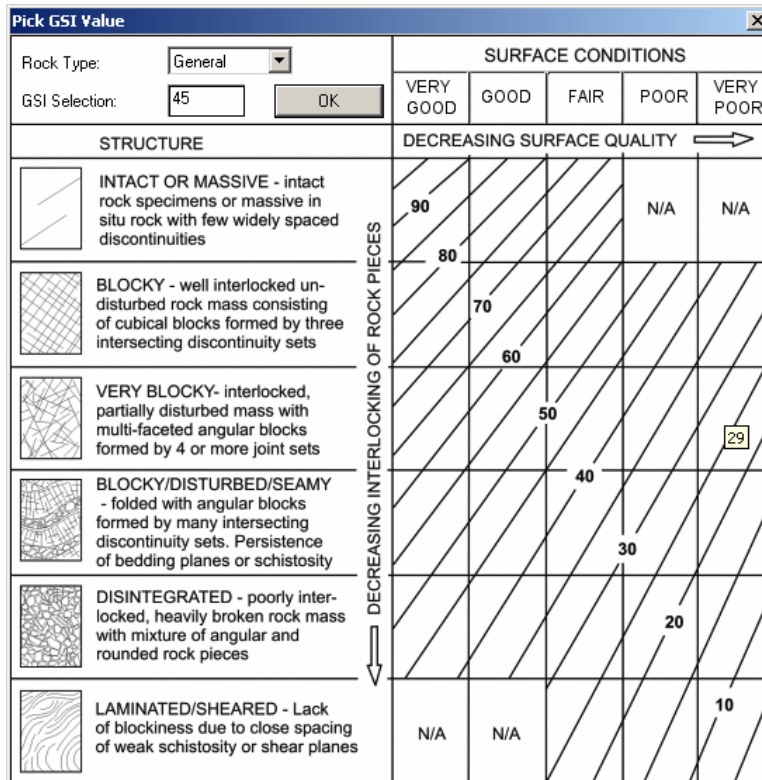
These charts and tables are accessed by selecting the “Pick” button located beside each of the input parameter edit boxes in the sidebar.



When you select a Pick button, a table or chart will appear, allowing you to determine a suitable value for the desired parameter. For example, the dialogs for estimation of **mi** and **GSI** (Rock Type = *General*) are shown below.



Once you have determined a value, select OK in the Pick dialog. The value will be automatically loaded into the sidebar input data area, and the **RocLab** calculation will automatically be carried out (ie. output parameters and failure envelopes will be re-calculated using the selected input data).



GSI chart (Rock Type = General)

Select the Pick button for each of **sigci**, **mi**, **GSI** and **D**, and experiment with the dialogs.

Notice that there are TWO distinct GSI charts:

- One for general rock mass types
- One for weak, heterogeneous rock mass types such as flysch, which extends the useful range of GSI down to values as low as 5.

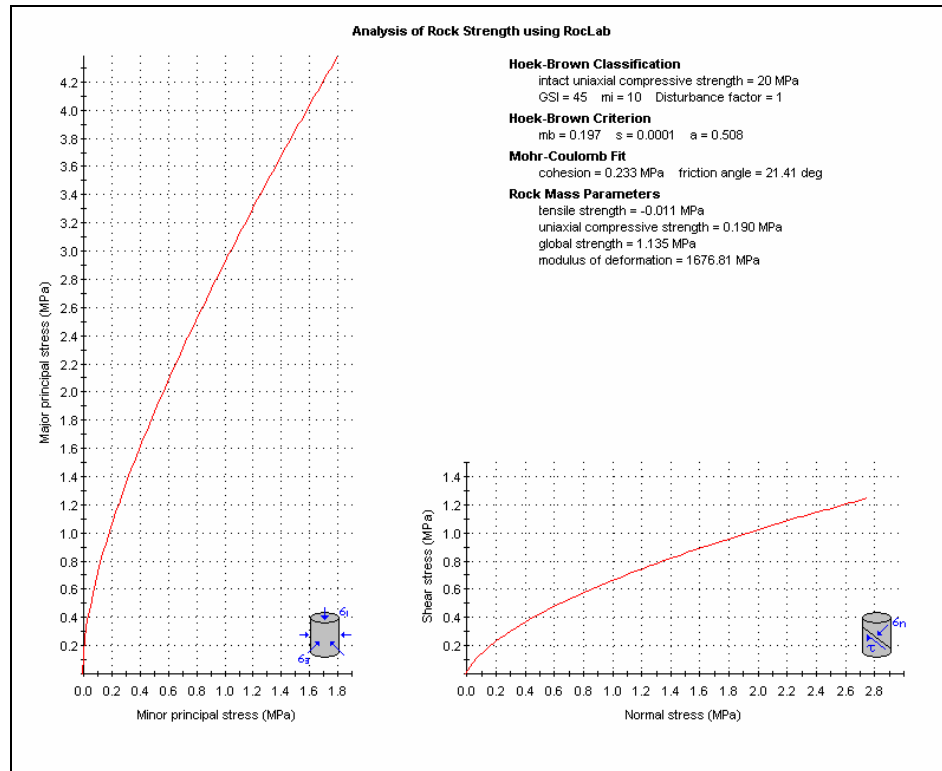
For further information about the Hoek-Brown classification parameters **sigci**, **mi**, **GSI** and **D**, please consult Ref.1.

Failure Envelope Plots

RocLab will plot the rock mass failure envelopes in:

- Principal stress space (σ_1 vs. σ_3)
- Shear – Normal stress space (σ normal vs. τ)

The plots correspond to the current data in the sidebar.



By default, BOTH principal stress AND shear-normal plots are displayed. However, you can choose to display either plot type on its own, by selecting the desired plot type from the toolbar, the Analysis menu or the right-click menu.

Various display and analysis options are available, such as:

- Display equivalent Mohr-Coulomb envelope
- Stress sampler / Instantaneous Mohr-Coulomb sampler
- Customize plot appearance with Display Options (eg. grid overlay, line thickness, fonts etc), and zooming

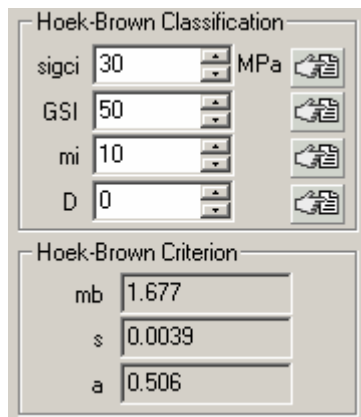
Right Click Menu

TIP – most of the plot display options, are also conveniently available in the right-click menu, if you right-click the mouse anywhere in the plot display area.

Hoek-Brown Parameters

For a given set of input parameters (**sigci**, **GSI**, **mi** and **D**), RocLab calculates the parameters of the generalized Hoek-Brown failure criterion (**mb**, **s** and **a**).

These are displayed in the sidebar, as shown below. The Hoek-Brown failure envelopes which are plotted in RocLab, are generated using these values of **mb**, **s** and **a**.



The image shows a software interface for calculating Hoek-Brown parameters. It is divided into two sections: 'Hoek-Brown Classification' and 'Hoek-Brown Criterion'. The classification section has four input fields: 'sigci' (30 MPa), 'GSI' (50), 'mi' (10), and 'D' (0). Each field has a spin button and a copy icon. The criterion section has three output fields: 'mb' (1.677), 's' (0.0039), and 'a' (0.506).

Hoek-Brown Classification	
sigci	30 MPa
GSI	50
mi	10
D	0

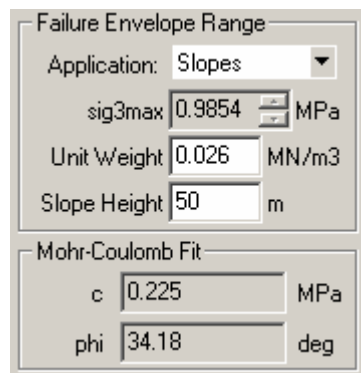
Hoek-Brown Criterion	
mb	1.677
s	0.0039
a	0.506

These parameters are calculated using the latest version of the Hoek-Brown failure criterion. For a definition of these parameters, and the equations which define them, please see Ref. 1.

Equivalent Mohr-Coulomb Parameters

In addition to the Hoek-Brown failure criterion parameters (**mb**, **s** and **a**), **RocLab** always calculates equivalent Mohr-Coulomb parameters (cohesion and friction angle) for the rock mass.

Since most rock engineering software is still written in terms of the Mohr-Coulomb failure criterion, the calculation of equivalent Mohr-Coulomb parameters from the Hoek-Brown failure criterion, is an important feature of the **RocLab** program.



The screenshot shows a software dialog box with two sections. The top section, titled "Failure Envelope Range", contains a dropdown menu for "Application" set to "Slopes", a text input for "sig3max" with the value "0.9854" and unit "MPa", a text input for "Unit Weight" with the value "0.026" and unit "MN/m3", and a text input for "Slope Height" with the value "50" and unit "m". The bottom section, titled "Mohr-Coulomb Fit", contains a text input for "c" with the value "0.225" and unit "MPa", and a text input for "phi" with the value "34.18" and unit "deg".



The corresponding Mohr-Coulomb envelope can be viewed by selecting the Mohr-Coulomb Envelope option from the toolbar or the Analysis menu.

Failure Envelope Range

It is important to note that the **Failure Envelope Range** option has a direct effect on the calculated Mohr-Coulomb parameters.

- For details about the Mohr-Coulomb fitting procedure, and the significance of the Failure Envelope Range option, see Ref. 1 (section 4: *Mohr-Coulomb Criterion*, and section 6: *Determination of σ'_3 max*)
- When the Failure Envelope Range option = General, notice that σ_3 max = $\sigma_{ci} / 4$. This is based on the empirical observation that the stress range associated with brittle failure, occurs when σ_3 is less than about one-quarter of **sigci**.
- When the Failure Envelope Range option = Custom, you may enter any value of σ_3 max.
- The Failure Envelope Range has NO effect on the calculated Hoek-Brown parameters.

Other Rock Mass Parameters

At the bottom of the sidebar, you will notice that the following rock mass parameters are also calculated:

- σ_{gt} (rock mass tensile strength)
- σ_{gc} (uniaxial rock mass compressive strength)
- σ_{gcm} (global rock mass compressive strength)
- E_m (rock mass modulus of deformation)

Rock Mass Parameters		
σ_{gt}	-0.014	MPa
σ_{gc}	0.352	MPa
σ_{gcm}	2.302	MPa
E_m	2002.05	MPa

For the definitions of these parameters, and the equations used to calculate them, please see Ref. 1.

In particular, you will notice that there are two values of rock mass compressive strength which are calculated by **RocLab** – σ_{gc} and σ_{gcm} . For a discussion of how these two parameters are defined, and how they may be used, please see Ref. 1 – section 5: *Rock Mass Strength*.

Triaxial Lab Test Data

Another feature of **RocLab**, is the ability to input triaxial lab test data (sigma1 / sigma3 data pairs), in order to determine the intact rock parameters **sigci** and **mi**. This is done as follows:



1. Select the **Use Lab Data** option from the **Analysis** menu or the toolbar.
2. The data can be entered in a spreadsheet, or imported from a file, as shown in the dialog below.
3. A curve fit is then performed on the data, using the Marquardt-Levenberg fitting technique, and values of **sigci** and **mi** are obtained.
4. After entering the data, select OK in the dialog, and the calculated values of **sigci** and **mi** will be used to calculate the Hoek-Brown strength parameters and failure envelopes.

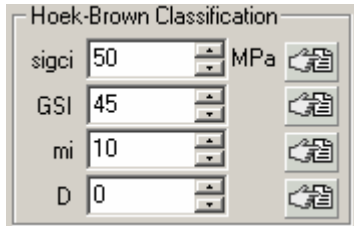
#	sig3 (MPa)	sig1 (MPa)
1	1.72	78.61
2	3.45	89.33
3	5.17	99.81
4	6.9	123.79
5	6.9	125.23
6	10.34	125.65
7	10.34	138.37
8	13.79	137.38
9	13.79	146.6
10	17.24	150.77
11	17.24	160.76
12	20.69	173.79
13	27.59	187.9
14	34.48	205.99

Obtaining actual values of **sigci** and **mi** from triaxial lab test data, is of course always recommended, if such data is available. It should be emphasized that a large number of test results is not always necessary, and good results can be obtained from a relatively small number of data points (eg. 6 or 7 triaxial tests).

If triaxial lab data is not available, values of **sigci** and **mi** can always be estimated in **RocLab**, using the Pick dialogs described previously.

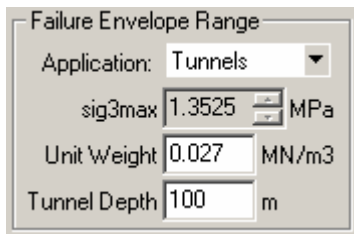
Example 1 – Tunnel, undisturbed (D = 0)

Consider an undisturbed in situ rock mass surrounding a tunnel at a depth of 100 meters, with the following Hoek-Brown classification parameters.



Hoek-Brown Classification	
sigci	50 MPa
GSI	45
mi	10
D	0

Enter this data in the sidebar input data area. Also, enter the following data to determine the Failure Envelope Range (sig3max). This is used for the equivalent Mohr-Coulomb calculation:



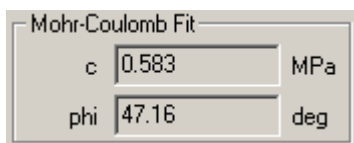
Failure Envelope Range	
Application:	Tunnels
sig3max	1.3525 MPa
Unit Weight	0.027 MN/m3
Tunnel Depth	100 m



Now press **Compute**.

The resulting output will be displayed in the sidebar, and the failure envelopes will be calculated.

Notice the equivalent Mohr-Coulomb parameters which have been calculated:



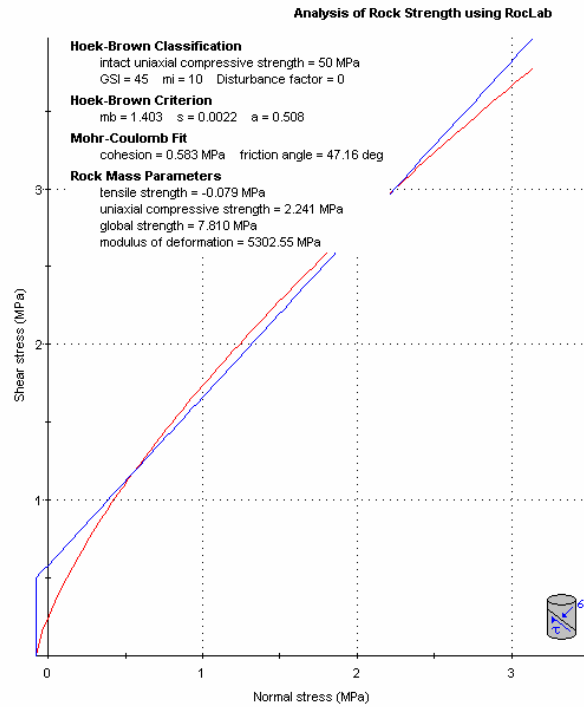
Mohr-Coulomb Fit	
c	0.583 MPa
phi	47.16 deg



The envelope corresponding to these parameters, can be viewed on the plots, by selecting the Mohr-Coulomb strength envelope option, from the toolbar or the Analysis menu.



To get a better look at the MC envelope, let's view only the Normal vs. Shear stress plot. Select the Normal vs. Shear Stress option from the Analysis menu or the toolbar. This will hide the principal stress plot, and show only the Normal vs Shear stress plot, maximized in the view.

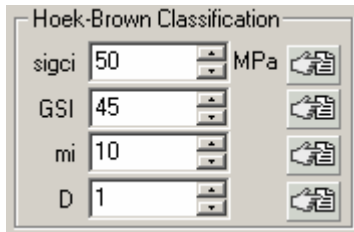


If you examine the MC envelope, you can graphically confirm the calculated values of cohesion, friction angle, and also the rock mass tensile strength **sigt**. The tensile strength is the negative value of normal stress, at the origin of the failure envelope.

Example 2 – Slope, disturbed (D = 1)

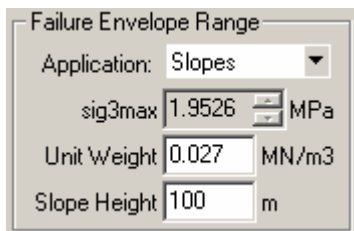
Consider a rock mass with the same basic parameters as the previous example, but in a highly disturbed slope of 100 meters height, with a disturbance factor $D = 1$.

Enter disturbance factor $D = 1$.



Hoek-Brown Classification	
sigci	50 MPa
GSI	45
mi	10
D	1

Enter the following data to determine the Failure Envelope Range (sig3max):



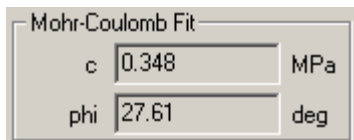
Failure Envelope Range	
Application:	Slopes
sig3max	1.9526 MPa
Unit Weight	0.027 MN/m3
Slope Height	100 m



Now press **Compute**.

The resulting output will be displayed in the sidebar, and the failure envelopes will be calculated.

Notice the equivalent Mohr-Coulomb parameters which have been calculated:



Mohr-Coulomb Fit	
c	0.348 MPa
phi	27.61 deg

Analysis of Rock Strength using RocLab

Hoek-Brown Classification

intact uniaxial compressive strength = 50 MPa
GSI = 45 $m_i = 10$ Disturbance factor = 1

Hoek-Brown Criterion

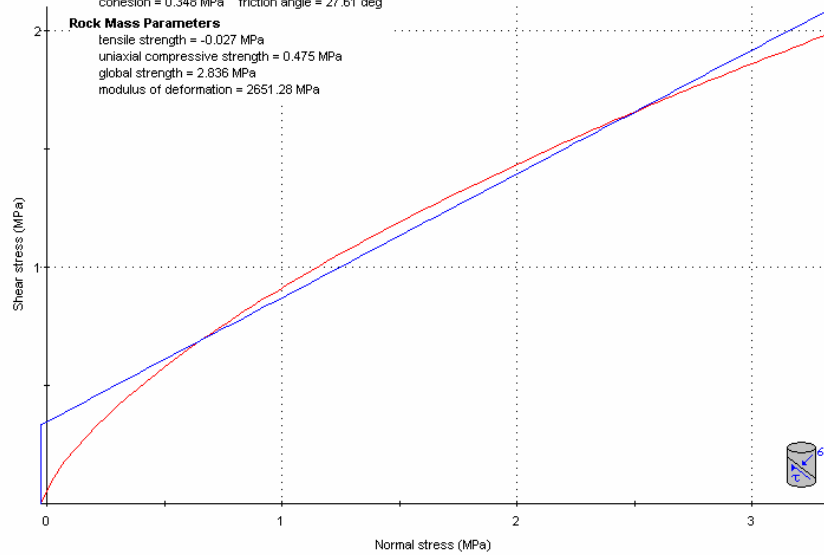
$m_b = 0.197$ $s = 0.0001$ $a = 0.508$

Mohr-Coulomb Fit

cohesion = 0.348 MPa friction angle = 27.61 deg

Rock Mass Parameters

tensile strength = -0.027 MPa
uniaxial compressive strength = 0.475 MPa
global strength = 2.836 MPa
modulus of deformation = 2651.28 MPa



Compare the equivalent Mohr-Coulomb parameters and envelopes, calculated in Example 1 and Example 2. This demonstrates the significant effect which the disturbance factor **D**, can have on the calculated rock mass strength.

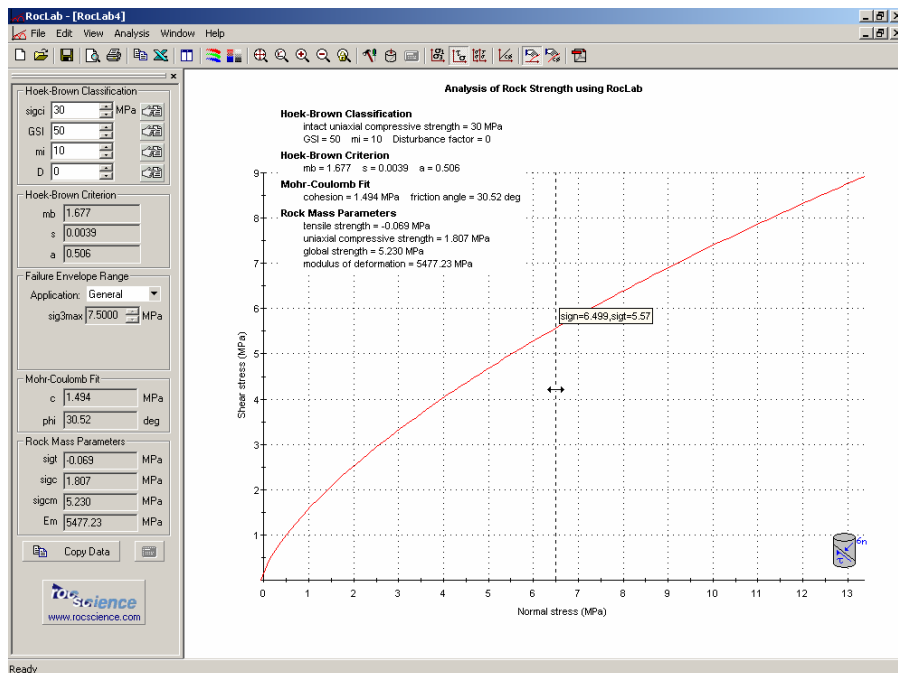
For information about the Disturbance Factor, see Ref. 1 – section 7: *Estimation of Disturbance Factor D*.

Stress Sampler

The **Stress Sampler** option allows the user to graphically obtain the exact stress coordinates at any point along the failure envelopes. This is done as follows:



1. Select the **Stress Sampler** option from the toolbar, the right-click menu or the **Analysis** menu.
2. Single click the left mouse button, at any value of σ_3 (on the principal stress plot), or any value of normal stress (on the shear-normal stress plot).
3. The stress coordinates will be displayed, corresponding to the value of σ_3 or normal stress, at which the mouse was clicked. A vertical dotted line will be displayed on the plots, to mark the location.
4. Alternatively, if you click and HOLD the left mouse button on either of the plots, and DRAG the mouse left or right, the stress coordinates of the failure envelopes will be continuously displayed, as you move the mouse.
5. NOTE: if the equivalent Mohr-Coulomb envelopes are also displayed, then the stress coordinates of BOTH the Hoek-Brown, and equivalent Mohr-Coulomb envelopes will be displayed.

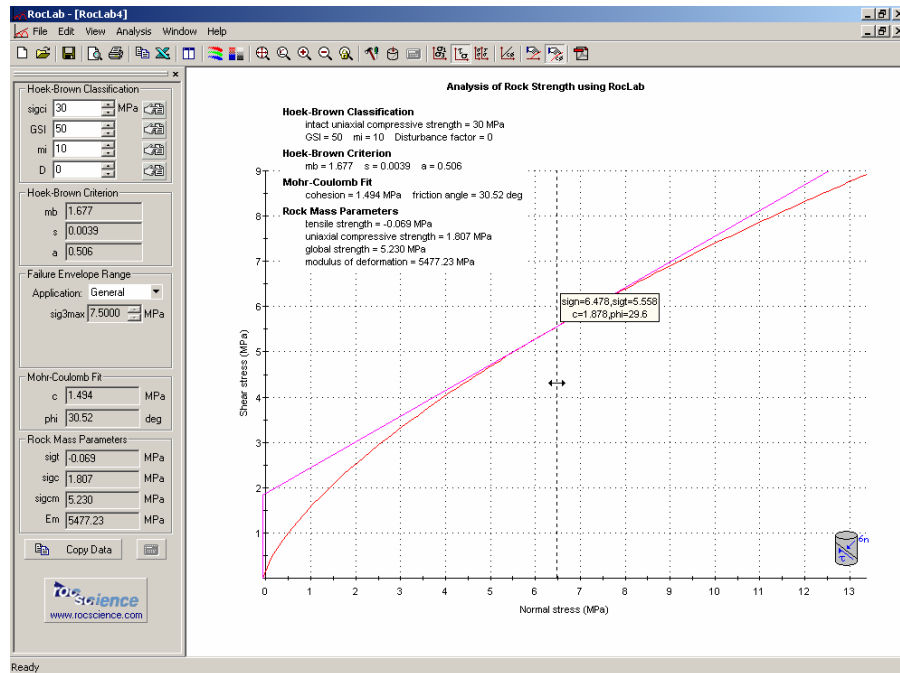


Instantaneous Mohr-Coulomb Sampler

The **Instantaneous Mohr-Coulomb Sampler** option allows the user to graphically obtain the instantaneous Mohr-Coulomb parameters (cohesion and friction angle), at any point along the Hoek-Brown failure envelopes. This is done as follows:



1. Select the **Instantaneous MC Sampler** option from the toolbar, the right-click menu or the **Analysis** menu.
2. Single click the left mouse button, at any value of σ_3 (on the principal stress plot), or any value of normal stress (on the shear-normal stress plot).
3. The instantaneous Mohr-Coulomb envelope (tangential line) will appear on the plots, for the value of σ_3 or normal stress, at which the mouse was clicked. The instantaneous values of cohesion and friction angle will be displayed, as well as the stress coordinates. A vertical dotted line will be displayed on the plots, to mark the location.
4. Alternatively, if you click and HOLD the left mouse button on either of the plots, and DRAG the mouse left or right, the instantaneous Mohr-Coulomb envelope and coordinates, will be continuously displayed, as you move the mouse.



Exporting Data / Images

The **RocLab** analysis results and failure envelope plots, can be exported to other programs for report writing, further analysis, etc. This can be done in various ways.



- The **Copy Data** option in the sidebar or the **Edit** menu, will copy the contents of the sidebar (ie. all input and output parameters) to the clipboard. From the clipboard, this can be pasted into a word processor or spreadsheet. This provides a handy analysis summary.
- The **Copy** option in the toolbar or the **Edit** menu, will copy an image of the current failure envelope which is displayed, to the clipboard. From the clipboard, this can be pasted into reports or image editing programs, etc.
- The failure envelope plots can also be saved directly to a JPEG or BMP image file, with the **Export Image File** option. This is available in the **File** menu, or the right click menu.

One Click Export to Excel

The most powerful data export feature is the following – with a single mouse click, all data AND plots can be exported to Microsoft Excel. To do this:



1. Select the **Export to Excel** toolbar button.
2. If you have Excel installed on your computer, the Excel program will be automatically started, and all analysis input and output data will be exported to an Excel spreadsheet.
3. Failure envelope plots will then be generated in Excel.
4. This all takes place with a single mouse click !!!

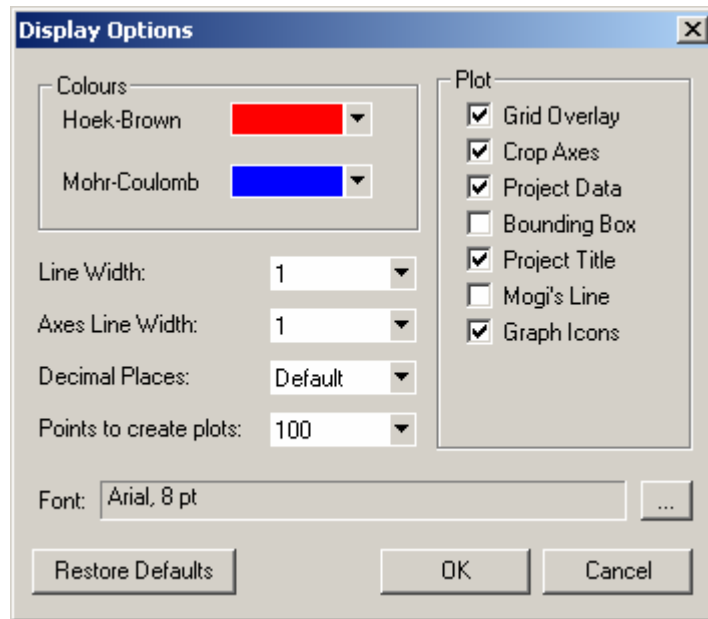
Note that the plots which are generated in Excel, correspond to the failure envelope plot(s) which you are currently viewing. For example, if you are only viewing the shear-normal plot, then only the shear-normal data and plot, will be generated in Excel. If you are viewing both plots (principal stress and shear-normal), then both plots will be generated in Excel. Also, if the equivalent Mohr-Coulomb envelope is displayed, this will also be plotted in Excel. Finally, note that the number of data points used to create each failure envelope, is controlled in the **Display Options** dialog in **RocLab**.

Display Options

The appearance of the Failure Envelope plots may be customized with Display Options, zooming, and other options.



- Display Options is available in the toolbar, the **View** menu, and also in the right-click menu (if you right-click the mouse anywhere in the Failure Envelope display area).



Most of the Display Options are self-explanatory, and it is left to the user to experiment with the options. However, we will note the purpose of the following options:

Mogi's Line

Mogi's Line defines the ratio of major and minor effective principal stresses at which there is a transition from brittle to ductile failure. This line is simply defined by $\sigma_1/\sigma_3 = 3.4$, and is plotted as a green line on the principal stress plot, when the Mogi's Line option is selected in the **Display Options** dialog.

- If the principal stress failure envelope lies ABOVE Mogi's line, this indicates a brittle failure mode.
- If the principal stress failure envelope lies BELOW Mogi's line, this indicates a ductile failure mode. This may occur with low values of GSI, for example.

Zoom Extents

The **Zoom Extents** option will automatically scale the axes of the failure envelopes, so that all possible failure envelopes, for the current value of **sigci**, will be visible on the plot.

This corresponds to maximum values of **GSI** (= 100) and **mi** (= 40).



1. To demonstrate this, select the **Zoom Extents** option.
2. Use the interactive arrow buttons, to increase the value of **GSI** to 100, and the value of **mi** to 40.
3. Observe the failure envelope plots. When **GSI** = 100 and **mi** = 40, the extent of the principal stress envelope will correspond to the maximum extent automatically calculated by the **Zoom Extents** option.

You may find the **Zoom Extents** option useful for interactive demonstration of parameter changes on the failure envelope.

References

1. Hoek, E., Carranza-Torres, C.T., and Corkum, B. (2002), Hoek-Brown failure criterion – 2002 edition. *Proc. North American Rock Mechanics Society meeting in Toronto in July 2002.*
2. Hoek, Evert, (2002), A Brief History of the Hoek-Brown Failure Criterion, unpublished document.
3. Hoek, Evert, Practical Rock Engineering – An Ongoing Set of Notes, available on the Rocscience website, www.rocscience.com