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# INTEGRATING HEALED INTRABLOCK ROCKMASS STRUCTURES INTO GEOTECHNICAL DESIGN

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**Abstract:** In modern rock engineering projects such as civil base tunnels and base metal mines featuring particularly deep underground excavations and large open pit slopes, effective geotechnical characterization of the rockmass is critical to the initial excavation and ground support design, and to the accurate prediction of rockmass behaviour throughout project development. Many modern projects around the world are being excavated through complex rockmasses that contain healed intrablock rockmass structures, which occur within fracture-bounded blocks of otherwise-intact rock and influence rockmass deformability and strength. Intrablock structures are not conventionally considered during geotechnical characterization and analyses in rock engineering projects. However, in particularly deep excavations at high stress, these structures have been observed to control additional or delayed development of ground failures, through what is traditionally considered to be intact rock, or a predictable, naturally-fractured rockmass. This paper will discuss methods to integrate intrablock rockmass structures into various stages of geotechnical design of deep excavations in complex rockmasses. These stages include (i) site investigation and field data collection from outcrops and drill core; (ii) laboratory testing for both mineralogy assessment at hand sample, millimeter-, and micrometer-scales as well as geotechnical intact compressive, intact tensile, and discontinuity direct shear tests; and (iii) numerical modelling with options for continuous and discontinuous methods.

## 1 Introduction

In modern rock engineering projects such as civil infrastructure base tunnels and base metal mines featuring particularly deep (>500 m) underground excavations and large open pit slopes, effective geotechnical characterization of the rockmass is critical to the initial excavation and ground support design, and to the accurate prediction of rockmass behaviour throughout project development. Base tunnels are being constructed to expand civil transportation and irrigation infrastructure through major mountain ranges such as the Andes in South America. Large-scale open pit and block cave mining methods are popular approaches to exploit large orebodies due to the high projected global supply and demand forecasts, increased production rates, and improved worker safety.

Modern geotechnical design of these projects typically incorporates field examination of rockmasses, preliminary assessment using conventional rockmass classification systems, laboratory analyses of mechanical properties, and numerical simulations to predict ground behaviour and investigate detailed ground support options. Various suggested methods and guidelines have been developed for these design stages in conventional rockmasses that are composed of blocks of intact rock that are bound by natural fractures such as joints, bedding, and foliations. Many modern tunnelling and mining rock engineering projects, however, are now being developed in more complex rockmasses that contain healed intrablock rockmass structures, such as hydrothermal veins and stockwork, within blocks of intact rock (Figure 1). Intrablock structures influence rockmass deformability and strength, but are not conventionally considered during geotechnical characterization and analyses in rock engineering projects. However, in particularly deep excavations at high stress, these structures have been observed to control additional or delayed development of ground failures, through what is traditionally considered to be intact rock, or a predictable, naturally-fractured rockmass. With design practices for conventional rockmasses being applied to these complex rockmasses at great depths, occurrences of unexpected ground failures require additional ground support on a reactive basis, which increases the safety risk to workers as well as project excavation and ground support costs. As excavations continue to go deeper, fractures will have less influence on rockmass behaviour, but intrablock structures have no depth limit and will have increasing effects on stability, safety, and mine economics.

Inaccurate rockmass characterization that leads to inadequate ground support has been documented to increase worker safety risk related to ground failure. For example, from 2000-2014, 45 fatal injuries occurred in Ontario, of which 8 (18%) were caused by fall of rock (MOL 2015). While the number of injuries associated with rock falls has decreased since the mid-1900s with improvements to excavation and ground support (MOL 2015), significant work remains to achieve a zero harm workplace.

Figure 1: Drill core from Chilean porphyry and Canadian magmatic ore deposits with various infill-wall rock contact qualities of intrablock structure; (a-b) strengthening welded quartz veins; (c) healed and broken gypsum veins; (d) sulphide veins (pyrite, chalcopyrite) with quartz alteration halo; (e) epidote vein that broke during drilling; (f) weak swelling clay infilling that expanded with water application during core logging

This paper discusses multiple methods that are available to integrate intrablock rockmass structures into various stages of geotechnical design of deep excavations in complex rockmasses. These stages include (i) site investigation and field data collection from outcrops and drill core; (ii) laboratory testing for both mineralogy assessment at hand sample, millimeter-, and micrometer-scales as well as geotechnical intact compressive, intact tensile, and discontinuity direct shear tests; and (iii) numerical modelling with options for continuous and discontinuous methods. A workflow of these stages is presented in Figure 2 and is discussed in the following sections.

Geological characterization of intrablock structures is already a standard part of ore deposit characterization for mining, and the process to define geological units and models, mineral occurrences, and alteration histories are documented in the literature (e.g. Sinclair 2007). Such geological characterization practices are necessary to include in geotechnical characterization of complex rockmasses. Classic empirical geotechnical design of mines using the Mining Rock Mass Rating, MRMR (Laubscher and Jakubec 2001), considers the effect of veins on stability and fragmentation using vein frequency and Mohs' hardness. To move beyond empirical design and into numerical based design that can accommodate the variable nature of complex rockmasses, however, MRMR and other empirical classifications do not provide enough data to fulfill the input parameter requirements of numerical models. For this, measurements of geotechnical and geometric properties of intact rock as well as interblock and intrablock rockmass structures from both site investigations and laboratory experiments are needed.

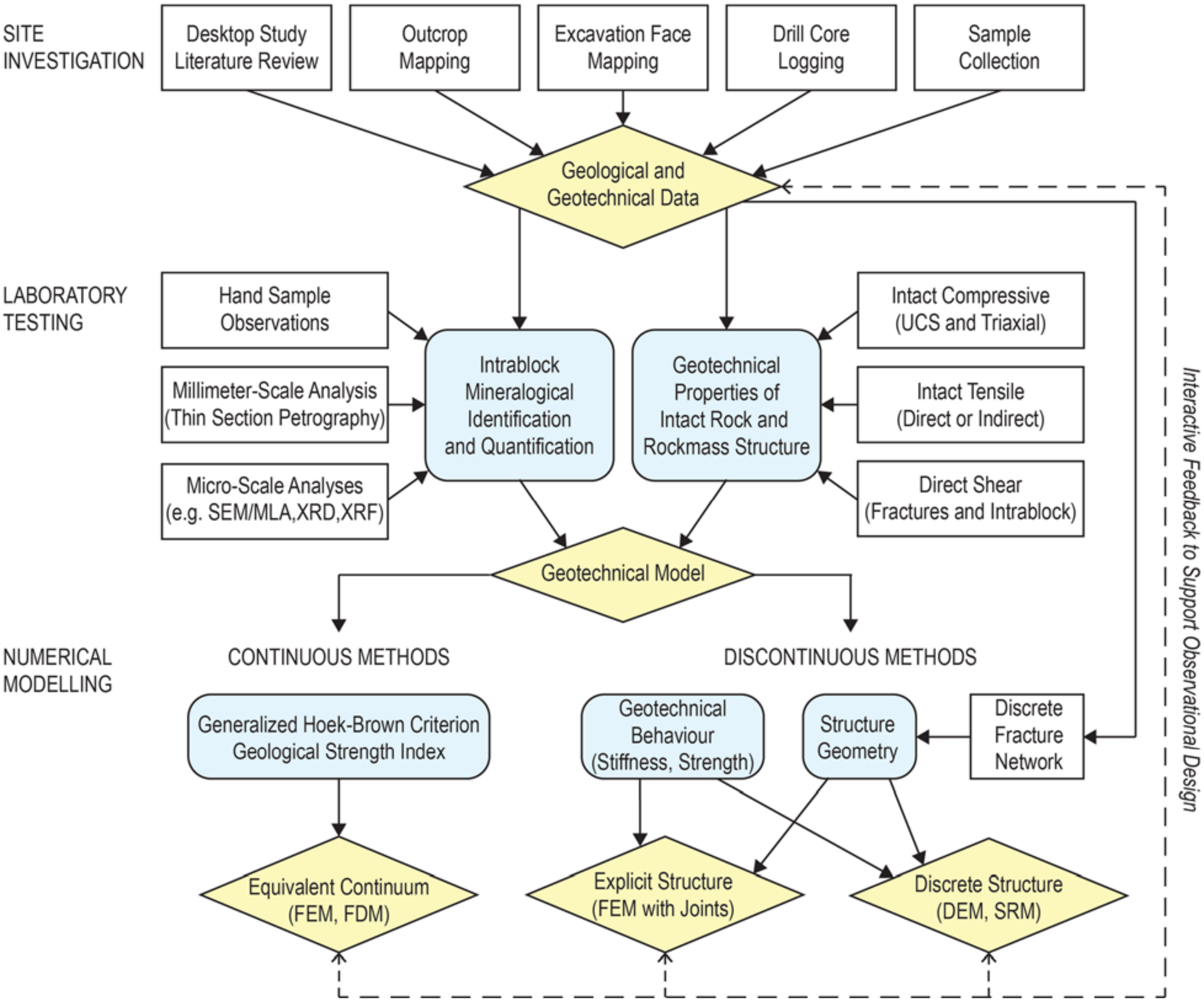


Figure 2: Workflow of data input and analyses for numerical geotechnical design of excavations in complex rockmasses that contain healed intrablock rockmass structures

## 2 Site Investigation and Field Data Collection

Many conventional site investigation programs are designed to collect data through the lens of empirical classification parameters; however, this does not satisfy the input parameters needed for a sophisticated numerical approach. Particularly for block cave mining, the collection and use of high-quality geotechnical data and accurate prediction of fragmentation have recently been highlighted as two significant challenges in industry (Chitombo 2010). Improvements to numerical geotechnical design must begin with effective site investigation and field data collection programs.

The Geological Strength Index (GSI) (e.g. Hoek et al. 2013) and the Generalized Hoek-Brown strength criterion (Hoek et al. 2002) continue to be effective methods to assess conventional rockmasses comprised of intact rock and interblock structures (traditional fractures such as joints and bedding). GSI is designed to characterize and quantify rockmass quality, in terms of joint condition and configuration of structure, during field observations at rock outcrops, excavation faces, and drill core. To characterize complex rockmasses at the field rockmass scale, the Composite GSI (CGSI) methodology (Figure 3) can be used to evaluate complex rockmasses that contain multiple suites of rockmass structure (Day et al. 2017). Adapting GSI to complex rockmasses retains the benefits of the system that enable calculation of parameters for the Generalized Hoek-Brown criterion that can be input directly into numerical models.

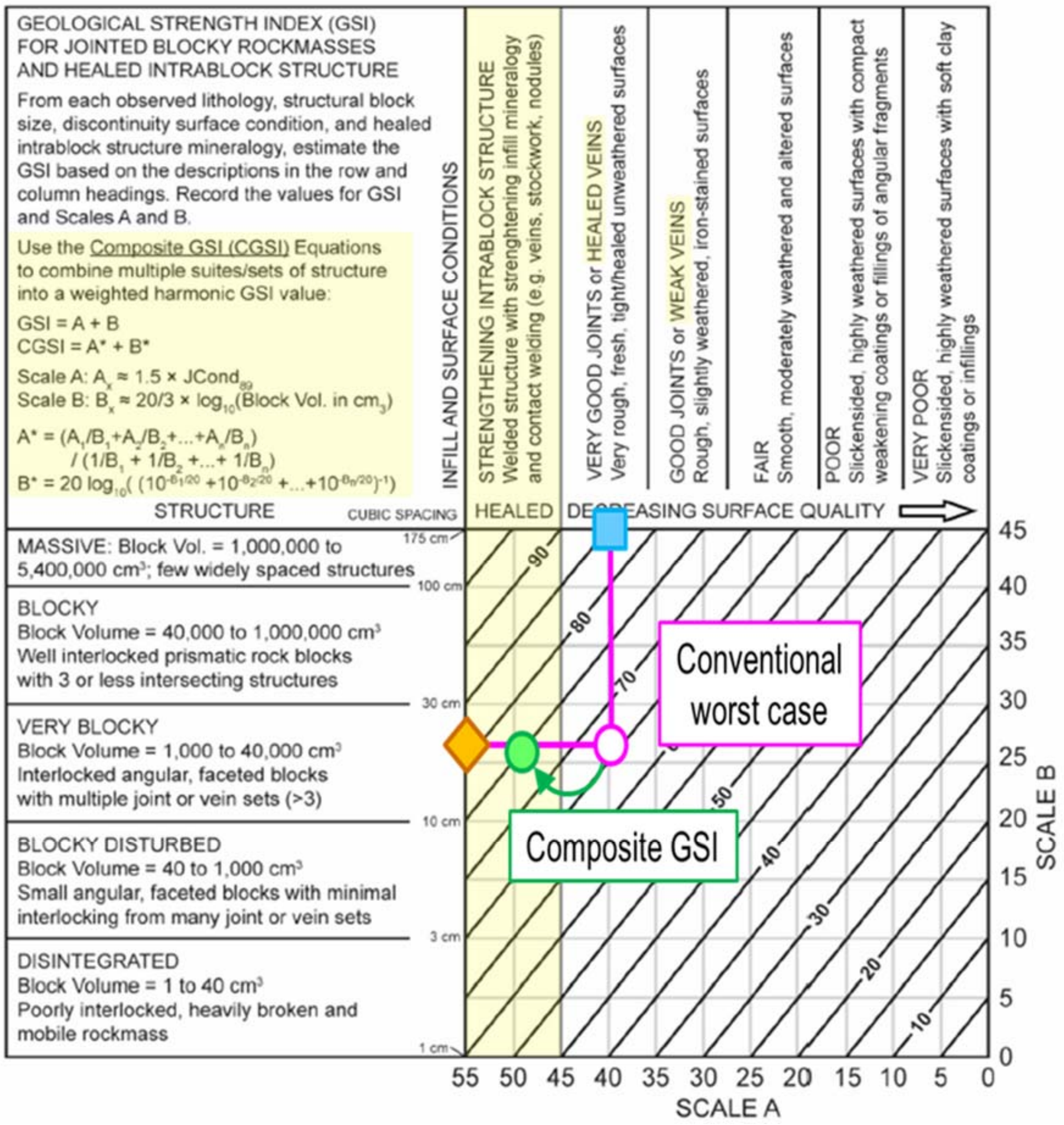


Figure 3: Geological Strength Index (GSI) chart and CGSI equations for complex rockmasses that contain intrablock structures (after Day 2016) including an example of combining two suites of rockmass structure (blue square, orange diamond) into conventional (worst-case) and CGSI (green circle) values

Geotechnical drill core logging is a ubiquitous and essential means of data collection for mines and tunnels. The nature of data collected for conventional geotechnical consideration is often directed by inputs to empirical classification systems such as Q (Barton et al. 1974) and RMR (Bieniawski 1989). At the time when these systems were introduced, no practical numerical tools for routine use were available, so design relied on an empirical process. Now for numerical design, and especially for excavations in complex rockmasses, additional data should be collected from drill core (Table 1) (Day et al. 2015a).

Sample selection guidelines for geotechnical laboratory tests of intact rocks were initially developed using homogeneous rocks devoid of any flaws, micro-defects, or intrablock structure (e.g. Westerly Granite, Indiana Limestone, and Carrara Marble), to capture the best available intact matrix rock quality. The ISRM (1979) even suggests maximum acceptable mineral grain sizes. In heterogeneous rocks rich with stockwork vein networks, these conditions are practically impossible to achieve, especially for a suite of tests that captures any statistical property distribution. The development of sample selection protocols are an area of active research by the author. Furthermore, in the context of diamond borehole drilling for drill core, many samples are selected on an ad hoc basis, driven by experience and intuition of the practitioner. While this may be a successful practice for homogeneous rocks, the variability of heterogeneous rocks requires structured selection protocols, which is also a topic of ongoing research by the author.

Table 1: Geotechnical parameters available from field observations for complex rockmasses (Day et al. 2015a)

| Parameter | Outcrop & Excavation Face Mapping | Drill Core Logging |
|---|---|---|
| CONVENTIONAL INTERBLOCK ROCKMASS STRUCTURES | | |
| Rock Quality Designation (Deere et al. 1969) | In multiple orientations | Parallel to core |
| Fracture frequency | In multiple orientations | Parallel to core |
| Joint roughness | X | X |
| Joint alteration | X | X |
| Joint infilling/gouge | X | X |
| Barton-Bandis joint shear strength criterion (Barton and Bandis 1990) | | X |
| INTRABLOCK STRUCTURES | | |
| Block size | X | X |
| Mineralogy | X | X |
| Thickness | X | X |
| Alteration halo | X | X |
| Mohs’ hardness | X | X |
| Orientation of all structures | X | Relative to core axis if unoriented core;<br>real orientation if oriented core |

## 3 Laboratory Testing

The laboratory testing components needed to develop a geotechnical model of complex rockmasses with intrablock structures include both mineralogical identification and quantification of intrablock structures and geotechnical property testing. Evaluating intrablock mineralogy may include measurements at hand sample scale, millimeter-scale thin sections, and micro-scale thin sections and powdered rock. Geotechnical property testing includes evaluation of the intact rock in unconfined compression, axisymmetric triaxial compression, and tension, which may include varying behaviour that is controlled by either failure through the rock matrix grains, failure through intrablock structure(s), or both. Direct shear testing can be used to measure geomechanical properties of interblock structures and intrablock structures.

### 3.1 Mineralogical Identification and Quantification of Intrablock Structure

The geomechanical behaviour of intrablock structures is primarily controlled by healed infill mineralogy and geometrical properties. Therefore, it is essential to conduct geological characterization of these structures in order to effectively integrate them into geotechnical design. Mineralogy identification and quantification can be conducted at multiple scales, including hand sample observations, millimeter-scale analyses using thin sections, and micro-scale analyses. The type(s) of analyses that are needed depend on the mineral grain compositions and grain sizes. A hand lens (typically 10-30x magnification), streak plate, and knife are effective tools to determine mineralogy and hardness at the hand sample scale. Thin sections are needed for millimetre-scale petrographic observations using either transmitted or reflected light microscopes, or both. Micro-scale analyses can be conducted with Scanning Electron Microscopy (SEM) with Back Scatter Electron detection and Mineral Liberation Analysis (MLA) for elemental compositions, coupled with X-Ray Diffraction

(XRD) for bulk crystallographic mineral analysis of powdered rock. X-Ray Fluorescence (XRF) is available as portable equipment and can be used in the field directly on drill core. The results of all mineralogy testing can be integrated into geotechnical numerical models that can accommodate complex material geometries for laboratory scale calibration (Figure 4) into geotechnical parameters, which can then be up-scaled for use in numerical joint elements (Day et al. 2014).

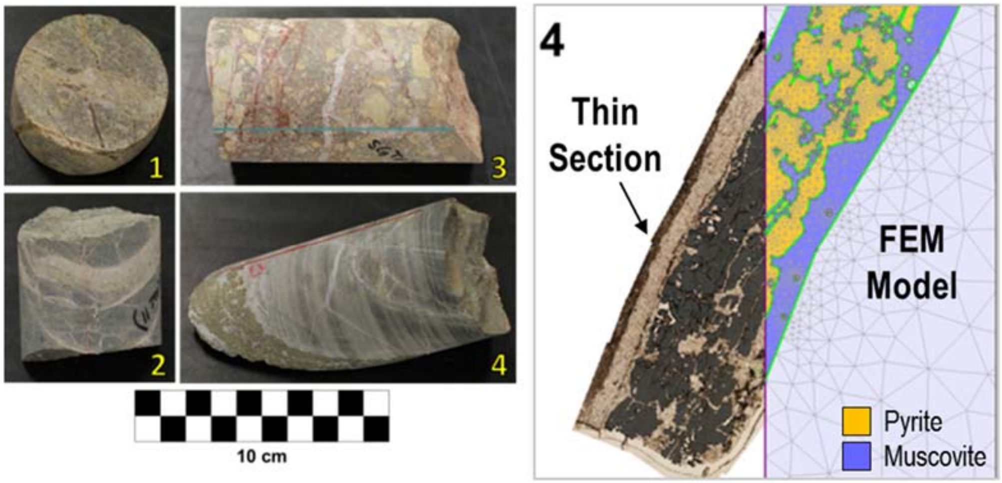


Figure 4: (left) Hand samples of rocks with intrablock structure; (right) Petrographic analysis of veins in thin section applied to FEM models for geomechanical property calibration (Day et al. 2014)

### 3.2 Geotechnical Laboratory Testing of Intact Rock and Rockmass Structures

In geotechnical laboratory testing programs for intact rock, the Hoek-Brown failure envelopes can be defined from a suite of Unconfined Compressive Strength (UCS) with axisymmetric triaxial and/or tensile test data (Hoek and Brown 1997). Several studies have explored effects of intrablock structures on laboratory tests, including UCS (Bewick et al. 2015), axisymmetric triaxial (Turichshev and Hadjigeorgiou 2016), and direct tensile (Jacobsson et al. 2012). These results focus on conventional parameters for deformation and strength (peak and residual). Ghazvinian (2015) highlights the importance of high-quality and consistent laboratory protocols for intact rock with variable results from homogeneous rocks tested at several labs, which emphasizes the need for rigorous evaluation and implementation of high testing standards for the heterogeneous and anisotropic rocks. It is important to select and test samples with varying amounts of intact mineral grain matrix and intrablock structures (at various orientations) to define the full stiffness and strength variability. This intact test data from UCS, triaxial, and tensile tests of complex rocks can then be sorted by failure mode, through the intact rock matrix versus structural failure through veins, and generate distinct failure envelopes (Figure 5). These appropriately sorted failure envelopes and associated Hoek-Brown properties can then be used for both continuous and discontinuous numerical modelling approaches.

Direct shear laboratory testing is used to measure geomechanical properties of discontinuities, including normal stiffness, shear stiffness, shear strength, and dilation. Some experimental work has been conducted on intrablock structures in direct shear (e.g. Day et al. 2017; Jacobsson et al. 2012). Normal stiffness is measured during the initial application of normal load, while shear stiffness is measured during the application of shear load before reaching maximum shear stress. Shear strength is typically evaluated using the Mohr-Coulomb strength criterion and considered for interblock structure in two components: peak and residual. The shear strength of intrablock structures has been expanded to a three-stage constitutive model based on Mohr-Coulomb parameters (tensile strength, cohesion, and friction angle): primary (pre-peak), secondary (immediately post-peak), and tertiary (ultimate, after continued shear displacement) (Figure 6) (Day et al. 2015). This development provides more effective input parameters to define the behaviour of intrablock structures in explicit and discrete numerical models. Dilation controls the post-peak opening behaviour of discontinuities and is expressed with a dilation angle measurement and, particularly for numerical models, a total dilation potential (Packulak et al. 2018).

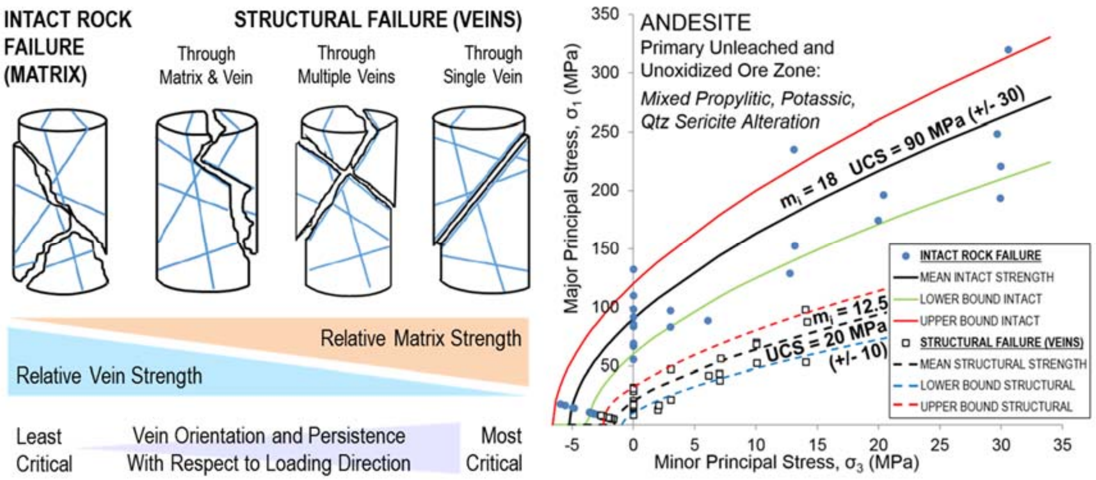
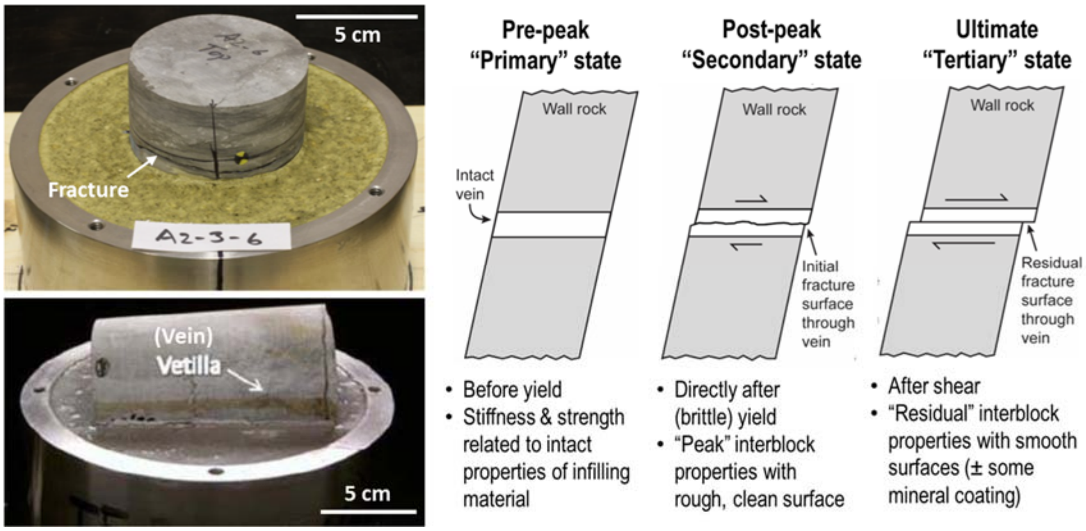


Figure 5: (left) Failure modes of complex rock UCS testing from intact matrix to intrablock structure; (right) Hoek-Brown strength criterion failure envelopes for an altered andesite in a porphyry copper deposit, with failures sorted through intact rock or weakening hydrothermal vein-type intrablock structure



- Before yield
- Stiffness & strength related to intact properties of infilling material

- Directly after (brittle) yield
- "Peak" interblock properties with rough, clean surface

- After shear
- "Residual" interblock properties with smooth surfaces (± some mineral coating)

Figure 6: Photos of direct shear samples to test: (top left) open joint fracture (Day 2016) and (bottom left) hydrothermal vein (de los Santos Valderrama 2011); (right) description of expanded three stage constitutive model using Mohr-Coulomb parameters for shear strength of intrablock structure, including primary (pre-peak), secondary (immediately post-peak), and tertiary (ultimate) stages (Day et al. 2015)

## 4 Numerical Modelling

Numerical methods in geomechanics range between purely continuum and discontinuum approaches (Figure 7). Purely continuum methods (e.g. Boundary Element Method, BEM) represent the problem using homogeneous materials that implicitly incorporate rockmass structure through the stiffness properties and strength criterion of the material (Crouch and Starfield 1983). Purely discontinuum methods (e.g. Particle Flow Code, PFC) discretely model all discontinuities and boundaries within the problem (Itasca 2008). Several intermediate methods can model rockmass structures both implicitly and explicitly (or discretely), such as Finite Difference Method (FDM), Finite Element Method (FEM) (e.g. RS2 by RocScience 2015), and Discrete Element Method (DEM) (e.g. UDEC and 3DEC by Itasca (2014; 2016)), and this flexibility makes them popular tools for modelling at the excavation scale. Greater amounts of explicit or discrete structures are more computationally demanding; therefore, there are scale and complexity limitations with present day computation capacities that are addressed by optimizing relative proportions of implicit and explicit rockmass structures (Day 2016). An example of equivalent implicit and explicit models of a rockmass at the excavation scale is illustrated in Figure 8. General input parameters that are required for implicit (continuum) and explicit or discrete (discontinuum) models are listed in Table 2.

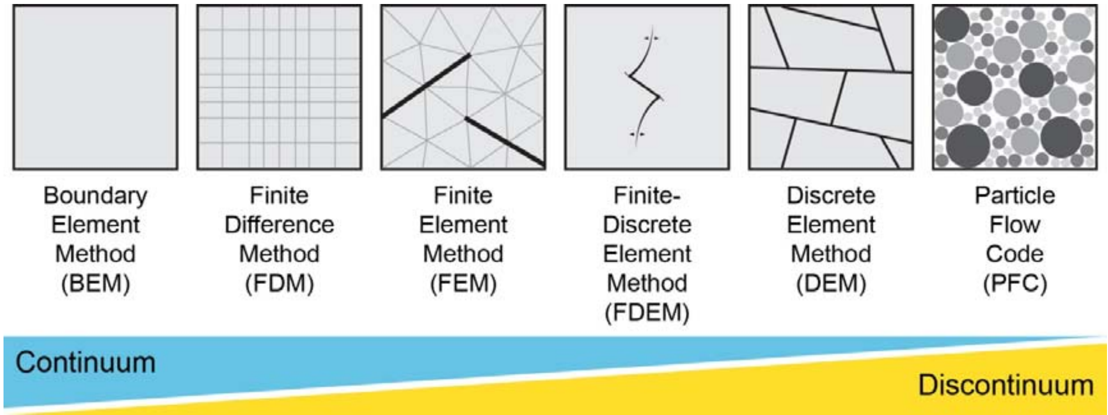


Figure 7: Range of numerical methods used in geomechanics from continuum to discontinuum codes

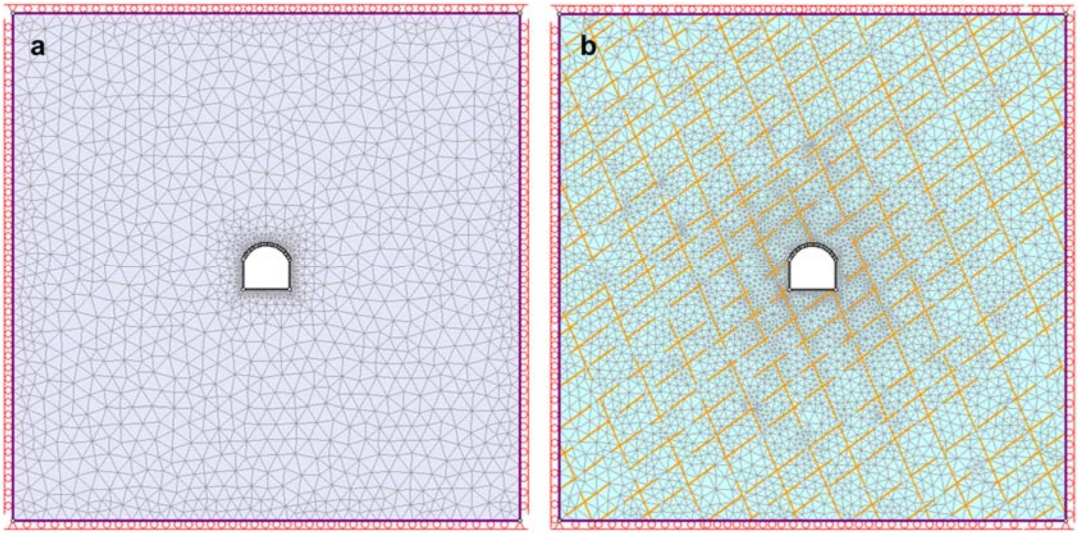


Figure 8: FEM models of a 6 m diameter excavation; (a) equivalent continuum material with implicit rockmass structure (structure accounted for by reduction of strength using GSI); (b) explicit rockmass structure with 2 sets of structure where the material represents intact rock

Table 2: General numerical input parameters using Generalized Hoek-Brown and Mohr-Coulomb criteria

| Parameter | Continuum (FEM, FDM) | Discontinuum (FEM, DEM, SRM) |
|---|---|---|
| Intact stiffness (e.g. Young's Modulus, Poisson's Ratio) | X | X |
| Intact rock strength (UCS, Tensile Strength) | X | X |
| Hoek-Brown intact material parameters ($m_i$, s, a) | X | X |
| Geological Strength Index value of rockmass quality to calculate Hoek-Brown rockmass material properties | X | Sometimes (depends on scale of DFN) |
| Normal stiffness, shear stiffness, and shear strength properties (in Mohr-Coulomb parameters) of rockmass structures (interblock and intrablock) |  | X |
| Geometry of structures (interblock and intrablock) |  | X |

Synthetic Rock Mass (SRM) tools (Mas Ivars et al. 2011) are currently the state-of-art for discontinuous geomechanics modelling with multiple suites of rockmass structures. SRM integrates modelling of intact rock (e.g. using PFC) with structure geometries generated using Discrete Fracture Networks (DFNs) and associated geomechanical properties (Elmo et al. 2014). DFN and SRM developments have been applied to block caving (Vallejos et al. 2016) and deep seated open pit slope stability (Dershowitz et al. 2017). It is, however, important to note that recent lessons learned by engineering practitioners from design and construction of excavations using SRM models recommend the emphasis of design be returned to collecting useful, site-specific data, in order to adequately define the design problem, before rushing into a sophisticated modelling exercise (Carter 2015). Adequate site investigation and laboratory testing, as discussed in this paper, are therefore necessary to move from models dominated by statistical analyses to models that are anchored by site-specific observations and measurements.

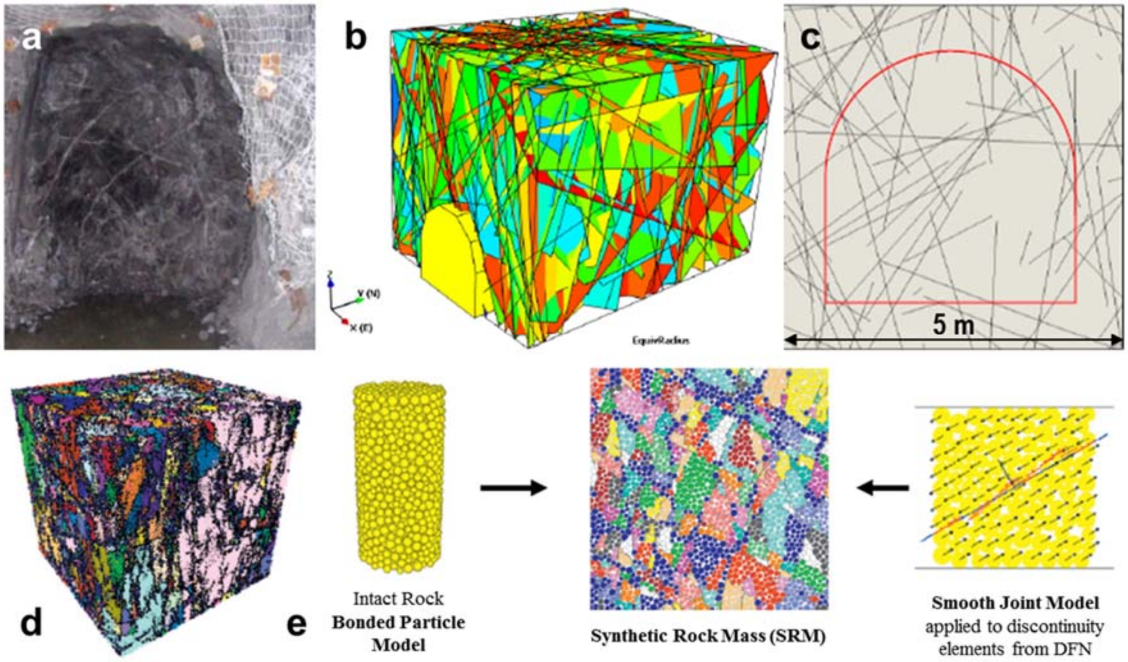


Figure 9: Discontinuous numerical modelling; (a) photo of vein intrablock structure network in an excavation, (b) 3D Discrete Fracture Network (DFN) representing vein network, (c) 2D slice of DFN superimposed on a cross section of an excavation simulation (Brzovic et al. 2015); (d) 3D Synthetic Rock Mass (SRM) sample, (e) SRM components into a 2D slice of a SRM model (Mas Ivars et al. 2011)

## 5 Conclusions

A numerical approach for geotechnical design of excavations in complex rockmasses is significantly more effective than empirical or analytical methods, since numerical codes can adapt to the variability present in complex rockmasses and excavation geometries. To ensure numerical models adequately capture and predict complex rockmass behaviours, the observation and measurement of geomechanical and geometrical input properties must be strongly supported by field observations and laboratory testing of geological and geotechnical parameters. The workflow of data input and analyses discussed in this paper presents a structured methodology to integrate the complexity of intrablock structures, while in particular highlighting the importance of mineralogy, into geotechnical design.

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