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Convergence of synthetic rock mass modelling and the Hoek–Brown strength criterion

B.A. Poulsen*, D.P. Adhikary, M.K. Elmouttie, A. Wilkins

CSIRO Energy Flagship, Queensland Centre Advanced Technology, Brisbane, Australia

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ABSTRACT

Synthetic rock mass modelling is based on estimating the mass scale properties of rock directly from properties of the intact material and observed jointing geometry and strength. This technique explicitly represents characteristics of the rock mass that are implicit in the widely applied, empirical Hoek–Brown strength criterion. We demonstrate here that the two approaches converge in mass strength and the strength envelope when the necessary conditions for the empirical method are satisfied. However, the synthetic rock mass approach is advantageous whenever the necessary conditions of the empirical method are not satisfied. As an example, we use the synthetic rock mass method to describe an anisotropic strength envelope for a rock mass with four independent joint sets, where the orientation-specific strength has a significant impact on rock mass stability. In addition we show that rock mass strength is controlled strongly by joint persistence and the resultant connectivity of discontinuities, and only weakly by joint density and intensity.

1. Introduction

Synthetic rock mass (SRM) modelling is a promising technique for estimating mass scale properties of rock, such as strength, representative size, and the anisotropic strength envelope. The SRM approach explicitly represents the following rock mass features which have been identified as controlling large-scale compliance and strength: (1) intact rock stiffness and strength, (2) defect density and orientation, and (3) the properties of these defects.

By site sampling and then directly representing the local attributes of the rock mass, SRM modelling is thought to better estimate the site-specific mass properties that govern stability.[1–6] However, despite its many benefits, the SRM modelling database of applied examples is still limited. This is partly due to the technique's relative newness and its significant computational requirements, in terms of both practitioner skill level and computational power. Researchers may also be hesitant to adopt the method due to the lack of comparative result sets, as opposed to the widely used and trusted empirical rock strength criteria.

To address these issues, this paper seeks to compare strength estimates from SRM modelling with those gained from the traditional empirical Hoek–Brown strength criterion.[3,7–12] When the necessary conditions for the Hoek–Brown criterion are met, SRM modelling would be expected to produce very similar estimates of rock mass properties.

Among the necessary conditions is the requirement for an approximately isotropic distribution of jointing orientation and strength, as illustrated in the widely reproduced, two-dimensional results displayed in Fig. 1(a).[13] This figure demonstrates that with regular spacing of transecting joints, sample strength anisotropy reduces to an effective isotropic response. The three-dimensional equivalence of the two-dimensional figure is presented in Fig. 1(b), which plots the planes of joint sets at a relative spatial orientation of 45° on a lower hemisphere projection. Fig. 1 shows that 13 individual joint sets have been used at a relative 45° orientation in three dimensions, compared with four joint sets in two dimensions. This is not entirely equivalent to the two-dimensional case, in which the relative orientation between one set and any of the others is guaranteed to be a multiple of 45°. Rather, this condition is satisfied in a local sense such that the relative orientation of any set and its neighbouring sets (on the stereonet) is 45°. This necessary condition is captured by the statement in;[14] as: 'it is assumed that there are several discontinuity sets and that they are sufficiently closely spaced, relative to the size of the structure under consideration, that the rock mass can be considered homogeneous and isotropic.'

Hoek and Brown, along with other authors, emphasise that the Hoek–Brown criterion is not applicable for estimating the strength of samples represented in Fig. 1(a), since the strength is governed by sliding on one of the joint planes – all of which transect the sample. This implies a second necessary condition, which is that the jointing is of a smaller scale than that of the representative

* Corresponding author. Fax: +61 7 3327 4495.
E-mail address: Brett.Poulsen@csiro.au (B.A. Poulsen).

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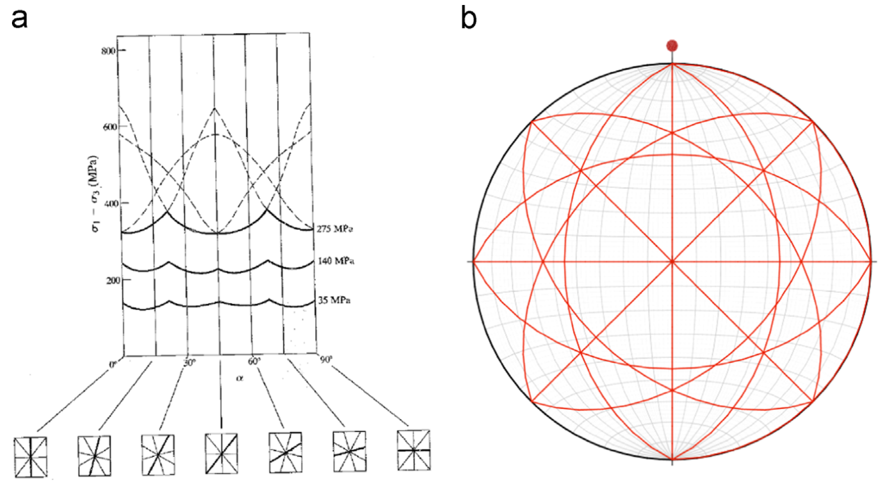

Fig. 1. (a) Two-dimensional and (b) three-dimensional representations of joints with 45° relative spacing of poles (b) is a plan view of lower hemisphere plane projections from 13 joint sets at 45° relative orientations (one joint set is horizontal and not immediately obvious in the figure).

rock mass size. This idea is captured in another of the necessary conditions stated, in;[11] as: 'Where the block size is of the same order as that of the structure being analysed, the Hoek–Brown criterion should not be used'.

In the empirical criteria, joint intensity and strength are implicitly captured in the Geological Strength Index (GSI) chart, which describes these features in descriptive terms.[15–17] In a quantification of the GSI chart, Cai et al. relates block volume and joint condition factor to *GSI*;[18,19] while Hoek et al.;[14] utilise rock quality designation (*RQD*);[20,21] and 1989 version of the Bieniawski joint condition ($JCond_{89}$).[22] By these approaches *GSI* is directly calculated from quantification of the degree of jointing and strength, including degree of weathering, of those joints.

As properties of the intact rock are necessary and identical inputs to both the Hoek–Brown criterion and SRM modelling, and if the isotropy condition for joint orientation and properties is satisfied, then the characteristics of the discrete fracture network (DFN);[23,24] need only to be related to the GSI to link the two approaches. We attempt to provide this link by the unbiased P32 metric of jointing intensity,[25] as discussed in Section 2.

SRM modelling is well described in the literature and is briefly summarised in Section 2, along with a short description of the Hoek–Brown criterion. The SRM method is based on explicitly representing both the intact rock, as tested at typical laboratory scales, and the jointing responsible for reducing the intact strength to a representative mass strength. SRM modelling typically uses discrete element particle codes. However, these codes are computationally intensive, and conducting numerical tests on sufficient samples at multiple scales and orientations is time consuming. This work utilises a lattice code, which comprises point masses connected by springs. The lattice code runs without updating particle-to-particle contacts: i.e., in small-strain mode.[26] This method removes the time-consuming computational overheads of contact detection and many of the calibration requirements of full-particle discrete element methods (DEMs). The lattice code is described further in Section 2.

In Section 3, we demonstrate that the SRM approach converges with the Hoek–Brown criterion in terms of the mass unconfined strength estimate and strength envelope. This requires a method of estimating a GSI from a particular DFN. We make this equivalence from an *a priori* reduction of the P_{32}, non-biased, three-dimensional joint intensity measure of the DFN to the RQD index, together with an *a posteriori* relationship between Coulomb joint strength and $JCond_{89}$.

The considerable extra effort involved in SRM modelling would probably not be justified if it was limited to isotropic homogenous situation. These are better addressed by alternative, non-computational approaches to property estimation. Instead, SRM modelling is advantageous when the necessary conditions for empirical methods are not met – including the assumption of isotropy in joint orientation and homogeneity in joint strength. In Section 4 of this paper, we therefore attempt to demonstrate and quantify the advantage of the SRM approach by calculating an anisotropic strength envelope from (a more typical) four joints set DFN, and use the resultant orientation dependent strengths in a simple factor of safety (FoS) calculation for a slope.

In Section 5 we calculate the rock mass strength from DFNs with the same P_{32}, but different joint persistence. We demonstrate that joint persistence and the resulting fracture connectivity control the mass strength, rather than joint intensity and (counter-intuitively) the inverse of joint density. Our conclusions are presented in Section 6. The Appendix contains our derived intensity measures for a uniform joint distribution within a bounded domain, which we compare with the widely used relationships that assume the domain is unbounded.

2. Two approaches for estimating the properties of rock masses

2.1. The Hoek–Brown criterion

One of the most widely applied strength scaling methods is the empirical Hoek–Brown criterion for estimating the strength of rock and rock masses,[3,7–13] expressed as

$$\sigma_1 = \sigma_3 + \sigma_{ci}(m_b\sigma_3/\sigma_{ci} + s)^a \quad (1)$$

where σ_1 and σ_3 are the major and minor effective principal stresses, σ_{ci} is the intact unconfined compressive strength (*UCS*), and m_b, s and a are material constants that can be related to m_i and the *GSI*. Parameter m (In the original form of the criterion,[10] and m_i subsequently) is approximately the ratio of σ_{ci} to tensile strength of intact rock;[10] or, alternatively, a rock-type-dependent material constant estimated from triaxial testing if available.[11] Parameters m_b, s and a are estimated as follows:[8]

$$m_b = m_i \, exp\left[\left(GSI - 100\right)/(28–14D)\right] \quad (2)$$