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Considerations for developing intact rock strength parameters for open pit applications

K Condon *WSP, USA*

J Martin *WSP, Canada*

M Valerio *WSP, Canada*

Abstract

Intact rock strength is a fundamental parameter used in rock mass characterisation for open pit slope design. Obtaining reliable intact strength parameters is dependent on the quality of data collected, characterisation of the failure behaviour considered and implementation of appropriate strength criteria. The strength results from laboratory testing can vary significantly due to natural sources of variability (e.g. lithology, defects, alteration), variability introduced through specimen preparation and testing techniques, and variability resulting from the failure behaviour exhibited by tested specimens. Laboratory strength testing must be performed to an industry standard to mitigate laboratory-induced sources of variability. Natural variability is captured through development of geotechnical domains based on rock mass characteristics. Laboratory specimen failure behaviour can be captured through the characterisation of failure modes (e.g. specimen rupture through shearing, axial splitting, spalling etc.) and failure types (e.g. failure though homogeneous rock matrix, along defects or through a combination of both). Classification of these failure behaviours aids in filtering out invalid test results and non-applicable failure behaviours that can introduce additional strength variability and impact design parameters. In heterogeneous rocks comprising healed discontinuities such as veins, the impact of these features on strength can be investigated through failure type classification. Consideration of the failure behaviour exhibited by laboratory specimens can aid in explaining strength variability and yield higher confidence in the parameters selected for design.

The Hoek–Brown failure criterion is typically used to estimate the intact strength of hard rock by fitting a strength envelope to laboratory testing data. Variability among laboratory testing results can make it difficult to obtain reliable strength parameters even when failure behaviour, induced variability and natural variability are accounted for. Additionally, the approach used to fit the Hoek–Brown envelope to a dataset can result in different intact strength parameters depending on the selected optimisation algorithm and treatment of residuals. Thus it is often desirable to estimate a range of likely parameters and incorporate these ranges as sensitivities in modelling. Discussed in this paper are considerations for estimating intact strength parameters using the Hoek–Brown criterion for open pit applications.

Keywords*:* *intact rock strength, pit slope design, Hoek–Brown criterion, failure behaviour, failure type, core damage*

1 Introduction

Open pit slope design requires that potential failure mechanisms and rock mass behaviour are well understood. At the inter-ramp and overall slope scales, failure mechanisms in slopes consisting of strong rock typically involve a combination of failure along discontinuities and through the rock matrix. Therefore, establishing reliable intact rock strength parameters (for subsequent use in rock mass strength characterisation) is an important component of optimising a pit slope design.

For hard rocks with strength ≥ R3 (ISRM 1981), intact strength (i.e. peak strength of the rock as measured in the lab) is typically expressed through the Hoek–Brown (HB) criterion (Hoek & Brown 2019), which defines a strength envelope in principal stress space. This envelope is described by a set of parameters, σ_{ci} and m_i, obtained from fitting the criterion to laboratory testing results for rock core samples. Fitting an envelope to the criterion requires results from triaxial compressive strength (TCS) tests and can include uniaxial compressive strength (UCS) and indirect Brazilian tensile strength (BTS) results. As laboratory testing results are critical for fitting HB envelopes, the quality of sampling techniques, core handling and laboratory testing practices directly impact the reliability of these parameters. The concept of 'induced variability' is discussed in this paper as practitioners should be aware of how sampling and testing practices impact the quality of laboratory testing data.

Representing a rock mass through a small collection of samples is a challenging process. A sample collection strategy should consider a range of natural factors that contribute to strength variability (e.g. lithology, alteration, weathering, presence of defects and heterogeneity, anisotropy etc.) and aim to represent those components appropriately through the collected samples. Geotechnical domains are typically defined based on these natural characteristics to group together areas with similar mechanical behaviour. These domains form sample collection plans and subsequent laboratory testing plans. When characterising the intact strength of a given geotechnical domain, variability among the strength results can make it difficult to estimate appropriate strength parameters for design. Particularly with heterogeneous rock, strength variability among laboratory testing results can occur when multiple failure behaviours are present in a dataset and not appropriately classified. This paper discusses a framework for classifying the failure behaviour of laboratory testing specimens, the impact on strength and considerations for incorporating these failure behaviours into the design.

Once a reliable testing dataset is developed and proper consideration has been given to specimen failure behaviour, HB parameters can be developed and fitted using different statistical approaches and optimisation algorithms. These can result in different HB parameters for a given dataset and it is important that practitioners are aware of the impact of these approaches when developing parameters for open pit slope design. An overview of these approaches is discussed and additional guidance on applying the HB criterion to estimate intact strength is provided.

2 Considerations when planning a laboratory testing program and using a laboratory dataset

2.1 Sources of induced variability: sample collection, storage, preparation and testing practices

The reliability of rock strength parameters can be compromised at the very beginning stage of sample collection. Since a relatively small percentage of the rock mass is captured in samples and used in testing, it is important that the samples collected are representative of the rock mass. Having sufficient samples that are representative of the rock mass and the different rock types is crucial to adequately characterise the area. Additionally, the sample collection process can introduce human bias through preferential sampling of unrepresentative samples (e.g. over-sampling stronger rock or under-sampling a particular alteration type), which should be avoided.

It is paramount that industry standards and best practices be implemented and adhered to at the early stages of planning a geotechnical sample collection program. The standard used for future laboratory testing (e.g. ISRM [1978, 1979] or ASTM International [2014]) should be considered during the planning stage so samples are collected in accordance with the test standard. While it may appear that proper and consistent practices pertaining to sample collection, storage, preparation and testing are commonplace across the industry, observations from multiple geotechnical laboratory testing campaigns at various locations internationally suggest these areas remain to be improved upon. Establishing practices aimed at minimising sources of induced strength variability (i.e. variability introduced by human factors rather than the natural variability of the rock) and consistently documenting deviations from testing standards are key components to obtaining reliable laboratory testing results.

2.1.1 Core damage

Core damage can significantly impact the mechanical behaviour of a core specimen. Tests completed on damaged core can often exhibit strength and elastic properties that do not adequately represent the in situ rock properties. This can significantly impact the quality and reliability of models and analysis used for design.

Damage can be introduced to the core through multiple pathways including disturbance as part of drilling and logging, storing samples such that they are subjected to variable or adverse weather conditions (e.g. significant temperature changes, rainfall, freezing conditions etc.), and improper handling and packaging of samples during transport. Core samples should be inspected visually for signs of damage before shipping to the laboratory and after the samples are received, in the event that they were damaged during transport. This is particularly important for core containing weak, soft minerals in the rock matrix or as defects, which tend to be very susceptible to weathering, cracking or opening under light vibration. Figure 1 shows an example of a sample selected for testing after shipping to the laboratory. Large partially open fractures were present in the sample that were either undetected or not present in the sample during sample collection. Samples that are tested with partially open fractures often result in premature failure and low strength. Visual observations indicating core damage must be properly documented as part of a sample collection and testing campaign, since the quality of the core can significantly impact the results.

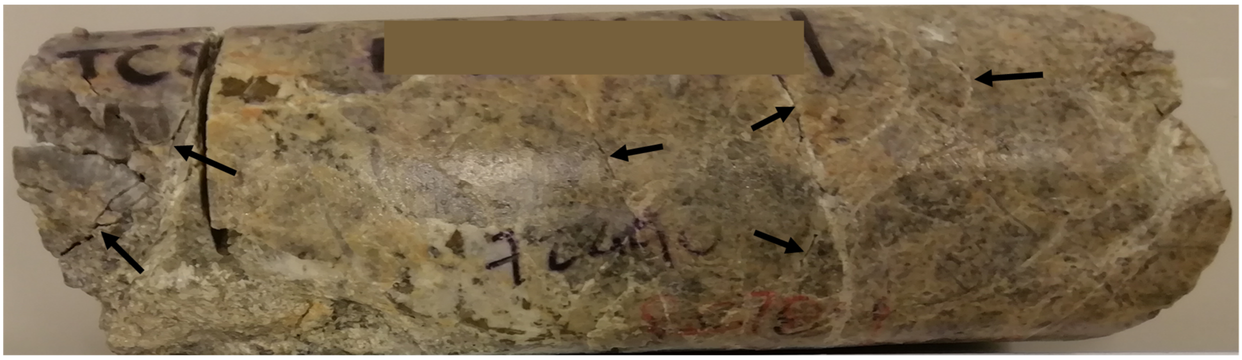
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Figure 1 **Photographs of core samples after transport to the laboratory, showing visual signs of core damage (i.e. large partially open fractures)**

Micro-damage present in the form of grain-scale micro-cracks can similarly impact the mechanical properties of the test specimen. Unlike obvious signs of core damage as shown in Figure 1, micro-damage is undetectable from visual observation without the use of microscopes and therefore can be difficult to identify. Figure 2 shows an example of an axial stress-strain response obtained from rock core tested at a commercial laboratory (figure modified for reporting clarity). Site observations indicated that sampled core was subjected to large temperature swings during storage, and there were concerns that sample quality had been jeopardised as a result. A significant portion of the strain response exhibits initial nonlinear behaviour, which is interpreted as the closure of micro-cracks before elastic loading (Goodman 1989). For rocks with near-zero porosity, this initial response is expected to be very close to linear as limited cracks and pores would be closed during this stage. A significant or prolonged stage of nonlinearity suggests that micro-cracks could have been introduced into the sample, indicating core damage. The ratio of the secant Young's modulus (E_s) to the tangent or average Young's modulus (E_{avg}) is a simple way to quantify initial nonlinearity of the stress-strain response. A ratio close to one represents a linear stress-strain response where few micro-cracks are closed during loading, suggesting there is a low presence of micro-cracks in the sample. In Figure 2, the ratio is approximately 0.5 to 0.6, suggesting micro-cracks are present in sufficient abundance to impact the stress-strain response. As a result, the Young's modulus obtained from the test may not be representative of the rock's in situ conditions.

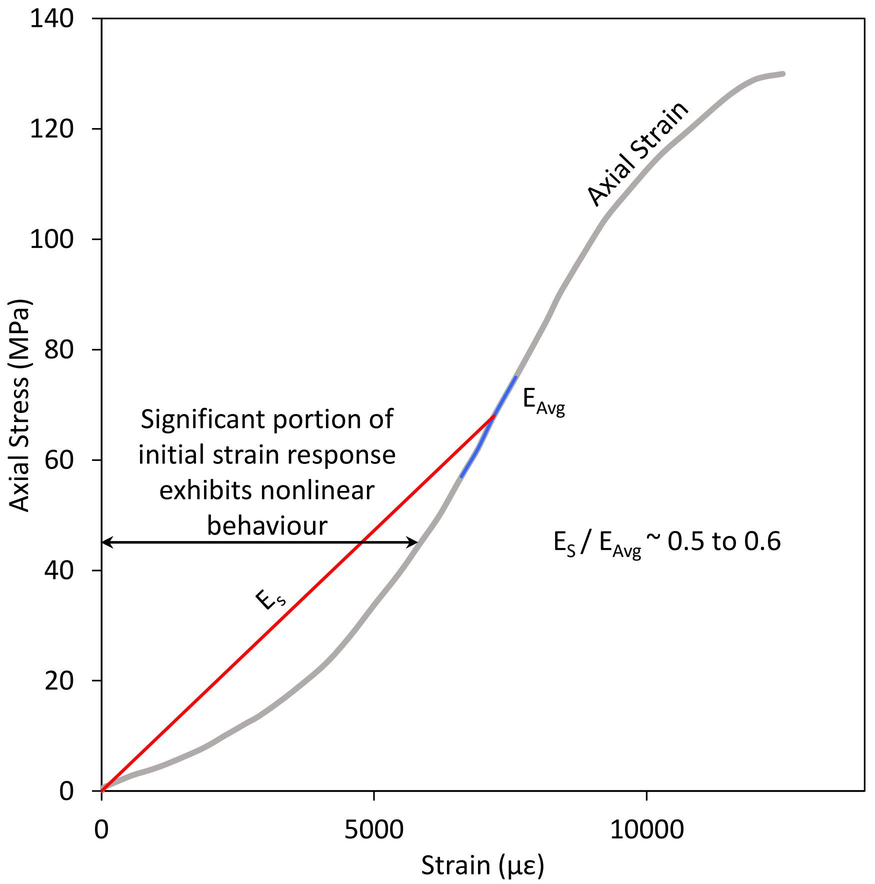


Figure 2 **Example stress-strain response exhibiting significant nonlinear behaviour, suggesting the presence of micro-damage**

The following are suggested best practices to reduce the likelihood of introducing damage to rock core samples:

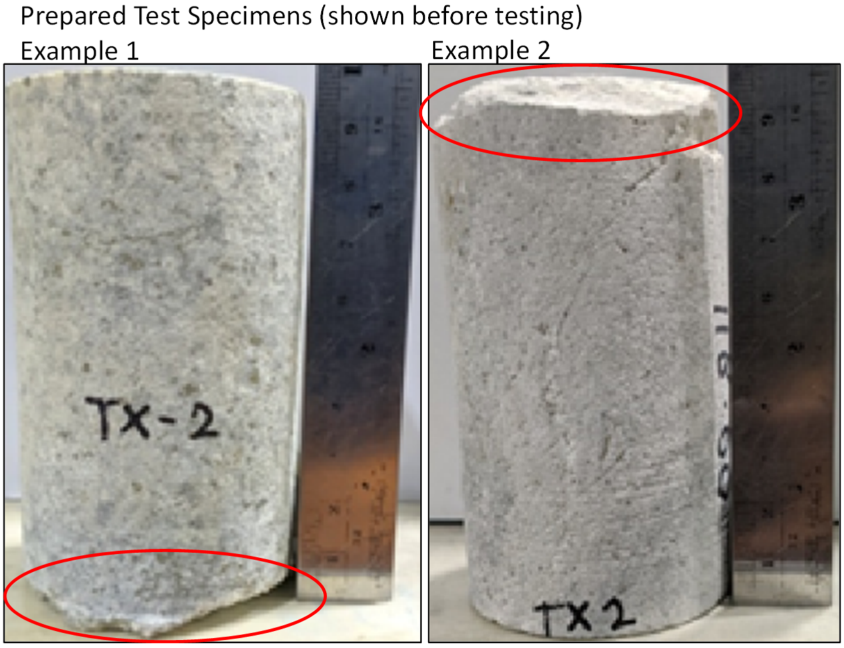
- Triple tube drilling is the preferred method for preserving the core during the drilling process. This method reduces the likelihood of mechanical breaks that occur during drilling and preserves natural structures present in the core.
- Core samples should be wrapped in aluminium wrap and plastic film to preserve moisture content, and wrapped in shock-absorbent material (e.g. bubble wrap) to protect the samples during transport. They should be transported in a solid container (e.g. a core tray, plastic bucket or tub, or PVC tubing) with additional cushioning material to keep the samples from moving during transport.
- When possible, core sampling should take place alongside drilling rather than sampling from the core material after it has been transported. This allows the core samples to be wrapped properly to protect them from damage during transport.
- Core material should be stored and transported under temperature-controlled conditions. It should not be exposed to freezing conditions or significantly hot temperatures (e.g. 40°C to 50°C, based on project experience) that may impact the quality of the samples. The temperature at which core material degradation can occur is dependent on multiple factors including the mineralogy and fragility of the rock, and the duration of storage.

2.1.2 Laboratory practices

Laboratory specimen preparation and testing practices are other avenues that can introduce unwanted variability in the test results and skew the data. Thus it is important that ASTM International (2014) or ISRM

(1978, 1979) standards for specimen preparation and testing are followed, and any deviations from the standards documented.

Compressive strength tests are particularly sensitive to the quality of specimen end preparation. The specimen ends serve as the interface through which stress is transferred from the loading platens to the rock specimen. Improper preparation of specimen ends, as depicted in Figure 3, can lead to inadequate seating of the specimen on the loading platform. Consequently, localised stress concentrations may occur and accelerate the coalescence of cracks forming the macroscopic failure surface. Ultimately, this can result in lower strength values.


Prepared Test Specimens (shown before testing)

Example 1

Example 2

Figure 3 Examples of improper specimen end preparation of compressive strength test specimens

Differences across laboratory testing procedures and practices can introduce variability in the results. Figure 4 presents UCS results obtained from four different laboratory testing facilities in different countries (Ghazvinian et al. 2012). Each laboratory received 10 to 13 specimens of the same medium-grained granite from a single site location and adhered to ASTM or ISRM specimen preparation standards. Notably, significant variations were observed in both the mean and standard deviations of the UCS results. The study suggested that differences in the loading control method (stress control in Laboratory A and radial strain control in Laboratories B and C), and/or whether specimens were tested dry or saturated, were the main reasons for the differences between results at Laboratories A, B and C. The low mean and large standard deviation observed from Laboratory D were suspected to result from core material damage that occurred during transport, based on observations from the strain data. These findings emphasise the importance of standardising laboratory testing procedures to reduce variability in the results and the importance of minimising core damage, as discussed in Section 2.1.1.

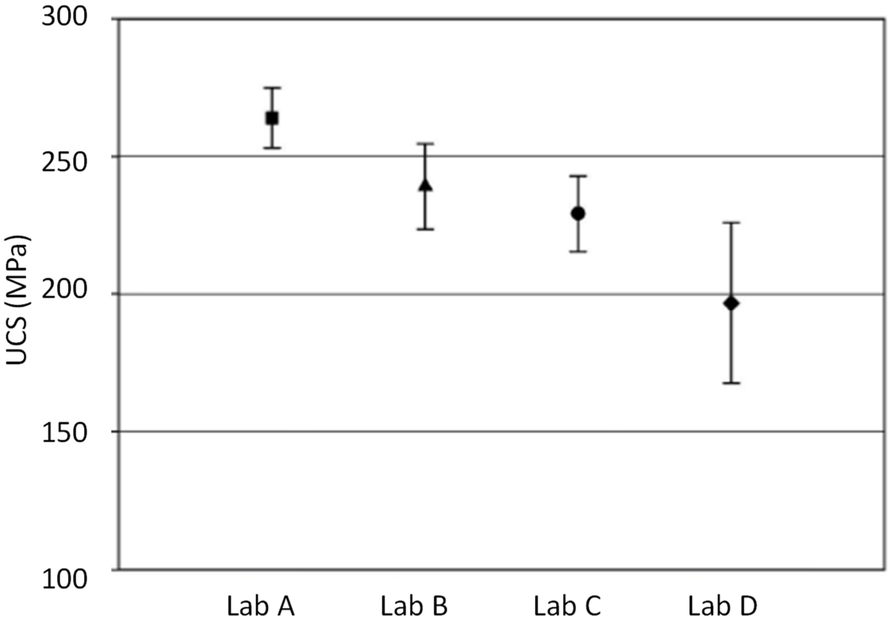


Figure 4 Mean UCS and +/- 1 standard deviation obtained from tests completed at four different laboratory facilities (modified from Ghazvinian et al. 2012)

2.2 Classification of failure behaviour

Proper classification of the failure behaviour of laboratory strength results is critically important to obtaining a well-characterised dataset for strength analysis and development of intact strength parameters. This includes characterising the rupture mechanism through the classification of failure mode and accounting for the impact of defects or heterogeneity through the classification of failure type.

2.2.1 Failure mode classification

Classification of failure mode is intended to capture the primary mechanism resulting in rupture of the specimen. The failure modes depicted in Figure 5 (modified from Szwedzicki 2007) are proposed for brittle rocks to capture extensional or axial splitting, shear, fracturing and spalling failure modes. Recording whether the failure occurred via a single mechanism or a combination of mechanisms (e.g. mixed extensional and shear) is important so that tests results can be filtered by failure mode to identify possible strength dependencies. Uniaxial compression tests and low confinement TCS tests typically express extensional failure modes due to the growth of long tensile fractures (Bewick 2017). As confining pressure increases, the failure mode typically transitions from extensional failure modes to a mix of extension and shear, and then to shear failure as short cracks coalesce into a larger shear failure plane (Bewick 2017). The failure mechanism assumed as part of an analysis approach (e.g. HB criterion assumes shear failure) should be considered with respect to the failure exhibited by the specimens.

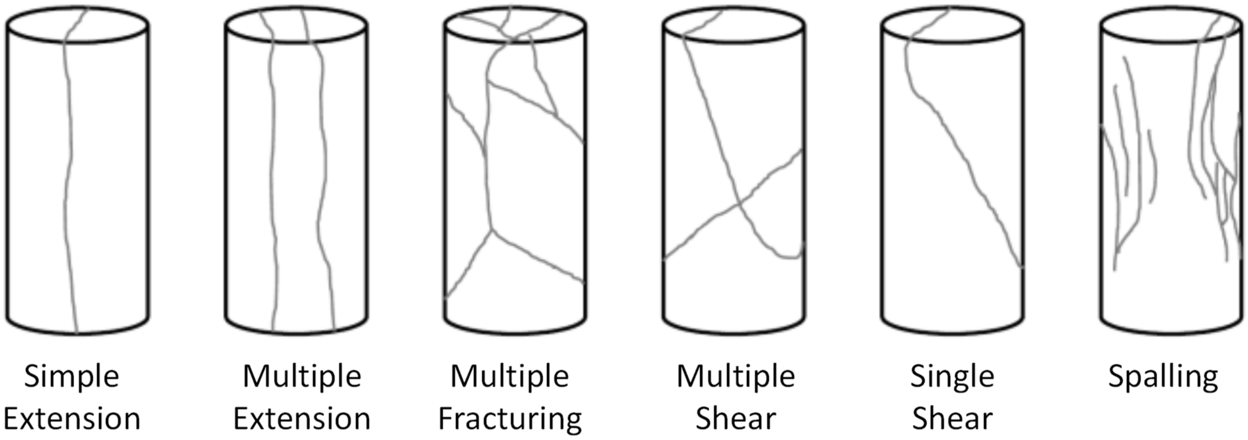


Figure 5 Failure mode categories (modified after Szwedzicki 2007)

Classification of invalid failure modes resulting from chipping or sloughing at the specimen ends should be documented so these results can be identified and excluded from analysis. Examples of invalid specimen breaks are presented in Figure 6, where the specimens exhibit localised spalling along specimen ends. Low-quality specimen end preparation can lead to an increase in invalid breaks as the stress is not uniformly applied across the sample, leading to stress concentrations near the specimen ends. Invalid breaks can typically be associated with lower-than-expected strength values as failure occurs prematurely.

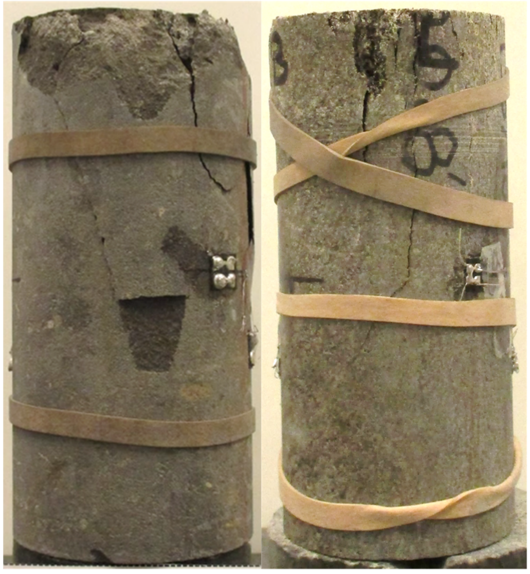


Figure 6 Examples of invalid specimen failure modes due to spalling and chipping along the specimen ends

2.2.2 Failure type classification

Failure type describes whether specimen failure during testing occurred through the homogeneous rock material, along defects or a combination of both. Classifying these failure types is important for engineering design because the failure types represent different strength components of the rock. The different failure types (Bewick et al. 2015, 2019; Bewick 2021) are defined as follows, and examples of the failure types are presented in Figure 7:

- Homogeneous – specimen failure through the homogeneous rock matrix.
- Combined – specimen rupture through a combination of rock matrix and discrete features (e.g. veins, foliation etc.).

- Discrete – specimen rupture completely along a single defect or healed discontinuity (e.g. vein, foliation, bedding).
- Weakness network – specimen rupture completely along multiple defects, or around clasts or nodules.

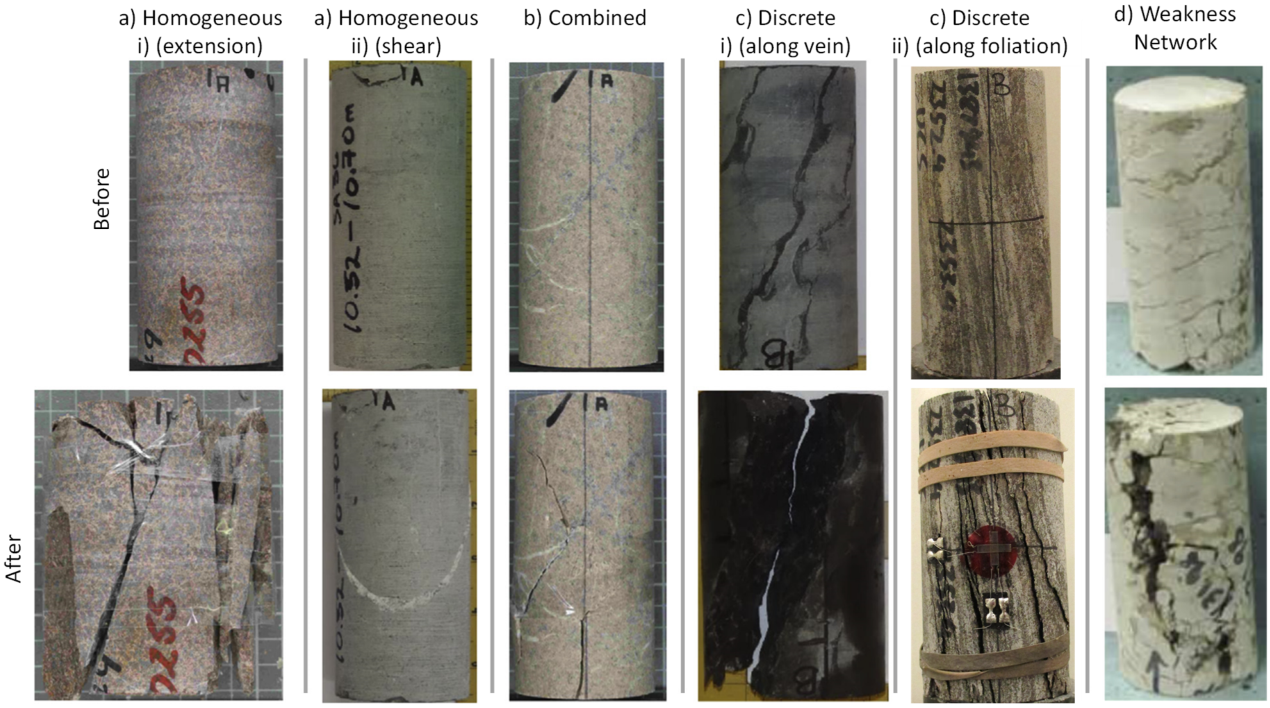
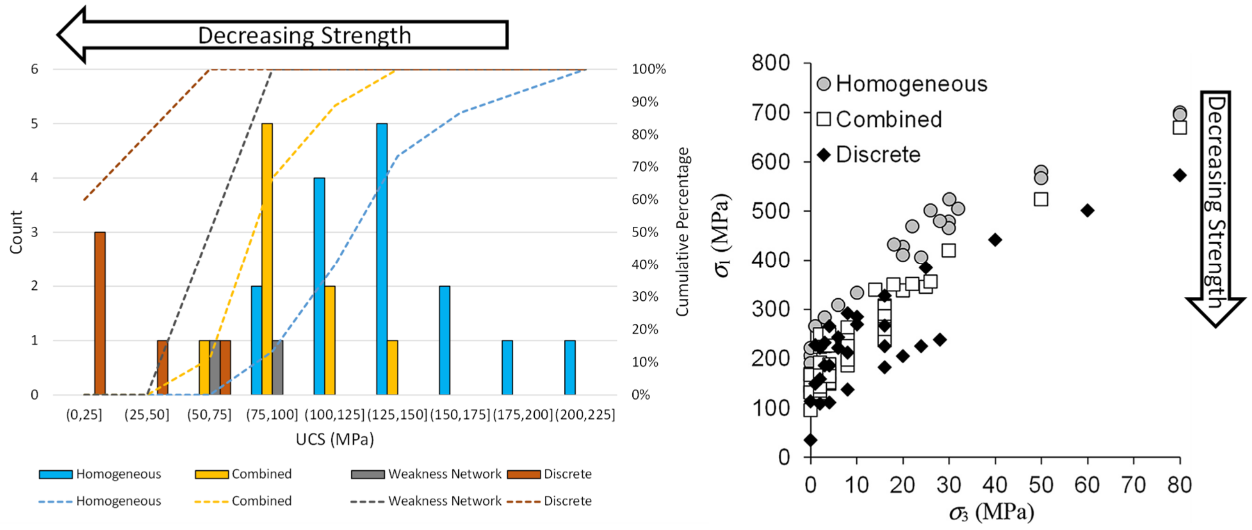


Figure 7 Failure type classification examples (modified from Bewick et al. 2019)

Failure type classification becomes increasingly important for heterogeneous rocks because it provides a standardised method of documenting the involvement of defects in the specimen failure surface. One of the main limitations of the ASTM and ISRM standards for UCS and TCS testing is that they were mainly developed for homogeneous rocks, where specimen failure is typically through the homogeneous rock matrix. However, when these standards are applied to heterogeneous rocks, the UCS and TCS test results typically exhibit high variability, which is largely due to the variable failure types (Bewick et al. 2015, 2019).

Laboratory datasets have shown that scatter in strength data can be reduced when failure type is accounted for. Figure 8a shows a cumulative frequency chart of UCS strength by failure type for a veined sedimentary rock. Specimens with homogeneous failure types exhibit the highest strength, followed by combined, weakness network and discrete failure types. Figure 8b demonstrates a similar trend for UCS and TCS results obtained from testing of heterogeneous biotite quartz monzonite specimens (Bewick et al. 2019). The involvement of veins in specimen rupture demonstrates a weakening effect on strength as the progression from homogeneous to discrete represents a progression from a failure surface not impacted by veins to the strength of the vein itself. In cases where the vein material is stronger than the rock matrix, such as rock with significant quartz veining, the opposite impact can occur where strength increases because of veining.



(a) (b)

Figure 8 **Laboratory datasets showing the impact of failure type filtering on strength variability. (a) Cumulative frequency chart of UCS results from veined sedimentary rock; (b) Principal stress plot of TCS and UCS results from a heterogeneous biotite quartz monzonite (Bewick et al. 2019)**

2.3 Post-processing guidelines prior to interpretation

Once the dataset has been developed through a reliable testing program and proper classification of the failure behaviour, additional steps must be completed to analyse the results. The following are typical steps recommended for post-processing a laboratory dataset of BTS, TCS and UCS results before establishing a strength envelope for brittle rocks:

- Remove specimens with invalid failure modes (e.g. chipping, sloughing).
- Remove specimens with invalid specimen dimensions. ISRM standards require a length-to-diameter ratio between 2.5:1 and 3:1 for UCS tests and between 2:1 and 3:1 for TCS tests (ISRM 1978, 1979). ASTM standards require a length-to-diameter ratio between 2:1 and 2.5:1 (ASTM International 2014) for UCS and TCS tests. In situations where data is limited, a ratio range between 1.8:1 and 2.5:1 has been used in practice (Bewick et al. 2017).
- Note specimens that exhibit signs of core damage (from visual observation or based on the strain results) so these results can be filtered during analysis.
- Normalise UCS and TCS results to a 50 mm specimen diameter to account for strength dependency on specimen size. Equation 1 (Hoek & Brown 1980) can be used: developed from empirical data for core diameters < 200 mm, it demonstrates an increase in peak strength with decreased core diameter:

$$\sigma_{peak50} = \frac{\sigma_{peak}}{(d/50)^{-0.18}} \tag{1}$$

where:

σ_{peak} = actual peak strength of a specimen with a diameter of d (in mm).

σ_{peak50} = peak strength of a specimen with a 50-mm diameter.

- Correct BTS results to estimate direct tensile strength. The following reduction factors have been proposed by Perras & Diederichs (2014) to apply to BTS values:
    - 0.70 for sedimentary rocks.
    - 0.82 for igneous rocks.
    - 0.86 for metamorphic rocks.

- Classify data by failure type (i.e. homogeneous, combined, weakness network and discrete). Discrete failure types must be processed separately in shear-normal space to estimate the strength of healed discontinuities and should not be processed in principal stress space for intact rock strength assessments (Bewick et al. 2017).

3 Developing intact Hoek–Brown strength parameters

3.1 Hoek–Brown criterion and guidance

The empirical HB criterion (Hoek & Brown 1980) is widely used in engineering applications to characterise the intact strength of brittle rocks failing through shear. For intact rock, the HB strength envelope is defined in principal stress space through the following equation:

$$\sigma_1 = \sigma_3 + \sigma_{ci}\left(m_i \frac{\sigma_3}{\sigma_{ci}} + 1\right)^{0.5} \tag{2}$$

where:

σ_1 and σ_3 = major and minor principal effective stress at failure, respectively.

σ_{ci} = unconfined compressive strength of intact rock.

m_i = material constant for intact rock.

This criterion was developed to handle shear failure of isotropic and homogeneous rocks (Hoek & Brown 2019). The presence of defects can significantly impact the intact rock strength, and the importance of separating strength testing data by specimen failure type (particularly for heterogeneous rock) before estimating intact strength has been demonstrated by Bewick et al. (2015, 2019). This underscores the importance of classifying failure types as part of laboratory testing and accounting for failure types during analysis.

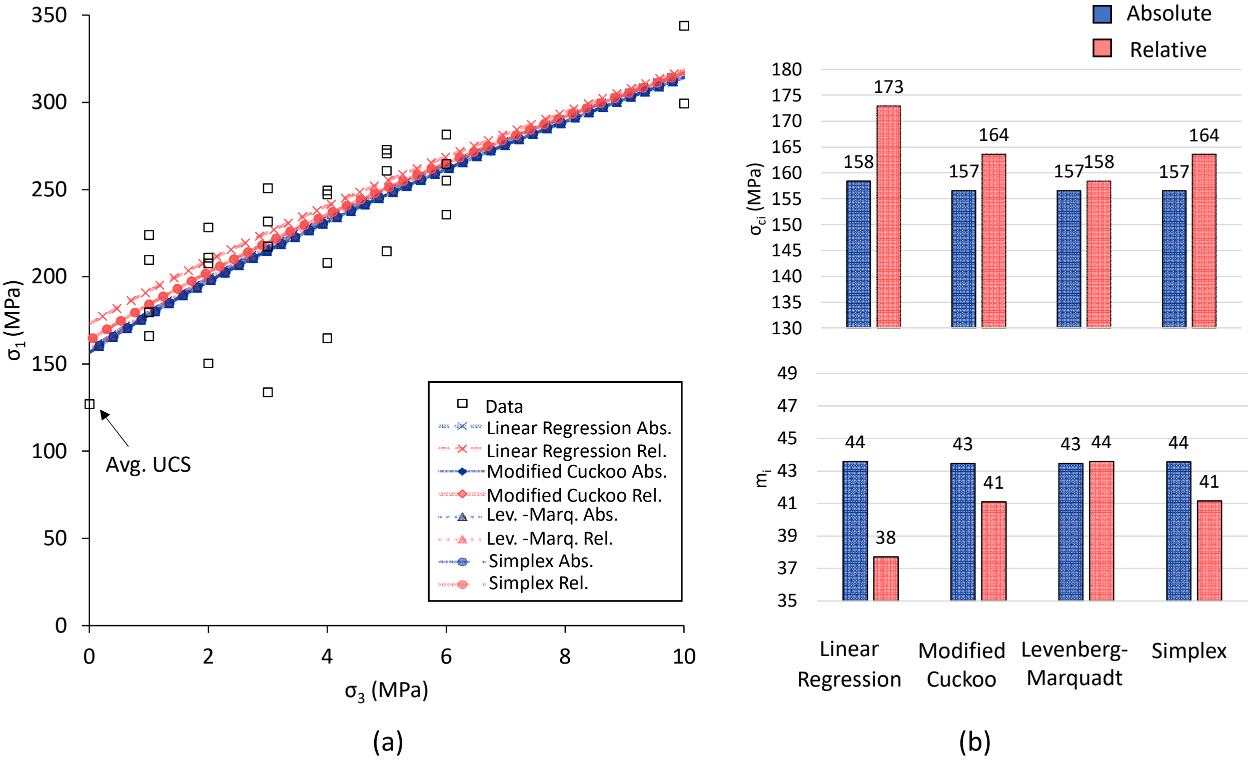
The HB criterion is only applicable for confining stresses between zero confinement and the transition from shear to ductile failure (Hoek & Brown 2019). When the HB criterion was first developed, it was recommended that the range of confining stresses for TCS testing should cover up to half the unconfined compressive strength (0.5 x σ_{ci}) of the rock (Hoek & Brown 1980). However, confining stresses that high are typically not applicable to most open pit problems, where failures are relatively shallow – even in large open pits. Therefore the range of confining stress selected for analysis should be representative of the range of stresses applicable to the problem. Hoek et al. (2002) provide additional guidance on the maximum confining stress to select for pit slope applications.

Using datasets that include many UCS results but only a small number of TCS results can lead to significant bias towards the zero confinement data when fitting the HB envelope. If a reliable UCS dataset is available, the average UCS value can be included in analysis as a single data point to avoid bias during the curve-fitting process (Hoek & Brown 2019). The TCS dataset, including the average UCS value, is then used to establish the σ_{ci} and m_i parameters.

As the HB criterion does not consider tensile failure ($\sigma_3 < 0$), tensile strength should not be estimated by projecting the HB envelope back to the σ_3 intercept (Hoek& Brown 2019). Two widely accepted approaches for handling tensile failure are: (1) defining a tension cutoff value for the envelope (Hoek & Brown 2019); and (2) including tensile strength data such as BTS results (appropriately corrected to estimate the direct tensile strength using an approach like that described in Section 2.3) to anchor the envelope in the tension region. Including tensile data can impact the estimated σ_{ci} and m_i parameters; therefore curve-fitting should be undertaken with and without tensile data, and the resulting parameters should be compared.

3.2 Curve-fit approaches

HB parameters (σ_{ci} and m_i) can vary based on the curve-fitting algorithm selected and how the residuals (difference between data and the fitted curve) are handled. Rocscience (2022) RSData software is widely used for establishing HB envelopes and includes several different algorithms for curve-fitting and the treatment of residuals. To illustrate the impact on resulting σ_{ci} and m_i parameters, four algorithms (linear regression, modified cuckoo, Levenberg-Marquardt and simplex) were used to fit the HB curve to TCS and average UCS data. Each algorithm was fitted with absolute residuals, which measure the absolute difference between the data and fitted curve, and relative residuals, which are normalised by dividing the absolute residuals by the σ_1 value of the fitted curve. The test data was obtained from laboratory testing on igneous rock collected from an open pit site. The resultant HB envelopes are shown in Figure 9a, and corresponding HB parameters are plotted in Figure 9b.



(a)

(b)

Figure 9 (a) HB strength envelopes in principal stress space; (b) The resultant HB parameters (σ_{ci} and m_i) obtained from RSData curve-fitting algorithms for relative and absolute residuals

In this example, the resultant HB envelopes with absolute residuals are very similar (or the same) for each curve-fitting algorithm. There is more variation in the HB parameters when relative residuals are considered. The modified cuckoo, Levenberg-Marquardt and simplex algorithms are generally in agreement with each other, whereas the linear regression envelope (with relative residuals) is slightly stronger than the envelopes fitted using the other three algorithms. Overall, the variability in the HB envelopes is generally minor due to relatively little scatter in the dataset and sufficient test quantities covering a range of confining pressures.

4 Further design considerations related to intact strength

In many cases it is desirable to understand the sensitivity of a model to intact strength as part of the design process. This is where it is advantageous to have a good understanding of the natural sources of variability to capture as a sensitivity and a way to visualise or represent that uncertainty via the selected parameters.

Fitting datasets separately based on failure type (refer to Section 2.2.2) can result in more than one set of HB parameters per domain to consider in the design. This can provide a range of parameters to incorporate in sensitivity modelling. At the inter-ramp and overall slope scales, failure mechanisms in slopes consisting of a strong rock mass typically involve a combination of failure along discontinuities and through the rock mass. Developing intact rock strength parameters that capture the appropriate failure mechanism is an important component in developing a reliable design.

Additionally, where characterisation studies have identified areas of the rock mass with variable defect intensity, different strength properties can be applied. For example, the strength parameters obtained from combined failure data may be more applicable to zones with moderate to high defect intensity, whereas the strength obtained from homogeneous failure data may be more applicable to zones with few to no defects.

Uncertainty in the intact strength estimates can be incorporated in modelling sensitivities by selecting upper and lower bounds of the σ_{ci} parameter to represent a range of strength values. These bounds can be estimated from ±1 standard deviation bands or specified prediction interval bands. Figure 10 shows an example of lower and upper bound envelopes defined by ±1 standard deviation from the mean envelope.

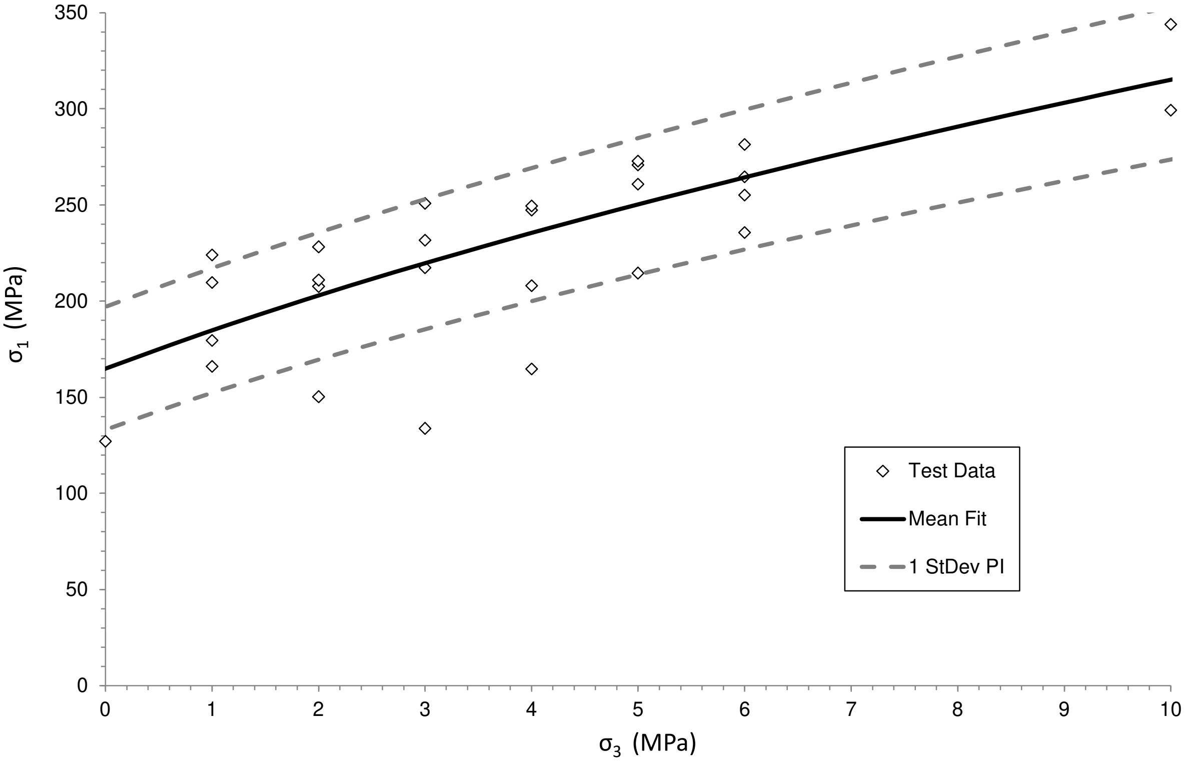


Figure 10 Lower and upper HB envelopes defined by +/- 1 standard deviation from the mean envelope

5 Conclusion

Discussed in this paper are considerations for developing intact rock strength parameters based on laboratory testing data for strong rock (i.e. ISRM [1981] field strength of R3 and above). The main topics covered in this paper are the following:

- Variability among laboratory test data can result from natural sources (e.g. weathering, alteration, lithology) and induced sources. Induced variability can occur because of core damage and differences in laboratory testing methods and preparation. As much as possible, steps should be taken to protect the core from damage, and consistent testing and preparation procedures should be used.
- Capturing specimen failure behaviour through failure type and failure mode classifications is an important component of interpreting laboratory results. Datasets from heterogeneous rocks show the importance of separating results by failure type because the involvement of defects in the failure behaviour impacts the strength. Discrete failure types are not applicable for intact strength estimates and should instead be used to estimate the strength of healed discontinuities.

- Guidelines for post-processing a laboratory dataset prior to interpretation are presented, including corrections for specimen size and estimating direct tensile strength from indirect BTS measurements.
- Once a reliable and well-characterised laboratory dataset is developed, intact strength for hard rocks is estimated from laboratory tests using the HB criterion. Commercial tools such as RSData present different methods for fitting the HB curve using different curve-fit algorithms and treatment of residuals. The selected curve-fit method and treatment of residuals can yield different intact strength parameters, and the fit that is most suitable to the problem should be selected.
- In design, sensitivity modelling of intact rock strength can be performed to account for the impact of natural strength variability (within a geotechnical domain) and uncertainty in parameter estimates. For example, ±1 standard deviation bands can be used to define reasonable upper and lower bounds for design parameters.
- HB parameters estimated separately by failure type can be incorporated into the design as sensitivities to represent different components of the rock strength. For example, the strength of the rock matrix free of defects can be represented by homogeneous failure types and the strength of the rock matrix with defects can be represented by a combined strength.

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