FREQUENTLY ASKED QUESTIONS – LOP PRACTITIONER'S GUIDELINES FOR SAMPLING AND LABORATORY TESTING FOR OPEN PIT OPERATIONS: ISRM R3 TO R6

Uniaxial Compressive Strength (UCS), Triaxial Compressive Strength (TCS), and Failure Envelopes

How often is the UCS size correction to 50 mm typically applied for generation of Hoek-Brown curves?

UCS test results should always be normalized to a specimen diameter of 50 mm. One of the most widely used empirical relationships used for UCS specimen size correction is the Hoek and Brown (1980) equation below:

$$\sigma_{c50} = \frac{\sigma_{cd}}{(d/50)^{-0.18}}$$

Where:

σ_{cd} is the UCS of a rock specimen with a diameter of d (mm)

σ_{c50} is the UCS of a 50 mm diameter specimen

Other empirical relationships for specimen size correction can be used, including the equations published by Thuro et al. (2001) and Darlington et al. (2011).

When using any of these empirical relationships, it is important to understand the datasets used to develop them, and the equations should not be applied outside of the measured specimen size ranges.

Is there a correction similar to the 50 mm correction used on UCS tests, that should be used for TCS test results?

While there are specific specimen size correction factors for UCS test results, none have been developed for TCS specimens. A TCS program should be done on core of the same diameter and length-to-diameter ratios as used for UCS testing such that only one core diameter is present in the TCS dataset.

Are there different failure type definitions for UCS and TCS tests or are they the same?

The specimen failure type definitions are the same for UCS and TCS tests (Bewick et al. 2015; Bewick et al. 2019):

- ***Homogeneous failure*** is failure through the homogeneous rock matrix, which can occur either by extension or by shear rupture.
- ***Discrete failure*** consists of shear failure along a single discrete feature or healed discontinuity, such as a vein, foliation, or bedding plane.
- ***Combined failure*** refers to failure by a combination of shear on healed discontinuities and extension or shear rupture through the homogeneous rock matrix.
- ***Weakness network failure*** is failure that occurs completely along multiple veins or around clasts.

The laboratory report for each specimen tested should be reviewed by a qualified practitioner to confirm that the failure type has been classified correctly.

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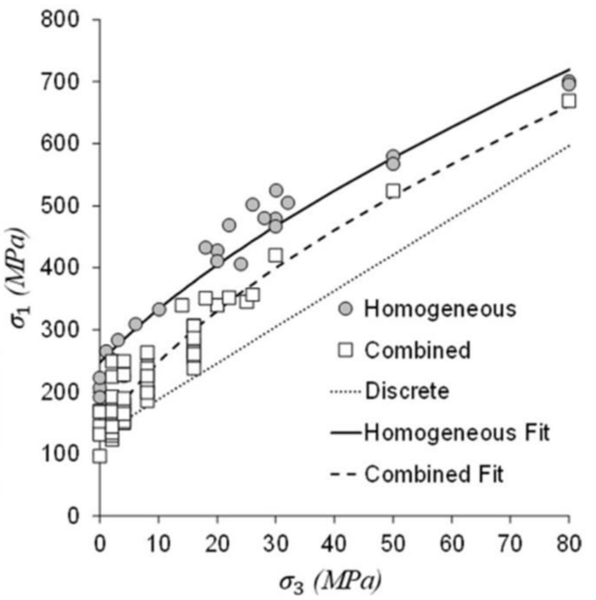
When you classify UCS and TCS data by failure type, would you expect the homogeneous envelope to always show higher strength than the combined envelope, and the combined envelope to always show higher strength than the discrete envelope?

Different failure types represent different strength components of the rock mass. For strong rock (R3 to R6), it is typical for strength parameters developed from homogeneous failure data to be higher than those developed from combined failure data, which in turn are higher than those developed from discrete failure data. This trend is illustrated in the figure below (Bewick 2021). An exception to this can occur in rock masses containing very strong healed discontinuities, such as quartz veins, which may exhibit higher strength than the homogeneous rock matrix.



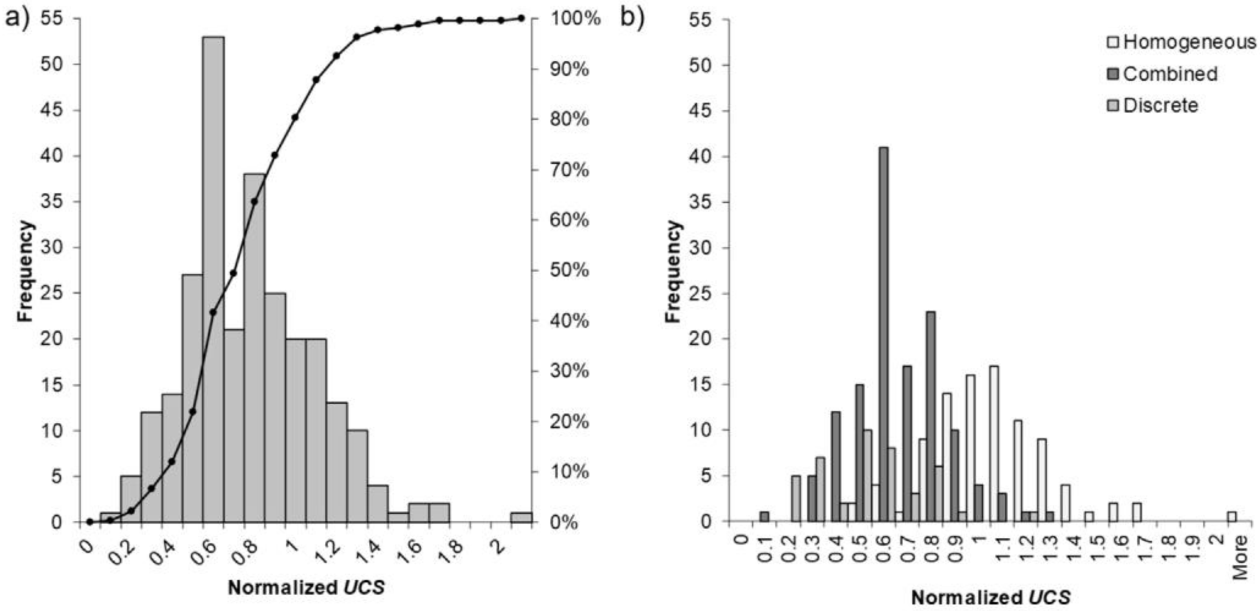
Source: Bewick 2021.
Figure showing progressive reduction in strength from homogeneous to discrete failure type. Note the discrete failure type data points are not plotted because this type of data cannot be processed in principal stress space; instead, discrete failure data are fit in normal-shear stress space and the resulting linear envelope is then transformed into principal stress space (dotted line).

A study published by Bewick et al. (2019) outlines the typical dataset ranges of each failure type, based on laboratory strength testing data for ten heterogeneous rock types. The summary of the impact of failure type on the mean UCS and the coefficient of variation is presented in the table below. The dataset was normalized to each rock type's homogeneous compressive strength (σ_{ci}) for comparison purposes.

Failure Type	Normalized UCS Statistics					
	Mean	Minimum	Maximum	SD	CoV	Count
Homogeneous	1.01	0.44	2.21	0.26	26%	92
Combined	0.61	0.10	1.28	0.19	32%	133
Discrete	0.47	0.12	1.19	0.22	47%	43
All Data	0.73	0.10	2.21	0.31	43%	268

Source: Bewick et al. 2019.
CoV = coefficient of variation; SD = standard deviation; UCS = uniaxial compressive strength.

The UCS values for the unsorted dataset (not classified by failure type) are shown in the histogram below on the left, compared to the values for the sorted data (classified by failure type) shown in the histogram on the right. Comparing the two figures, the mean UCS for homogeneous failure type is around the 80th percentile of the cumulative frequency distribution, whereas those for the combined and discrete failure types are centred around 40% and 20%, respectively (Bewick et al. 2019).



Source: Bewick et al. 2019.
UCS histograms showing (a) overall UCS distribution not sorted by failure type and (b) UCS distributions by failure types of homogeneous, combined, and discrete.

Is it part of the ASTM or ISRM standard to record the failure angle of the specimen?

The ISRM suggested methods for UCS and TCS testing do not directly mention recording the failure angle of the tested specimen. However, the ASTM D7012 standard indicates the following:

"[…] include a brief note indicating whether a pronounced failure plane was or was not developed during the test and the inclination of this plane with reference to the plane of major principal stress."

It is recommended to record the failure angle for every UCS and TCS test specimen failing along a single shear plane. Measurement of the failure angle is required for analysis of specimens that fail along a discrete feature or healed discontinuity (e.g., veins, foliation, bedding), in order to obtain information on anisotropic strength. Also, good practice is to measure the failure angle of any specimen such that the data may be plotted in normal-shear stress space if desired.

Before the start of a UCS/TCS testing campaign, it is good practice to request an example report from the laboratory to review the information typically provided for each type of test and assess whether additional information should be requested for analysis and data interpretation.

What are reasons we might have a large scatter in UCS and TCS test results?

A large scatter in UCS and TCS test results may indicate natural variability in the rock strength but often is a result of grouping data together that should be assessed separately (i.e., different failure types). Scatter may also result from: improper testing procedures or specimen preparation (depending on rock type and testing, these issues may have a significant impact on testing results); stress relief damage (can impact strength testing data by up to a 50% strength reduction); or poor laboratory testing quality (can impact strength testing data by up to a 70% strength reduction). To help reduce scatter in UCS and TCS test results, the following guidance is provided:

- Follow the specimen requirements and testing procedures outlined in the ASTM standards or ISRM suggested methods.
- Choose one standard (ASTM or ISRM) and use it consistently throughout the testing program.
- Identify and exclude invalid test results (e.g., specimens that fail primarily through spalling, chipping, or end sloughing).
- Normalize UCS test results to the diameter of a 50 mm specimen.
- Filter data for homogeneous, combined, discrete, and weakness network failure types, and process the different failure types as separate datasets.
- For specimens that fail along discrete features, transform the testing data into normal-shear stress space. Discrete failure data should not be processed in principal stress space because the recorded σ_1 and σ_3 data points are likely not principal stress data points due to the pre-existing plane of weakness influencing the rock strength.
- Filter data for axial splitting, shear-axial (or mixed mode), and shear failure modes, as strength can be failure mode dependent.
- Classify different weathering/alteration types that affect the rock strength into different geotechnical domains and process them as separate datasets.

Could you provide more specific guidance on the appropriate range of maximum confinement for TCS testing for open pit applications?

The Hoek-Brown criterion recommends that the confining stress for TCS testing should cover a range of up to 50% of the unconfined compressive strength (Hoek and Brown 1980). For example, for rock with an unconfined compressive strength of 120 MPa, testing at a confinement of up to 60 MPa would be required. However, this confining stress range may not be suitable for most open pit slopes.

The confining stress range selected for TCS testing should be representative of expected conditions for the problem being analyzed. Confining stress selection should satisfy two requirements:

- Demonstrate the validity of the Hoek-Brown intact rock strength envelope at the expected levels of confinement.
- Provide a sufficient spread in confinement to reduce the uncertainty in the selection of m_i values.

For open pit slopes, the confining stresses acting on potential failure surfaces is typically less than 10 MPa. Therefore, conducting TCS testing at confining stresses significantly higher than 10 MPa would typically not be representative of expected conditions. When TCS testing is carried out at confining stresses lower than the range recommended by Hoek and Brown (1980), the resulting m_i and σ_{ci} values are problem-specific and cannot be used to extrapolate the envelope because the higher confinement extrapolation would be invalid. This should be clearly stated in work where the original Hoek-Brown testing requirements are not being met. The extrapolation could be significantly different and thus must not be used.

Additional guidance on the maximum confining stress to select for pit slope applications can be found in the study published by Rafiei Renani and Martin (2020), which presents the following empirical equation:

$$\frac{\sigma'_{3max}}{\gamma H} = \frac{0.175}{\tan(\beta)}$$

Where:

σ'_{3max} is the upper limit of applicable confining stress

γ is the unit weight of the rock mass

H is the height of the slope

β is the slope angle

For example, for a slope with a height of 300 m and a slope angle of 50°, excavated in a rock mass with unit weight of 27 kN/m^3, the upper limit of applicable confining stress would be approximately 1.2 MPa based on the above equation. In this example, the practitioner should therefore test most of the TCS specimens at confining stresses ranging from 0.1 to 1.2 MPa. A limited remainder could be done at higher confinement, but less than 10 MPa, to help define the curve of the strength envelope.

The equation published by Rafiei Renani and Martin (2020) produces more appropriate estimates of the confining stress range for slope analysis than previous equations published by others (e.g., Hoek et al. 2002; Li et al. 2008), which do not consider the slope angle and tend to overestimate the applicable confining stress.

How many TCS data points should be used to develop a Hoek-Brown envelope when you only use one UCS (average) value in the curve fit? If the TCS dataset is very large, could averaging the UCS data lead to the single UCS point not having enough weight in the curve fit, and if so, how should this be addressed?

To adequately characterize the rock strength behaviour at varying confinement, Hoek and Brown (1980) recommend conducting TCS tests at a minimum of five confining stress magnitudes per rock type. For homogeneous rocks, ASTM standards recommend a minimum of three tests per confining pressure (i.e., a minimum of 15 tests in total). For heterogeneous rocks, a minimum of eight tests per confining pressure is recommended (i.e., a minimum of 40 tests in total; Bewick et al. 2019).

When applying the Hoek-Brown criterion, using datasets that include many UCS test results but only a small number of TCS results can lead to bias towards the UCS data when fitting the Hoek-Brown envelope. To address this issue, Hoek and Brown (2019) recommend using the average value of the UCS dataset as a single data point to represent the value of the principal stress at zero confinement. The TCS dataset, including the average UCS value, is then used in a regression analysis to determine the σ_{ci} and m_i parameters.

However, for datasets containing a very large number of TCS test results, representing the UCS dataset as a single average point could result in the UCS data not having sufficient weight when fitting the Hoek-Brown envelope. In such cases, the average TCS value for each confining stress tested can be used instead of the entire TCS dataset to provide equal weighting to each confinement included in the curve fitting process (Kaiser and Kim 2014). The Hoek-Brown envelope developed using average values should be compared to the envelope developed using the entire TCS dataset, in order to select the method that provides the most appropriate fit for the available data.

What is the guidance on whether we should or should not include tensile data in the Hoek-Brown curve fit?

For applications where tensile failure is an important factor, there are two widely accepted methods:

- Use UCS and TCS data and define a tension cut-off (σ_t) for the intact strength envelope using the following empirical equation (Hoek and Martin 2014; Hoek 2023):

$$\frac{\sigma_{ci}}{|\sigma_t|} = 3.25{m_i}^{0.67}$$

- Another approach is to include tensile strength data in the curve fit as a way of “anchoring” the envelope at the σ_3 intercept. If only Brazilian indirect tensile data are available, the test results should be reduced by factors of 0.70, 0.82, and 0.86 for sedimentary, igneous, and metamorphic rocks, respectively, to estimate the direct tensile strength (Perras and Diederichs 2014).

These two methods can produce different σ_{ci} and m_i values, particularly for sparse or scattered datasets. If tensile failure is an important factor for the problem being analyzed, Hoek-Brown curve fitting should be carried out both with and without tensile data, for comparison.

Which of the curve fit approaches available in RSData is preferred?

RSData provides several different methods for fitting a Hoek-Brown failure envelope to a set of laboratory testing data. The available curve fitting algorithms, error summation methods, and residual types are summarized in the table below. Details on each of the curve fitting options listed below can be found on the Rocscience (2024) website:

https://www.rocscience.com/help/rsdata/documentation/calibrate

Curve Fitting Algorithm	Error Summation Method	Residual Type
Linear Regression	• Vertical • Parabolic Tensile	• Absolute • Relative
Modified Cuckoo	• Basic • Fairhurst	• Absolute • Relative
Levenberg-Marquardt	• Basic • Legacy	• Absolute • Relative
Simplex	• Basic • Legacy	• Absolute • Relative

Reference: Rocscience 2024.

Each of the curve fitting algorithms available in RSData should be compared to select the method that provides the most appropriate fit for the dataset. For example, the linear regression algorithm typically works well for robust datasets with minimal scatter and that include TCS test results at several different confining stresses. However, for scattered or sparse datasets that cover only a few different confining stresses, more sophisticated algorithms such as Modified Cuckoo or Simplex typically produce a better curve fit than linear regression.

The main difference between the different error summation methods is in how residuals are calculated in the tensile region. In the region of compression, all the error summation methods calculate residuals in the vertical direction. Therefore, if a dataset includes only compressive strength test results (UCS, TCS), the derived σ_{ci} and m_i parameters are independent of the error summation method selected.

In terms of residual types (absolute vs. relative), the difference in the resulting failure envelope tends to be more significant for TCS datasets that cover a wide range of confining stresses. In general, the absolute residual method tends to be more strongly influenced by high confinement data, whereas the relative residual method normalizes the fit where errors may increase with larger confining stresses.

The key takeaway is that the different curve fit approaches available in RSData may produce different values for σ_{ci} and m_i. Therefore, it is recommended to carefully consider and compare the different options and the resulting strength parameters to identify the most suitable approach for the intended application.

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