

The importance of robust validation of geotechnical data and systematic domaining in defining appropriate rock mass parameters as inputs for modelling and design

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Abstract

Robust review and validation of project geotechnical data are essential to provide valuable inputs for subsequent mine modelling and design but are sometimes poorly understood. It is particularly important to ensure that data collection by logging personnel and storage within geotechnical databases are in the best condition possible. The quality of, and confidence in, subsequent design and modelling are reliant on the acquired dataset including derived rock mass properties. This paper discusses the importance of effective validation of geotechnical, structural, and laboratory data, and suggests some tools to guide the reader through the validation of such data. Once the data have been 'cleaned' of errors and further processed in a way that makes them easier to measure, visualise and analyse for a specific purpose, they become more valuable information.

Following the robust validation of logging and laboratory data, a systematic domaining process is suggested, incorporating geological, hydrogeological, structural, and geotechnical data, to ensure the data are reliable and their variability is well understood. Knowledge and insights gained from the data validation and domaining process are crucial to select appropriate inputs into subsequent modelling and design.

Keywords: *core logging, geotechnical data, data validation, rock mass domaining, geotechnical design*

1 Introduction

Geotechnical design is challenging in many aspects of the process, from data collection and interpretation, to derivation of rock mass properties, through to slope stability assessment and adoption of design parameters. If the properties used in stability assessments and modelling for open pit and underground mining projects are derived from core logging data, mapping, and rock mass characterisation, it is important to undertake robust validation of the data, focusing on identifying limitations or apparent inconsistencies and assessing the sufficiency of the data for rock mass and rock fabric characterisation (Fillion & Hadjigeorgiou 2016). Validation should be undertaken on logging data, including geotechnical and structural logging and subsequent laboratory results. This paper describes some important techniques that will help the reader during the validation process. It also describes an approach for rock mass domaining.

2 Data collection

Efforts should be made by all parties at the data collection stage to allow the collection of relevant and useful data and to reduce the data validation work. To facilitate this process, consistency of practices (also by all parties) is crucial during the project's life.

Suitability planned geotechnical and hydrogeological investigations should be undertaken to collect the necessary data to carry out subsequent design and modelling to the appropriate reporting level.

2.1 Geotechnical core logging

Triple-tubed rotary core (HQ3 or PQ3) drilling is the most widely used method to obtain high-quality core and engineering properties of the rock mass where the pit wall or stopes will be excavated. It is not the purpose of this paper to detail geotechnical core logging procedures, but the following parameters are suggested to characterise the rock mass and calculate rock mass indices: downhole start and end depths, total core recovery and core loss, rock quality designation (RQD) measured with reference to natural defects, lithology, weathering, rock strength, number of open discontinuities, number of joint sets, characteristic joint roughness, infill thickness and type, alteration for fabric and joints, observations concerning weak structure and conditions, and any additional observations or comments.

Geotechnical logging can be undertaken on different interval length bases. Some organisations prefer logging core on a metre-by-metre basis, or on a drilling run basis; others prefer core to be logged on a geotechnical interval basis, where the core is divided into geotechnically similar intervals based on rock type, weathering, fracture frequency, and joint infill characteristics. The adopted interval length depends on the variation in the rock masses encountered, and the standard operating procedures and validation processes in place.

For design purposes, logging on geotechnical intervals is the considered approach as it accounts for weak zones by treating them separately. This approach is followed by the authors.

Core logging should be undertaken at the drill rig to ensure that the core is as close as possible to its original state and to avoid disturbance by transportation. If this is not possible, weaker drill runs should be rolled from barrel splits into PVC splits before being placed into core trays, to avoid disturbance of the materials before logging is done at the core yard.

2.2 Structural logging

The purpose of structural logging of oriented core is to provide reliable information concerning the nature and orientation of discontinuity sets within a rock mass. Natural discontinuities include (but are not limited to) joints, faults, bedding, and foliation, which all need to be clearly identified within the drillcore alongside their orientation and characteristics.

Suggested data to be recorded for each discontinuity include the following: downhole depth, structure type, alpha and beta measurements, and reliability of the orientation line for the core run. Shape (planar, undulating, stepped, irregular), roughness (slickensided, smooth, slightly rough, rough, very rough), infill type and infill thickness, joint wall alteration, and any additional observations should also be recorded.

Inclined drillholes are often designed to capture discontinuities that would not otherwise be picked up with vertical holes (Terzaghi 1965). Statistically, discontinuities that are parallel or near-parallel to the drillhole direction are less frequently intersected than perpendicular or near-perpendicular structures of the same frequency (Terzaghi correction and bias). This concept is illustrated in Figure 1.

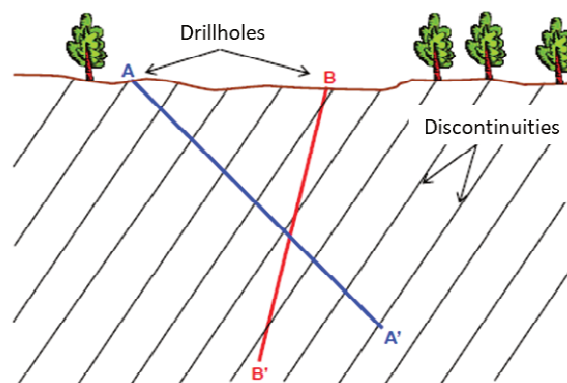


Figure 1 Apparent fracture frequency depending on drilling direction. Note: hole AA' is near-perpendicular to the discontinuities and intersects the structure set eight times. Hole BB' is near-parallel to the same discontinuity pattern and intersects the structure set three times

The core is oriented at the drill rig by means of one of the available orientation tools allowing alpha and beta angles to be measured during logging, which can then be converted into in situ dip and dip directions using a conversation calculation. In areas of friable material, physical orientation of the drillcore can be problematic (or even unsuccessful), resulting in intervals of the drillhole not being oriented or having a low-reliability orientation line, thus leading to the orientation of structures being of low confidence.

2.3 Geological units

For a green fields site, geological units should be identified at the exploration stage by an experienced site geologist, who should provide a crib sheet. This will be a project-specific document that should include all of the known lithologies encountered and their geological descriptions, including typical and unique characteristics, maximum assumed thickness, and coloured core photographs to illustrate the described units. Projects at various stages of development may have more detailed studies on geology that can be referred to.

2.4 Logging template

Some companies use a complex database for their logging systems with fixed formats that are deliberately inflexible, to avoid basic errors like typos or invalid entries. This offers some instantaneous checks for the logger to flag errors or inconsistencies; for example, if an RQD value entry is greater than 100% or if a depth (from) does not correspond to the end depth of the previous interval. There are dropdown lists providing options to select rock type, infill minerals and so on.

Other companies choose to adopt a simpler logging template such as a spreadsheet for data entry. This approach offers more flexibility but can cause more issues and additional validation work. If a company chooses this option, the professional in charge of developing the template should ensure that in-house validation tests are implemented to allow some instantaneous checks, for the logger to identify errors.

A good practice is to have the rock mass classification indices directly calculated in the template sheet, and have a good range of them, for instance, RMR_{89} , RMR_{90} , geological strength index (GSI), Q (or Q'). This could assist and lead the logger to adjust some logged parameters if the calculated rock mass indices do not seem to adequately represent the core conditions.

2.5 Sampling

A geotechnical laboratory testing program is essential to determine the rock properties of different materials encountered, for use in modelling and design.

Geotechnical samples should be taken to ensure that representative samples of all major geological units are collected. Samples should be selected carefully and wrapped specifically to maintain their in situ properties, and then transported carefully to an approved laboratory for testing. Care should be taken when selecting samples; they need to be of a minimum dimension for specific testing to be undertaken. As a rule of thumb, the length/diameter ratio's acceptable range is as follow: $1.8 < L/D \text{ ratio} < 3$, in accordance with international best practice International Standards for Rock Mechanics (ISRM) suggested methods (Hatheway 2009). Also, selected samples need to be cylindrical, with a smooth core surface and free of vughs or open defects and preferably free of healed defects.

2.6 Field testing

Geotechnical field testing can be undertaken to provide additional data, such as point load testing (PLT). Undertaking PLT in the field is a useful and economical tool to augment field strength estimates (Thomas 2014) and increase the opportunity for data comparison with laboratory data and field estimated strength (FES) values in order to define most appropriate intact rock strength values. Appropriate specific conversion factors (K) should be carefully selected to derive UCS values ($UCS = (K) \times I_{50}$ - where I_{50} is the point load strength index normalised to 50 mm diameter core), correlated where possible with laboratory UCS testing.

Although a value of K of 24 is generally quoted (Bieniawski 1975), Bowden et al. (1998) note that the relationship is variable and appears to be strength dependent. They suggest K should be determined on a site-by-site basis and that quoted values should not be relied upon (Thomas 2014).

Although widely used, various authors have highlighted a number of limitations of the PLT including unreliable results at low strengths (less than 25 MPa), scatter of results, and potential influence of anisotropy resulting in failure trough planes of weakness (Thomas 2014). These issues can be reduced when using the standard test method published by ISRM (ISRM 1985).

Other field testing includes in situ rock bulk density, hydrogeological testing such as Packer testing, and pumping tests or installation of vibrating wire and standpipe piezometers, which provide crucial input parameters for design work.

2.7 Other field investigations

Geotechnical mapping is often undertaken as part of geotechnical investigations to collect continuous geotechnical data for undisturbed materials with the purpose of building/adjusting the structural model of a project. There are different types of mapping including window mapping, scanline mapping, cell mapping, and ground blockiness index mapping, which, depending on the stage of the project, can only be done on outcrops if at exploration stage or as the pit/stopes develop on the actual mined faces.

Photogrammetry investigations are also a good option to capture structural data on a large-scale without access restriction issues; they allow assessment of structure orientation, dominance, persistence and spacing, based on produced 3D images of the photographed objects (pit walls/stopes). This is also a good tool for operational support and monitoring of slope/stope performances as they develop.

Acoustic/optical televiewer (ATV/OTV) surveys are also often recommended in a drilling program to increase the volume of and confidence in the structural data. The reliability of ATV/OTV orientation data is generally higher than that of physical logging data, although discontinuity conditions can only be reliably discerned from physical logging. ATV surveys improve the quality of the structural data and provide an additional, more accurate dataset of structure orientations. This is particularly pertinent in zones of low confidence in core orientation or poor core recovery.

2.8 Challenges

2.8.1 *Importance of well-qualified personnel collecting data*

Challenges are often faced at the data collection stage. Drilling and core logging quality can be inadequate, resulting in the acquisition of poor geotechnical data. Selection of a properly experienced drilling contractor and adherence to appropriate quality assurance/quality control contract procedures is important and is the responsibility of the project owner (Read 2013).

An additional concern related to a lack of experience for loggers is that many mine site geotechnical engineers have been educated as mining engineers or sometimes as civil engineers, not geological engineers (engineering geologists). Some loggers have geological backgrounds and little rock mechanics background, so even if they are trained to undertake geotechnical logging, their lack of understanding of the mechanical behaviour of the rock mass makes it difficult for them to collect the most meaningful data.

2.8.2 *Geotechnical parameters difficult to assess/log*

Apart from issues related to the level of experience of the person doing the logging, some parameters inherent to geotechnical logging can be difficult to log (even more so if the logger is inexperienced).

2.8.2.1 *Field estimated strength*

FES can occasionally be difficult to assess. First, there are many scales available which, despite having similarities, do present differences in the description of the field assessments and in the boundaries of the

intact rock strength classes (Thomas 2014). There are several classifications available, such as the ISRM, national standards (British or Australian), or best practice (US Army Corps of Engineers; Geological Society of London). Consequently, it can be confusing for the logger to use a classification they are not familiar with, causing potential mistakes in the FES, especially in very weak or very strong units. Again, a logger with experience will be more at ease to assess appropriately the FES.

Second, the difficulty of logging a parameter such as strength is that, while there are field classifications available for the logger, the descriptions are not always suitable for the rocks assessed. Care must be taken when the rocks exhibit micro defects or anisotropy such as foliation. The selection of core samples for the FES assessment depends on the encountered rock mass. If micro defects are numerous and small, and inherent to a specific rock mass domain, the FES assessment should be undertaken on core samples exhibiting these. There should be no further adjustment of strength as the micro defects are already taken into consideration (Jakubec 2013). If, however, the micro defects are not typical of a domain, the selected core samples for testing shouldn't exhibit these micro defects. In the case of an anisotropic bedded rock mass, the selected samples would most likely display foliation. The FES should be estimated with caution. If the sample breaks along a bedding plane, the FES might need to be upgraded to define the appropriate intact rock strength (IRS) (see Section 4.3.1).

2.8.2.2 Weathering

Weathering is another example of complexity in the logging process. Weathering descriptions differ across guidelines and are often generic or broad. As such, they can be misleading; for example, highly weathered materials are not necessarily disintegrated to a soil. In line with best practice, core logging of weathering recognises the assessment of both intact rock and the rock mass (intact rock plus fractures).

Figure 2 illustrates highly weathered rock core that is not decomposed to a soil; its texture is still visible.



Figure 2 Highly weathered core with preserved rock texture

At sites of known weathering, it may be appropriate to adopt a site-specific approach to weathering. The IRS (R0 to R6) is combined with the proportion of various-strength materials and the fabric observations to determine the overall engineering weathering class (1 to 6). The adopted approach is a more objective approach to weathering identification as it combines two largely objective measurements, i.e. the strength of the intact material and the percentage of core recovery. The method also ensures a higher degree of repeatability across a team of logging engineers with different experience.

2.8.2.3 Difficulties in logging soils to soil-like materials

The authors would define a material as 'soil' when it is logged with soil strength codes (S1 to S6) and as soil-like when logged as R0 (extremely weak). Very weak materials are logged as R1. Logging soils to soil-like materials is difficult and different interpretations have been observed by the authors in the datasets they reviewed as detailed:

- A high defect count (number of natural open defects) and a high joint set number (four or five), presumably to generate a low calculated rock mass classification value, and RQD = 0.

- A low (or even zero) defect count and a low set number (as few joints could be positively identified in such materials), with RQD equal to 100% resulting in a rock mass classification index that is too high and not reflective of the actual encountered material.

First comment is the relevance of using RQD to characterise such materials. RQD is aiming at characterising sound rocks. Pieces of core that are not 'hard and sound' should not be counted for the RQD even though they possess the requisite 100 mm length (Deere & Deere 1988). The assessment of soundness is not well defined though. Some would base their judgement on weathering, some on strength or both can also be considered, and the threshold might also be different from a professional to another. The highly weathered materials shouldn't categorically be considered as 'non-sound' rocks as the highly weathered materials are not necessarily weathered to soil-like materials (see Section 2.8.2.2). The authors suggest assessing the soundness of a material, considering both the FES and weathering of a material, FES usually prevailing. As a common practice, materials with strength equal or lower than R1 are usually attributed a zero RQD.

The second aspect is that rock mass classification indices are not designed to be assigned to soil and soil-like materials and these should be characterised differently, using laboratory results (triaxial testing and direct shear testing (DST)) for example (Warren et al. 2015). So, the attribution of RQD values becomes less important because these materials should not be characterised with rock mass rating (RMR) indices.

Judgement needs to be made for the characterisation of very weak materials (R1), as these materials still have their texture but are often highly weathered. In previous project experience, the authors have often defined these materials with a zero RQD but with RMR indices as structures could often be identified and characterised.

2.8.2.4 Rock quality designation

As explained in Section 2.8.2.3, the use of RQD as a parameter in Bieniawski's RMR (RMR_{89}) system presents some challenges but RQD is important to be captured adequately because this is an input that accounts for 20% in the RMR_{89} calculation and is also a direct input in Q calculation. It is highly subjective and often inconsistent, so it must always be used with engineering judgement that takes proper account of the geological characteristics of the rock mass being classified (Read & Stacey 2009).

One of the important sources of error that specifically detracts from RQD's usefulness as a parameter, as reported by Brown (2003) and Hack (2002), is the arbitrary and abrupt boundary of 100 mm of unbroken rock. Small difference in joint spacing can produce large differences in the RQD value. A rock mass with joint spacing of 9 cm has an RQD of 0%. In comparison, a rock mass with joint spacing of 11 cm has an RQD of 100%. Hence, it is important to carefully identify the natural defects and not overestimate the count by considering mechanical breaks. Otherwise, the RQD resulting would be underestimated.

It is often difficult to distinguish natural open defects from drilling-induced breaks, but several criteria can help to correctly classify defects, such as mineral coating or the profile of the defect surface. In case of doubts, the authors would suggest logging a break as natural but also advice against logging all the breaks as natural, as it will be too conservative. The RMR system relies largely on the identification of natural open structures, which account for 70–80% of the total RMR rating (when adding up the ratings obtained from RQD, discontinuity spacing and characterisation), so it is crucial that artificial breaks are discarded from the logging process.

Another aspect mentioned by Brown (2003) and Hack (2002) is the fact that the RQD is also biased by the orientation of the drillhole with respect to the joint orientation (Read & Stacey 2009).

3 Data validation

It is important to undertake robust validation of data, focusing on identifying limitations or apparent inconsistencies and assessing the sufficiency of the data for rock mass and rock fabric characterisation. This characterisation is used to derive input properties to use in subsequent geotechnical modelling and for design purposes. Validation should be undertaken on logging data including geotechnical and structural data, and field testing and laboratory results.

3.1 Geotechnical logging data

Some common visible errors or inconsistencies observed in geotechnical logging databases include:

- Incorrectly entered parameters or typographical errors.
- Undefined logging codes.
- Parameters outside logical ranges.
- Missing values.
- Inconsistencies between different parameters.

Observations, tools, and suggestions have been developed by the authors to identify these errors in order to assess and improve datasets. These are described in the following subsections.

3.1.1 Simple data checks for incorrect parameters

Validation checks should be implemented to identify any typographical errors or logging codes that are not defined in the logging template/manual. Data entry values should not be outside the typical range for each of the main input parameters for various rock mass classification calculations. When an 'error' is highlighted, the raw data should be left as originally logged and the parameters amended/modified in newly created columns. Examples of simple checks include:

- The interval length should be checked against core recovery and core loss, assuming an interval could not have a recovery greater than 100%.
- RQD values should not be greater than 100%.
- RQD values for weak materials (or soils) with a hardness (FES) of R1 or below are recommended to be set to 0%.

3.1.2 Validation check: discontinuity spacing and rock quality designation

One of the standard data checks performed is to plot RQD against joint spacing, as there should be a reasonable correlation between these two parameters. The authors suggest using the published Bieniawski graph (Bieniawski 1979) (RQD versus discontinuity spacing), which shows the range of joint spacing values expected for the logged RQD. Figure 3 shows an example of the correlation between RQD and discontinuity spacing data for a particular project. Points falling outside accepted typical average range (red curves) may be considered as outliers.

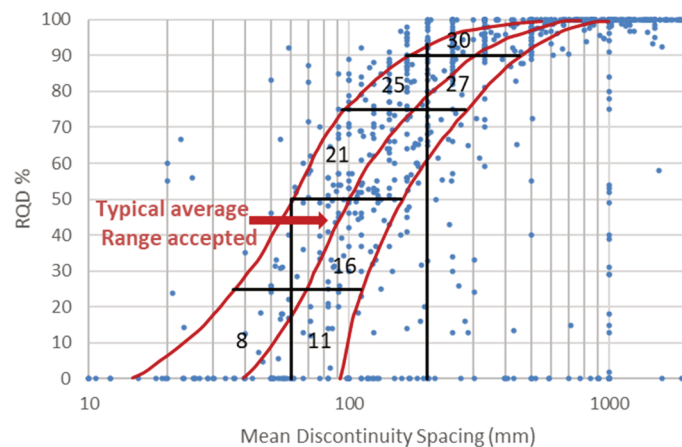


Figure 3 Correlation between joint spacing and rock quality designation

The authors suggest producing a graph like that shown in Figure 3 for each hole during logging, to check if the RQD and defect spacing being logged are appropriate and consistent between loggers.

The person in charge of the data validation should also produce such a graph for each hole and check the intervals falling outside the typical curve. These intervals should be flagged and verified by core photo examination/photologging.

3.1.3 Validation check: defect count and defect set number (number 0.5 to 5)

Checks can also be implemented between joint set number (0 to 5: 0 for massive and 5 for crushed or soil) and defect count (number of natural open defects) for an extra level of validation. Joint set number is not an input for the RMR calculation but is for Q calculation. Figure 4 shows areas of inconsistency between defect count and joint set number, reported for a particular project, indicated by red rectangles where many natural defects have been logged but a low set number has been assigned, or few defects have been recorded but a high set number has been assigned. This is especially evident at the extremities. Some of the cases highlighted in red correspond to the cases mentioned in Section 2.8.2.3. In this project, for example, one logger had logged soil-like materials with a high defect count but with a set number of 0 or 1; another logger had logged the soil-like materials with a low defect count but with a set number of 4 or 5. This illustrates the importance of consistency between logging practices. As mentioned earlier, the soil-like materials are not suggested to be characterised with rock mass classifications anyway so these inconsistencies were not crucial. For the other inconsistencies reported at extremities, validation through comparison with the RQD or joint spacing should help identify the inappropriate parameters. Alternatively, core photo examination is also an option.

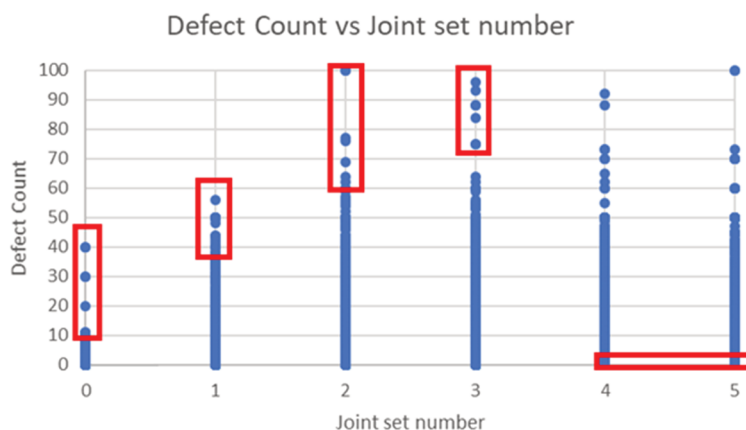


Figure 4 Comparison between defect count and joint set number

3.1.4 Validation check: rock quality designation and field estimated strength

Weak materials with an FES below 5 MPa are sometimes given an RQD, which is incorrect practice as this parameter is not suitable for characterisation of very weak to soil-like materials. As such, RQD values are suggested to be changed to zero for materials with an FES of R1 or lower.

3.1.5 Validation check: weathering and field estimated strength

An extremely or highly weathered interval is not expected to be strong or very strong. Fresh materials are also rarely extremely weak or are not soil strength materials unless they are highly altered.

Core photos can be examined to assess the logged weathering and compare it with the logged strength. The parameters can then be amended after core examination.

It is important to remember that core photos can be deceptive for gauging strength and weathering so although a material may look discoloured/weathered, it could have retained its strength and textural properties.

3.1.6 Missing data

Another aspect to consider while reviewing datasets is missing data. Many of the datasets received from mining companies have missing logging geotechnical parameters that are necessary for calculating the rock

mass classification system indices (values), which in turn are used to derive the input properties for stability assessments and numerical modelling. If such parameters are missing, rock mass classification indices cannot be calculated for that interval, so there is a risk that the rock mass is characterised only some of the time.

Options to address this include either relogging/photologging to capture missing data or using assumptions.

3.1.7 *Review versus assumptions*

When a parameter is missing, or when an inappropriate parameter has been identified, it is possible to amend it through relogging or by core photo examination. However, some parameters such as FES or defect infill characteristics (infill type, roughness and infill thickness) cannot be obtained through examination of core photographs. These infill parameters require examination of actual cores, remembering that core deteriorates with time, and strength is affected by the degradation process. In some cases, core photographs might not be available or do not represent the recovered core run.

When inconsistencies have been highlighted and two parameters are involved, for example, between RQD and joint spacing, it is possible to amend the reported inconsistencies after comparison with core photographs. However, this is not always possible, depending on the involved parameters and the extent of weathering. As discussed in Section 3.1.5, assessments of photographs need to be made cautiously.

Sometimes a scope of work excludes photologging of individual intervals, or the data are so numerous that it becomes impractical to review individual intervals. In these instances, assumptions can be used to amend inappropriate (outlier) values or to capture originally missing parameters.

If one of the two parameters is observed as being incorrect, it is reasonable to assume the other parameter is correct and fit for use. For example, FES can be correlated to rock type and weathering, and defect conditions can be based on typical infill conditions observed from existing data, correlated with lithologies.

3.1.8 *Data status*

As mentioned previously, the authors suggest creating additional columns and using different coloured cells for amended data but retaining the raw data in the original columns for reference. Further, creating additional columns for each main geotechnical parameter is suggested, to provide the status of the considered parameter and indicate if an interval has a value for the geotechnical parameter considered.

Particular cases are suggested as follows:

- The mention of 'Value' indicates that the parameter considered has a value based on the raw data.
- The mention of 'Value revised by core examination' indicates that a value was amended/assumed by photologging.
- The mention of 'Value based on assumptions' indicates that the parameter has a value derived/assumed based on representative values.
- The mention of 'Missing value' indicates that the parameter is missing (no assumption was made or photologging undertaken to amend/capture this parameter).
- The mention of 'Literature' indicates that in the absence of raw data or derived values, the parameter has been estimated from literature (published or in-house site reporting) values or similar site values.

The clean amended data can be used to calculate rock mass classification values for each geotechnical interval (see Section 4.1). Summaries and charts can be produced considering the amended dataset or just the raw data, allowing analysis of the impact of the validation on the summary rock classification values.

3.2 Structural data

Structural data provide key inputs for slope designs because they form the basis of kinematic analyses, which allow the determination of the main failure mechanisms. Structural data can be obtained from different sources, as detailed in the previous sections.

After the collection of structural data onsite, data are collated and stereonet of structural data are generated. Stereonets are analysed to identify structural domains (sets), which are used for better kinematic failure assessment and stability analyses. This allows for optimum batter/berm configurations to be identified.

If ATV/OTV data are available, part of the validation work includes the reconciliation of these data against the physical structural logging data. Occurrence of structures and major sets, their depths, the aperture/thicknesses of these structures, type of defects, and orientation of defects should all be compared. As part of this comparison, core photos should be examined and compared with the downhole ATV/OTV log/image. Stereonet plots should be compiled for logging data versus ATV/OTV data.

Figures 5 and 6 show examples of correlation between physical logging and ATV interpretation.

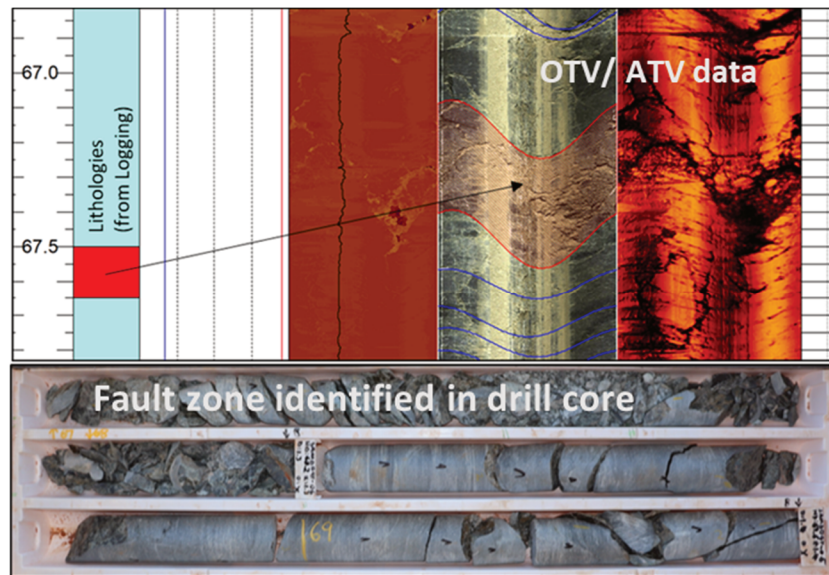


Figure 5 Correlation between a fault zone identified during core logging and the same one observed on the acoustic televiewer (ATV) log and optical televiewer (OTV) image. Depth and thickness are matching

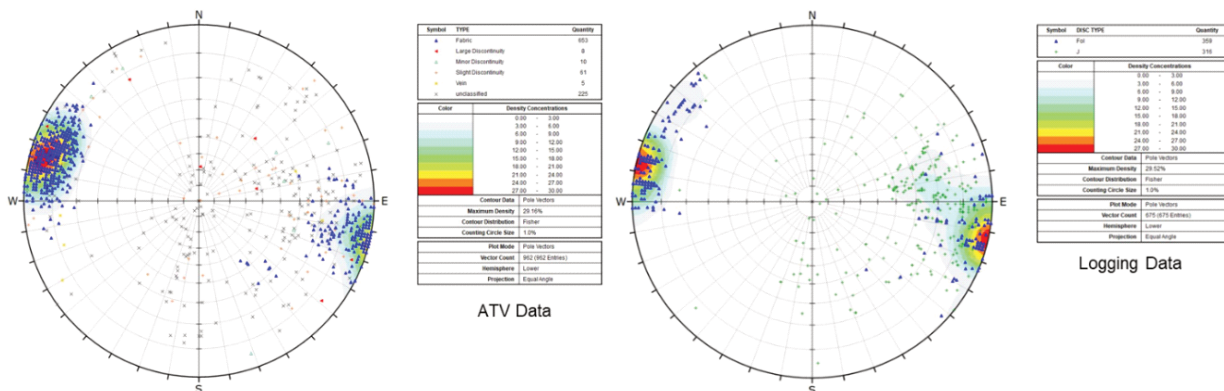


Figure 6 Stereonet correlation between acoustic televiewer (ATV) and logging data. Foliation orientation is similar between the two data sources

Mapping data should also be reconciled with structural data obtained from logging. The main structural set orientations and defect conditions (infill and roughness) should be compared between the two data sources.

3.3 Laboratory testing results

3.3.1 Testing required

Laboratory strength tests should include a diverse set of test types and a minimum number of samples for each test to provide an understanding of the data reliability and variability.

A minimum number of samples for compression testing (uniaxial or triaxial), direct shear and/or tensile strength tests should be taken per rock type in accordance with ISRM suggested methods (Hatheway 2009). Selected samples should show a range of weathering grades, alteration, and anisotropic features.

3.3.2 Laboratory results validation

It is not the purpose of this paper to go in details into the analysis and interpretation of laboratory results, but a few aspects in the validation of laboratory results are mentioned below. Samples before testing which show irregular core surfaces or exhibit vughs or defects should be cautiously considered. Samples which are not within the acceptable length/diameter ratio ($1.8 < L/D \text{ ratio} < 3$) should also be used with caution (Hatheway 2009). Particular attention should be given to the mode of failure and to the aspect of the failure surface. Examining the photos before and after a test can give important insight on the validity of the test performed.

The results provided by the laboratory should not always be used as provided, but analysed, validated, and amended, if necessary. In some cases, laboratory testing results do not reflect the expected behaviour of the tested samples, and such results may be required to be discarded. For example, in foliated samples, failure could occur along a foliation plane so the resulting unconfined compressive strength provided by the laboratory does not reflect the IRS of the sample and this value may not be considered for direct use in assessing the input properties. It is important that the professional analysing the laboratory results uses their engineering judgement to analyse the validity of a test result and discard inappropriate results.

In another example related to triaxial testing, the peak selected by the laboratory for deriving the properties may be considered inappropriate by the expert completing the design, and a different interpretation then applied to obtain the input parameters required. When validating triaxial data, it is a good practice to check the different diagrams and charts produced by the laboratory, i.e. the Mohr circle diagram, the stress path diagrams, and the deviator stress versus strain diagram to help select and derive the peak values for appropriate properties.

Saw cut results also need to be validated as they are often reported with cohesion, which is inappropriate, so these results should be used with caution or reinterpreted.

4 Rock mass domaining

It is not the purpose of this paper to describe the domaining process in full detail. Rather, the authors emphasise the importance of a systematic approach to understand data reliability and variability.

4.1 Classification systems

Using consolidated geotechnical logging data, rock mass classification system indices (values) are calculated for each geotechnical interval.

Several rock mass classification system indices can be calculated for each interval (where the required input parameters are available), as detailed in the following sections. For open pit studies, Bieniawski's RMR (RMR_{89}), Laubscher's RMR (RMR_{90}), and GSI are commonly used. For underground rock masses, Q and GSI are most commonly used, with RMR_{89} used as a supporting classification system.

4.1.1 *RMR₈₉ (Bieniawski 1989)*

RMR₈₉ values are calculated from the following geotechnical parameters: IRS, RQD, joint spacing (Js), joint condition, and groundwater.

4.1.2 *RMR₉₀ (Laubscher 1990)*

RMR₉₀ values are calculated from the following parameters: either option A (IRS, fracture frequency per metre (ff/m), and joint condition) or option B (IRS, RQD, joint spacing and joint condition).

4.1.3 *Mining rock mass rating*

To simulate the response of a rock mass in a mining environment, percentage adjustments are applied to RMR values to obtain mining rock mass rating (MRMR) values. Using the MRMR classification (Laubscher 1990), as adapted for slope design (Haines et al. 1991), provides a means to assess indicative overall slope angles.

4.1.4 *Geological strength index*

Hoek (1994) and Hoek et al. (1995) introduced the GSI as a tool for collecting field information. The GSI classification was set up to address the two principal factors considered to have important influences on the mechanical properties of a rock mass: the structure (or blockiness) and the condition of the joints.

GSI can be used to estimate the Hoek–Brown constants m_i and s , and these are defined by the Hoek and Brown criterion. GSI can be used to derive uncertain parameters from empirical equations given by Hoek et al. (2013).

4.1.5 *Q' index (Norwegian Geotechnical Institute 2015)*

The Q-system expresses the quality of the rock using a logarithmic scale, on which design and support recommendations for underground excavations can be based. Q' (Q prime) describes the rock mass in terms of the joint spacing, number of sets and defect roughness, and infill or alteration.

4.2 *Domaining process*

Following the data validation stage is the domaining process, which involves data interpretation. The data collected in the field from different sources are collated, validated, and interpreted to define the geotechnical model. This model is an amalgamation of the structural, geological, hydrogeological, and rock mass models. Typically, the level of confidence associated with each component varies. Depending on the project stage and geotechnical environment, the relative importance of each component also varies.

During the domaining process, data reliability and variability need to be assessed. To produce a robust dataset, various scenarios should be tested and compared.

Data reliability should be assessed by asking some key questions, assuming logging data validation was undertaken:

- Should drillholes with a low volume of original logging data be incorporated in the assessment?
- Should the data from such drillholes be incorporated with or without the assumptions made?
- How much do the rock mass indices vary with and without consideration of the assumptions made to replace the original missing parameters?

Data variability raises another series of questions:

- Which drillholes should be used for the characterisation of underground infrastructure or for analysis of a particular pit wall?
- Should the data be domained geographically, or just by main rock type or weathering?

- Should this specific unit be treated as a separate lithology/domain?
- Is this unit weaker than, or behaving differently to, the broader rock type?
- Should this highly permeable or highly altered zone or this major structure be domained separately in any numerical analyses?
- Is there an actual 3D shape interpretation for this unit or for this major structure to use as a material boundary in any numerical analyses?

To answer these questions, the data need to be analysed considering different scenarios or datasets. Then, by comparing the rock mass classification values for each scenario tested, final domains can be defined.

Once rock mass domains are defined, properties are derived for each domain based on the logging data analyses and laboratory testing results.

4.3 Rock mass model

4.3.1 *Intact rock strength*

Intact rock is defined as rock that contains no apparent structural defects. The IRS may be assessed based on the FES, laboratory UCS tests, and PLT results. The FES values are determined for an interval during logging, while PLT and UCS data are measured for individual samples (i.e. they are point data). Based on the FES, UCS, and PLT values, a suitable single IRS value may be selected using engineering judgement for the assessed material.

Length-weighted mean values should be determined for the FES. Length-weighted means are calculated by multiplying the representative value (in this case the FES) for each interval by the interval length, summing these values for all intervals, and then dividing the sum by the total length of all intervals.

Challenges are encountered in the characterisation of the IRS, especially for anisotropic rock masses.

- The FES can be wrongly assessed on site by the logger. While there are ISRM field test guidelines available for the logger, the descriptions are not always suitable for some rocks, such as for anisotropic rocks (see Section 2.8.2.1).
- Samples can break along foliation planes, resulting in low UCS values that are not representative of the IRS. Those UCS values may need to be discarded for direct use in assessing the input properties for stability analyses.
- Regarding PLT, correlation factors (see Section 2.6) may not always be reliable for obtaining corresponding UCS values, for the same reasons as explained earlier.

4.3.2 *Defect shear strength*

Discontinuity shear strength is needed for discrete structures that could have an impact on slope stability. The shear strength of the bedding planes may be critically important, especially when the stability of pit walls is expected to be structurally controlled by bedding planes within banded rock. Defect characteristics such as surface roughness, infill type, infill thickness, and joint alteration control discontinuity shear strength.

These parameters recorded during field logging should be analysed for all stratigraphic units, differentiating certain stratigraphic units. Typically, the joint roughness coefficient and the joint wall compressive strength data are summarised for use in Barton–Bandis analyses to estimate the shear strength of discontinuities with the use of a suitably constructed tilt table.

In the first instance, shear strength parameters can be determined:

- Directly from laboratory DST and saw cut testing.
- Semi-quantitatively via a combination of laboratory testing and discontinuity logging parameters.

The Mohr–Coulomb and Barton–Bandis criteria are widely used to estimate discontinuity shear strength.

4.3.3 *Rock mass shear strength*

Rock mass shear strength parameters can be determined using different failure criteria.

4.3.3.1 *Hoek–Brown criterion*

The generalised Hoek–Brown failure criterion for rock masses is widely accepted and used around the world (latest version is Hoek & Brown 2019). It is typically applied to characterise stronger discontinuous rock masses. Consequently, it is only applicable to consideration of larger inter-ramp slopes and overall pit slopes. Input parameters for the generalised Hoek–Brown criterion are as follows:

- Intact rock properties, comprising UCS and material constant for intact rock (m_i).
- Broken rock parameters, comprising GSI and disturbance factor (D).
- Maximum horizontal stress.

Yet, there are challenges associated with this criterion on the selection of appropriate values.

How to select appropriate GSI values

The primary option is to use the RMR₈₉ classification converted to GSI (RMR-5) for rock mass ratings greater than 23 (Hoek & Brown 1997). On occasion, it may be possible to estimate the GSI from high-quality core photographs.

Another option is to rearrange the correlations suggested by Hoek et al. (2013) based on the RMR₈₉, Q, measured RQD, and joint conditions ($GSI = 1.5 JCond_{89} + RQD/2$).

How to select appropriate m_i values

One of the challenges for engineers is choosing appropriate m_i values. It is not the purpose of this paper to discuss the selection of meaningful values. Three methods are commonly used for estimating the Hoek–Brown constant m_i : regression analysis, guidelines, and the R index. The choice of method depends on the quantity and quality of data. If no data are available, literature values (Cai 2010) should be adopted with care.

How to select appropriate D values

The disturbance factor (D) reflects the effect of relaxation and blasting on the slope. Guidance for selection of an appropriate D value should follow the guidelines by Hoek (2012).

4.3.3.2 *Mohr–Coulomb criterion*

For weaker materials such as detrital materials, for which the Hoek–Brown failure criterion is not considered applicable, the Mohr–Coulomb criterion is usually applied and triaxial test results are used to derive the Mohr–Coulomb strength parameters (c and ϕ).

4.3.3.3 *Other empirical criteria*

Other criteria such as the Call et al. (2000) approach is not recommended due to being poorly adopted in the international mining sector and their complex data requirements.

5 Conclusion

Data validation is essential because design confidence relies on the properties derived from analysis of various types of acquired data. There are no shortcuts that replace working systematically through robust validation and detailed domaining processes to ensure the reliability and variability of data are well

understood. Breaking this daunting task down into manageable steps and asking key questions about the data makes it a more sustainable and rewarding task.

Acknowledgement

The authors are grateful to the many current and former colleagues who have participated in interesting discussions on the validation of geotechnical data issues over the years. They are too many to list individually, but cover the full spectrum of industry, consulting, and university. They are all known and appreciated.

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