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Application of Synthetic Rock Mass modeling to veined core-size samples

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ABSTRACT

Rock masses of the primary copper ore at the El Teniente mine fail mainly through the infill of preexisting veins during the caving processes, especially through those composed of less than 35% hard minerals (quartz and pyrite). In this study, the Synthetic Rock Mass (SRM) approach is used to reproduce the results of ten uniaxial compression tests on veined core-size samples of El Teniente Mafic Complex (CMET) lithology, from El Teniente mine, Codelco-Chile. At the scale of the tested samples it is observed that veins composed mostly of quartz dominate the failure process. The developed methodology considers generating a deterministic Discrete Fracture Network (DFN) based on the veins mapped at the surface of each core sample. Then, the micro-parameters of the Bonded Particle Model (BPM) are calibrated to represent the macro-parameters of the average block of intact rock within all samples. Next, the micro-parameters of the Smooth-Joint Contact Model (SJCM), which represent the mechanical properties of veins, are calibrated to reproduce the stress–strain curves and the failure modes of the veined core-size samples measured during the laboratory tests. Results show that the SRM approach is able to reproduce the behavior of the veined rock samples under uniaxial loading conditions. The strength and stiffness of veins, as well as the vein network, have an important impact on the deformability and global strength of the synthetic samples. Contrary to what was observed in the laboratory tests, synthetic samples failed mainly through weak veins. This result is expected in the modeling given that anhydrite veins are considered weaker than quartz veins. Further research is required to completely understand the impact of veins on the behavior of rock masses.

1. Introduction

Discontinuities are structural breaks characterized by their geometry and strength properties, which may or may not impact the rock block and rock mass strength. In the case of El Teniente mine, the largest known copper–molybdenum deposit in the world,[1] discontinuities recognized within the primary copper ore are mainly widely spaced faults[2] and a stockwork formed of a high frequency network of small veins characterized by an intermediate to high tensile strength.[3,4] Therefore, rock masses of the primary copper ore at the El Teniente mine can be conceived of as an assemblage of intact rock blocks bounded by veins.[5] Traditional rock mass classification systems are not well suited to represent these rock masses,[3] mainly because these methodologies consider mainly open joints[6–8] and do not take into account the multiple mineral ensembles of the vein infill.[9] Furthermore, the ability of rock mass classification systems for considering strength anisotropy, scale effect, and post-peak response is limited. Numerical modeling can improve the understanding of the rock mass behavior and rock mass disassembly during caving propagation; therefore, improve rock mass characterization.[5]

The Synthetic Rock Mass (SRM) approach has been implemented in PFC^{3D} 4.0 software[10] and uses the interface SRMLab 1.7.[11] PFC^{3D} solves the problem by using the explicit formulation of the Distinct Element Method,[12] where particles are rigid spherical bodies joined by deformable contacts. The complex interactions among the particles define the macroscopic response of such an assembly. The input parameters cannot be measured directly with conventional laboratory tests. Therefore, a calibration process is required, that is, the micro-parameters are chosen to match the laboratory test response of the rock material. A trial-and-error approach is the basic way to define a suitable set of micro-parameters.[10]

The SRM technique can be used as a virtual laboratory to perform numerical experiments in order to represent in a qualitative and quantitative manner the mechanical behavior of a rock

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mass.[13–15] The main potential is to simulate fracture propagation and slip on discontinuities in a rock mass under selected loading conditions. The SRM method has been validated through comparison of micro-seismicity, fragmentation, and yielding in SRM samples with rock mass response observed in cave mining operations.[13,16] Other uses of the technique are related to study the effect of sample size on rock mass strength[15,17–19] and the derivation of equivalent rock mass properties.[20] Few studies have performed rigorous comparisons of SRM tests with well-documented laboratory tests. Existing studies in the area have only considered non-cohesive joints and weak intact rock.[21] These studies have concluded that the SRM approach is able to reproduce the UCS and failure mode of jointed samples under uniaxial loading conditions. Further improvement and validation are still required, especially under controlled conditions that can be easily simulated.

Several studies have been carried out by the El Teniente mine to estimate vein strength and stiffness[22–24] and their influence on the disassembly of the rock mass.[3] These studies enable to evaluate the ability of the SRM methodology to reproduce direct shear tests on chalcopyrite vein[25] and uniaxial compression tests including the explicit vein network of laboratory size samples.[26] Even though there is not enough evidence to validate the SRM technique with field cases, simulations of large-scale samples have been performed. These results are compared with estimations based on classification systems and other numerical model estimations [23,27–29].

The objective of this study is to apply the SRM technique to reproduce the behavior of laboratory scale samples from El Teniente mine (Codelco-Chile) under uniaxial loading conditions. Samples are from a veined rock mass, specifically El Teniente Mafic Complex (CMET) unit. This paper first reviews the main aspects and limitations of the components of the SRM modeling technique. Next, the input and validation data are presented, which are obtained from laboratory tests developed for this study and from the El Teniente mine laboratory tests database. Subsequently, Section 4 presents the procedure used to calibrate each component of the model, and how they are combined to calibrate the SRM sample. Finally, results from the calibration are presented and discussed. It is expected that these results provide a fundamental understanding of the behavior of veins in a synthetic sample, particularly with the purpose of its application to larger samples.

2. Synthetic Rock Mass (SRM)

The SRM model represents the intact rock as an assembly of bonded particles using the Bonded Particle Model (BPM),[30] and an embedded Discrete Fracture Network (DFN) in SRM samples to represent discontinuities. Each discontinuity is modeled explicitly using the Smooth-Joint Contact model (SJCM).[31] Fig. 1 shows the main components of a SRM sample. The following paragraphs present the main aspects and limitations of each model.

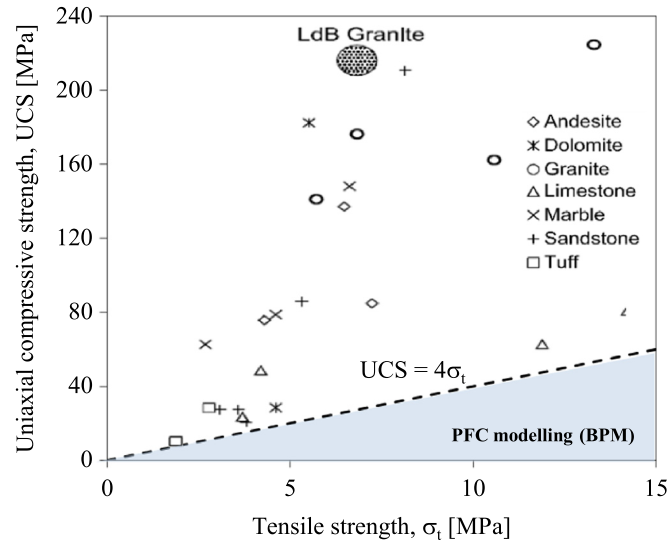

Fig. 2. Comparison between compressive strength and tensile strength for different rock types.[39]

Conventional PFC^{3D} modeling of intact rock considers the standard BPM,[30] which has two main limitations. First, the reproduced compressive to tensile strength ratio is lower than 4. Fig. 2 presents a summary of the uniaxial compressive and tensile strengths for different rock types,[32] indicating that PFC^{3D} could not represent them properly. Second, the failure envelope is linear providing friction angles lower than 30°. Some options to solve this problem are changing the particle size distribution, so the porosity is reduced,[33,34] or changing the particle shape by using clusters[30] or clumps.[35] New models have been created to overcome these limitations: an enhanced version of BPM[36] and the Flat Joint Model.[37,38] The present study uses the enhanced BPM, a parallel-bond refinement, to represent intact rock behavior.

In general, BPM represents the mechanical behavior of a collection of spherical grains joined by cement. The particle diameters satisfy a uniform particle size distribution bounded by D_{min} and D_{max}, where D_{max}/D_{min} controls the packing fabric. Two models characterize the BPM: the Particle Contact Model and the Parallel Bond Model. The first model is defined by the following micro-parameters: Young's modulus (E_c), ratio between normal and shear stiffness ($\frac{k^n}{k^s}$), density (ρ), and friction coefficient (μ), while the second model by: the normal strength ($\bar{\sigma}_c$), cohesion ($\bar{c}$), friction angle ($\bar{\phi}$), Young's modulus ($\bar{E}_c$), ratio between normal and shear stiffness ($\frac{\bar{k}^n}{\bar{k}^s}$), and radius multiplier parameter used to set the parallel-bond radius ($\bar{\lambda}$). The main differences between the standard and the enhanced BPM are in the Parallel Bond Model. The enhanced version considers that all loads are carried by the parallel-bond until it breaks, and then transferred to the contacts

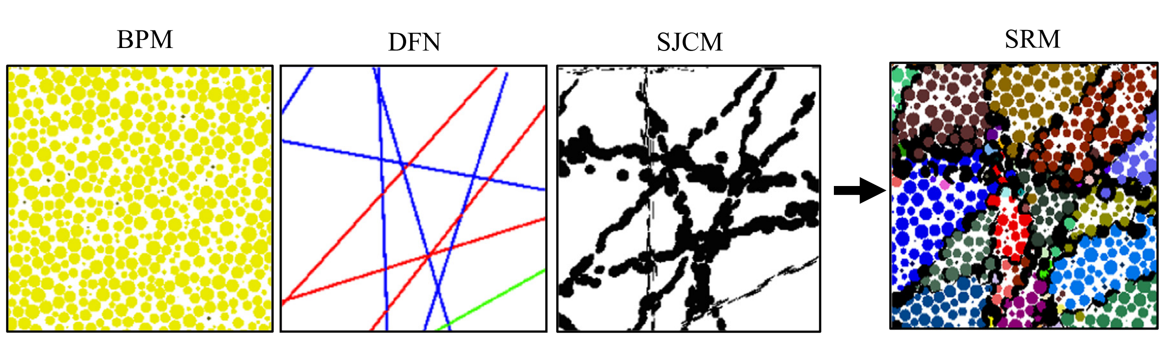

Fig. 1. Synthetic Rock Mass basic components.