Use of Synthetic Rock Masses (SRM) to Investigate Jointed Rock Mass Strength and Deformation Behavior

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ABSTRACT: A technique termed Synthetic Rock Mass (SRM) modeling has been developed to study the strength and deformation behavior of jointed rock in three-dimensions. It uses PFC3D to represent the intact rock as an assembly of bonded particles and an embedded Discrete Fracture Network to represent the joints as disc-shaped flaws. This new technique overcomes limitations in model size and joint representation that were present in earlier work and allows for rapid construction and testing of 10-100m diameter samples of moderately to heavily jointed rock containing thousands of non-persistent joints. The method has been used to estimate the pre-peak properties (modulus, damage threshold, peak strength) and post-peak properties (brittleness, residual strength, fragmentation) of rock masses and has been employed in the analysis of large-scale boundary value problems. This paper summarizes the results of studies performed to date and describes new research aimed at further validation and application of the technique.

Keywords: Synthetic Rock Mass

1. INTRODUCTION

A Synthetic Rock Mass (SRM) model has been developed to study the strength and deformation behavior of jointed rock in three-dimensions. It uses the Particle Flow Code in Three Dimensions (PFC3D) [1] to represent the intact rock as an assembly of bonded particles and an embedded Discrete Fracture Network to represent the joints. Unlike previous approaches, this methodology allows for consideration of large complex non-persistent joint network in three dimensions as well as block breakage that includes the impact of incomplete joints on block strength. The technique has been applied to the detailed analysis of rock mass strength and deformation behavior over a range of scales. This paper discusses some of the key computational developments behind the methodology, summarizes recent applications of the technique and outlines some areas for further research and development.

2. COMPUTATIONAL DEVELOPMENTS

Using the Bonded Particle Model (BPM) for rock [2] and similar schemes, it has been possible for some time now to simulate the mechanical behavior of intact rock in PFC and other DEM codes. Using these models as a basis, attempts have been made to synthesize jointed rock masses through selective debonding within the assembly [3,4]. As discussed in [4], the potential power of the approach is that a rich emergent material response can be derived from relatively simple particle contact laws at the rock and joints rather than more complex user-specified constitutive models. The technique suffered, however, from the use of selective debonding of particle contacts for joint representation, which resulted in overly rough and ñbumpyò joints, as well as computational constraints, which limited analysis to a relatively small number of joints in 2D.

Several recent key developments have allowed SRMs to overcome these limitations so that large-scale three dimensional rock masses with high joint density can be studied on a more routine basis. One of the most significant advances relates to the development of a new ñSmooth Jointò contact model in PFC for the simulation of joint planes within the bonded assembly. This model allows the user to specify the orientation of the contact between individual particles that will be used in the calculation of inter-particle forces (Figure 1). With this new model, macroscopic joints with a given dimension and orientation can be embedded within the assembly and can experience shearing in the manner of a smooth, frictional surface (Figure 2) without resorting to particle size refinement or particle relocation along the joint surface. It has been demonstrated that the model could be used to reproduce the extension and coalescence of multiple, isolated, embedded flaws observed in laboratory experiments [5]. A complete description of the Smooth Joint contact model can be found in [1] and [6].

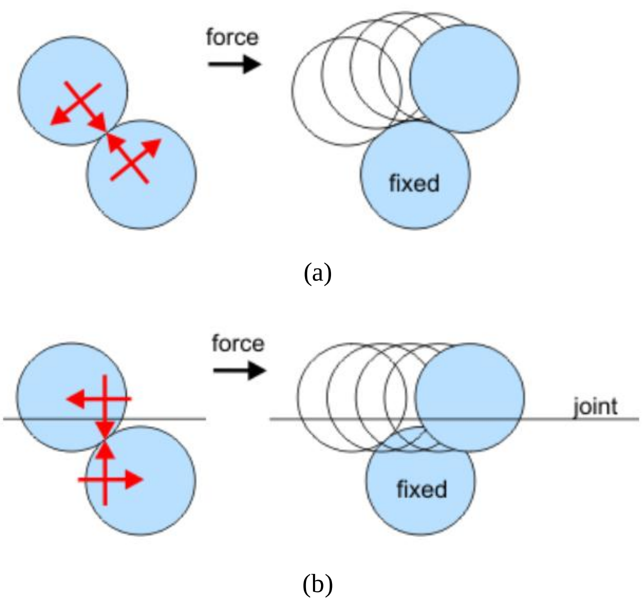

Fig. 1. Graphical representation of how the smooth joint contact model can be used to realign the default contact orientation (a) to one that honors a macroscopic joint orientation (b).

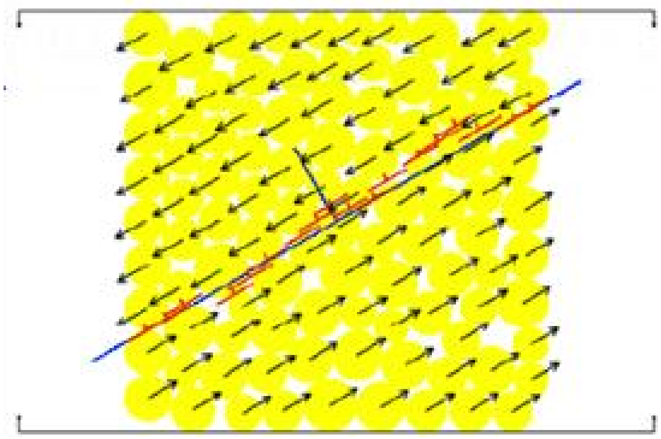

Fig. 2. By using the smooth joint contact model to reorient all contacts lying along the macroscopic joint plane, sliding along a smooth planar feature can be more accurately modeled.

When a dense joint network is embedded within the assembly of bonded particles using the Smooth Joint logic, the user must ensure that the particle size is sufficiently small to resolve slip on the joints and breakage of the intervening blocks of rock. The limiting factor (joint resolution or block resolution) depends on the character of the joint network bring embedded. In most rock masses, joint size (e.g. diameter) will be large relative to joint spacing and so block resolution becomes the limiting factor. For practical purposes, the average block dimension can be estimated by the inverse of the scanline or borehole fracture frequency. If five particles are desired across this average block dimension, then a million-particle cubical model will be approximately 20 blocks wide. As discussed in [7], this is likely to be near or above the Representative Elemental Volume (REV) for the rock mass. While smaller scales are often of interest, analysis of million-particle models at or near the REV requires approximately 3.5 GB of RAM in PFC3D, which is generally not available on 32-bit systems. This limitation is overcome in Version 4.0 of PFC, which supports a 64-bit architecture. (Actual memory requirements in PFC3D will vary depending on the model features present but a rough estimate in Bytes is given by multiplying the number of particles by 3400).

Million-particle models offer other challenges when trying to create and test Synthetic Rock Masses. These relate to the time required to achieve a dense initial packing of particles and to subject the model (with bonding and joints installed) to the desired stress or strain path. In order to speed up sample creation, we make use of the ñpbrickò feature available as part of the AC/DC (Adaptive Continuum/Discontinuum) Logic in PFC. A pbrick is simply a compacted, bonded assembly that may be replicated many times to construct a large model. The pbrick is derived (in a separate PFC3D run) by compacting an assembly of particles within periodic space and then storing it in compact form; copies of this assembly can then be fitted together perfectly, because the geometrical arrangement of particles on one side of a pbrick is the negative image of that on the opposite side. Using this approach, large models may be constructed very quickly because the pbricks are already compacted and in equilibrium. (Note that contact forces are also stored within the pbrick, and these automatically balance at the junction between two pbricks, if the original forces were in equilibrium). Details of the approach can be found in [1].

The time required to simulate testing of a large SRM model can also be prohibitive when using the traditional platen-based strain application schemes employed in PFC. With these techniques, strain rates must be set quite low to ensure pseudo-static conditions. This can result in very long solution times. To overcome this problem, an internal-based strain-application scheme was developed. With this scheme, all of the particles within the sample are displaced along with the platens to conform to a small increment of a user-defined strain tensor. Following this, the bounding walls are fixed, the particles are freed (with zeroed velocities) and the system is cycled to static equilibrium. This is repeated until the test is complete. Tests conducted to date suggest that order-of-magnitude decreases in solution time can be achieved without impacting material response, even for brittle jointed materials experiencing strain-softening (Figure 3). Details of the internal-based strain application scheme can be found in [1].

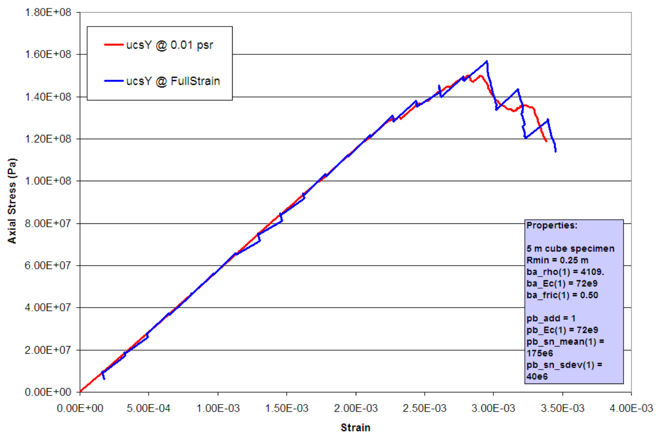

Fig. 3. A comparison of stress-strain behavior derived from a normal platen-based test on an SRM material versus one in which full strain logic is employed.

3. RECENT APPLICATIONS

3.1. Analysis of Sample-Scale Problems

The SRM methodology described here was first applied to analysis of the Lift 2 rock mass at Northparkes Mine in Australia [8]. The purpose of the testing was to quantify the strength and brittleness of four different lithologies and to estimate the block size distribution at residual strength. The densely jointed lithologies (scanline fracture frequencies of 4-5/m) were simulated with 12m diameter samples. The response of the SRMs during testing provided significant insight into the stages of failure, which involved joint slip on a subset of the dense joint network, growth and coalescence of new cracks and deterioration of the resulting fully-formed blocks under further straining. The samples also exhibited a sensitivity of strength, brittleness, modulus softening and block size distribution at residual strength to the intact strength of the bonded particle assembly, the smooth joint shear strength, joint orientation and expected stress path. Results of this testing are discussed in more detail in [8-10].

In parallel with the assessment of rock mass properties and fragmentation at Northparkes, the monitoring of joint slip and bond breakage within the SRM samples provided information on the likely seismic signature of the units. These responses have been compared with the actual seismic response of the rock mass as monitored during mining [11]. The orientations of pre-existing and induced fractures contributing to microseismicity in situ corresponded well with those predicted by the SRM testing, providing a practical means to validate the numerical approach.

By constructing SRM samples of differing size and subjecting them to standard stress paths, it has been possible to quantify the impact of scale on rock mass strength at Palabora Mine in South Africa. As expected, both the strength and modulus of the rock mass were found to decrease with increasing scale. Results of this work are documented in [7] and [12]. The anisotropy in rock mass strength has also been quantified by subjecting SRM samples to compression and tension in three different directions [12].

3.2. Analysis of Boundary Value Problems

It is possible to study very large boundary value problems with the SRM in two dimensions. [13] describes how a 2D SRM was used to isolate slope failure mechanisms in a large open pit mine slope. 2D joint trace maps were extracted from 3D DFNs in order to represent jointing and faulting in the 2D model (Figure 4). The model exhibited natural slope-failure mechanisms, including tension cracks along the surface and toppling in the upper pit walls that have been observed in reality.

Due to the fact that out-of plane joint truncations are not accounted for, the rock mass strength is likely to be underestimated within a 2D SRM model. In order to achieve a more accurate strength, joints lying sub-parallel to the plane of analysis can be removed from the DFN. A direct comparison of rock mass strengths derived from 2D and 3D sample SRM samples (employing the same DFN) was carried out by [14]. The analysis demonstrated that the 2D SRM was much weaker and that a significant number of joints had to be removed from the DFN for use in the 2D model in order to achieve similar strengths to the 3D SRM samples. For the particular case examined, all joints oriented within 80 degrees of the plane of analysis had to be removed to achieve strength equivalence between the 2D and 3D SRMs.

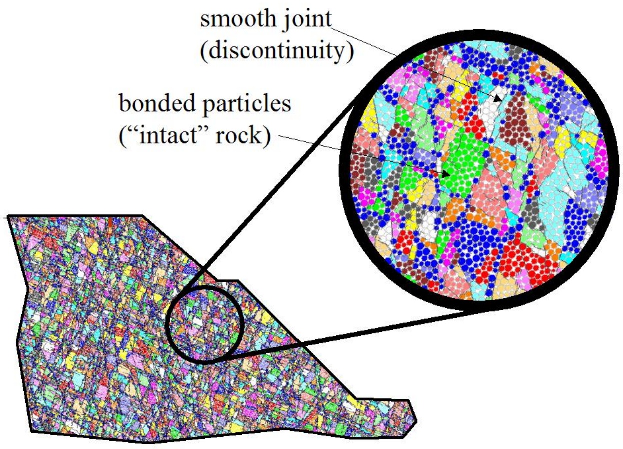

Fig. 4. A two-dimensional SRM model used to study slope failure mechanisms.

The application of 3D SRMs to large-scale (e.g. >100m) boundary value problems in densely jointed rock has been relatively limited to date. Computational constraints continue to restrict application of the technique to smaller-scale boundary value problems (e.g., [15]). Due to this constraint, a technique has been developed to calibrate the material behavior defined by SRM testing to a continuum constitutive model. The technique, based on ideas first developed by [16], involves the specification of a plane of weakness at the zone level in FLAC3D [17] (via the Ubiquitous Joint Model). By varying the orientation from zone to zone via random sampling of the true joint orientation distribution, it is possible to achieve a continuum model in 3D that honors the joint fabric. [18] and [19] describe how the matrix and joint properties comprising the model can be adjusted (based on lab properties as well as iteration) to achieve large-scale continuum representations of jointed rock that honor the rock mass properties (including associated scale effects and anisotropy) observed in SRM tests.

This process of carrying the intact strength and jointing through to the large-scale model is illustrated in Figure 5. The technique has been successfully applied to the back analysis of cave mining of the Lift 2 Mine at Northparkes and Lift 1 of Palabora Mine [19].

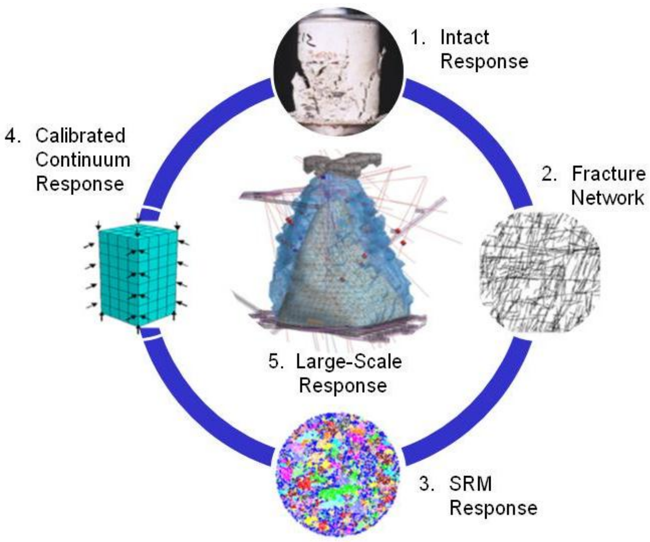

Fig. 5. Characterization of the large-scale response of a rock mass using the Synthetic Rock Mass approach combined with continuum modelling.

4. ONGOING RESEARCH

The SRM methodology is currently being applied to a number of new study cases (e.g., [20]) and this brings the opportunity for further development and validation. A number of new features are planned to be included in the near future.

The dilatancy exhibited by the jointed rock mass has not been measured in previous study cases. In future SRM applications the dilation angle will be monitored to help improve the understanding on the role of dilation on the pre-peak and post-peak behavior of jointed rock masses.

At present, fragment size distribution is estimated by converting the volume of each cluster to an equivalent spherical diameter. (A cluster is defined as a rock block within the SRM sample whose component particles can all be reached via one another through bonded contacts). Therefore, prediction of primary fragmentation has not taken into account fragment shape. It is planned in the future to obtain not only the fragment size distribution but also a characterization of the fragments depending on their shape.

Two new types of synthetic test are going to be developed. The first one will have the objective of obtaining the relation strength vs. size and shape of the ñintactò rock blocks once the SRM sample has reached residual state. Results from this test will help improve the prediction of secondary fragmentation.

The in-situ rock mass very seldom follows a stress path as simple as that used in a UCS or triaxial test as employed in [7] and [12]. Therefore, a second new type of test will make the SRM samples follow a stress path that is closer to the stress path the rock mass follows to failure and residual state in a systematic manner so it can be repeated in different directions and different sample sizes. This new test will be incorporated into the Standard Suite of tests methodology [12].

The current SRM methodology does not consider the time-dependent yielding of the rock mass. It is planned to further develop the SRM method to take into account time ïdependent mechanisms such as stress corrosion [21], and groundwater redistribution due to changed loading ð e.g. flow in joints; exchange of fluid with matrix.

At present the nature of fracturing and slip in pre-existing fractures resulting from SRM testing has been compared to that derived from the in-situ microseismicity as a way of validation of the SRM methodology [11]. As a means of further validation, the synthetic seismic event interpretation can be further developed to estimate microseismic event magnitudes from SRM tests that can be compared to the magnitudes measured in-situ.

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