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A step towards the end of the scale effect conundrum when predicting the shear strength of large in situ discontinuities

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ABSTRACT

The shear strength of rock discontinuities is known to be scale dependent, and past research has revealed that both positive and negative scale effects could be observed. It is far from trivial to predict the occurrence of the scale effect and, to date, there is still no consensus on how to satisfactorily predict the shear strength of large discontinuities. A new stochastic approach was proposed and validated at laboratory scale by the authors. The approach consists of (1) using the information available from visible traces to create synthetic surfaces via a random field model and (2) estimating the shear strength of each one of the synthetic surfaces in order to obtain a distribution of shear strength and a mean shear strength. This paper presents the first application of this new approach to a large discontinuity that was surveyed with a resolution of 1 mm and an accuracy in the order of 150–230 µm in the Pilkington reserve of Newcastle, Australia. The paper first confirms that a scale effect does exist for the surface tested, before demonstrating that the new stochastic approach produces a strength envelope that is very close to the deterministic failure criterion of the whole surface. The key conclusion of this research is that there is enough information on visible traces, if surveyed accurately, to obtain an estimate of the shear strength of the discontinuity.

1. Introduction

The scale dependence of strength and deformability of rock discontinuities has long been recognised as a key challenge in the field of rock mechanics.[1] From the 1960s until quite recently, researchers have investigated how "scale" affects the stiffness and shear strength of rock discontinuities. Interestingly, different conclusions were drawn from the various experimental studies conducted. For example, many researchers[2–5] have observed an increase of shear strength with the diminution of discontinuity size, which is commonly referred to as a positive scale effect. In contrast, other researchers[6,7] reported the opposite trend: the smaller the specimen, the lower the shear strength. This latter case is referred to as a negative scale effect. Some studies mention an absence of scale effect.[8,9] The main reason behind the scale effect is that roughness, a key parameter governing shear strength, is itself scale dependent.[10–12] It has also been suggested[6,8] that joint matedness could contribute to the phenomenon.

Interestingly, all the studies cited above draw conclusions from comparing the shear strength of a large surface and that of smaller sub-surface, but the effect of the method employed to select sub-surfaces is hardly discussed. Recently, the authors of the present paper[13] showed that the strategy employed to downsize the specimen and the way to express the results matter and could hide or reveal a scale effect. In the light of this result,[13] it is possible that the lack of consistent observation of the scale effect comes from the variable nature of roughness and the fact that some features (e.g. steps) may be present or not in the sub-surfaces considered.

Another interesting point to note is that most of the studies that have investigated the effect of specimen size on shear strength have relied on relatively small specimens, i.e. less than 700 mm per 700 mm.[3,10,14–16] This can be explained by the technical difficulties associated with shearing large surfaces. Studies in which surfaces larger than 1 m^2 are reported often focus on the scale dependence of roughness rather than shear strength.[12,17–20]

The scale effect was investigated via fractal approaches[21–23] or by resorting to scale-dependence descriptors,[24,25] which does not fully capture the origin of the scale dependence. In other words, such models have a scale dependence function built in, which can predict either the positive scale effect or the negative one, following a due calibration.

To date, there is still no consensus on the most appropriate method to estimate shear strength of large in situ discontinuities, which is not a surprise considering the inherent difficulty to account for the scale effect. Barton's empirical model for shear strength[26] can be adopted for large discontinuities by scaling up the joint roughness coefficient.[27]

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However, Barton himself recognises that there has been some confusion about his model,[28] and the JRC is known to be scale-dependent (it is defined on a 10 cm length). From back analyses of existing slopes, McMahon[29] concludes that small-scale roughness is irrelevant for large discontinuities, which seems correct for unmated discontinuities, and proposes to treat the response as frictional with an effective friction angle. Identifying a suitable method to assess the shear strength of large discontinuities is still a timely topic.[9]

This paper presents the application of a new stochastic approach for the prediction of shear strength of large in situ discontinuities. The idea is to use the information available directly at the scale of the problem, i.e. from visible traces and to use random field theory to generate possible representations of the surface being assessed. Using a stochastic approach, a distribution of shear strength is obtained. This new approach was validated at laboratory scale[1] and this paper presents the first application of this new approach to a large discontinuity (of about 2 m per 2 m).

2. Description of the new approach for shear strength prediction

2.1. Rationale of the new approach

The new approach was developed for cases where it is required to estimate the shear strength of a discontinuity that is contained within a rock mass with only some traces (intersection of the discontinuity plane and the rock face) visible. As such, the surface as a whole is not accessible and cannot be fully surveyed. The idea that was validated on small-scale specimens by the authors[1] advocates that a visible trace contains enough information to support the creation of synthetic surfaces of similar statistical characteristics. In the rest of this paper, such a visible trace is referred to as a seed trace. The creation of synthetic surfaces is achieved via the rigorous development and application of a random field model. Once the synthetic surfaces are obtained, their shear strength is estimated using an adequate shear strength model, resulting in a probabilistic distribution of shear strength. This stochastic approach offers the advantage to work directly at the intended scale without the need to downscale specimens and upscale shear strength estimates. The key steps of this scale-free and rigorous solution to predict shear strength of large in situ discontinuities are illustrated in Fig. 1.

Implementing this new approach requires (1) a cost-effective model to predict shear strength and (2) a random field model to create the synthetic surfaces from the input of a seed trace. The two specific models that were developed to conduct the research are only briefly presented in the next sections and the reader is invited to refer to 1 for more details.

2.2. Shear strength model

The surface morphology is described in the form of (x, y, z) coordinates and the model first turns the (x, y, z) data into a triangulated surface made of facets (see Fig. 2). The x and y directions are contained within the discontinuity plane (defined as the mean plane) while direction z is orthogonal to the discontinuity plane.

For a given shearing direction, defined by a unit vector contained within (x,y) plane, the apparent dip of the facets (β_{app_i}) is estimated by

$$\beta_{app\_i} = \quad acos(\bar{n}_i : \bar{s}) - 90 \tag{1}$$

where $\overline{n_i}$ is the unit vector normal to facet i and $\bar{s}$ is the unit vector indicating the shear direction in the discontinuity plane (i.e. x,y plane). $(\bar{n}_i : \bar{s})$ is the dot product of both vectors.

The concept of apparent dip was proposed by Grasselli[30] and is here used to identify the facets that can possibly contribute to the shearing resistance. Indeed, the model is based on the idea that, under low normal stress, a joint dilates upon shearing leading to a redistribution of the load on the steepest facets that remain in contact during the early stage of shearing (see Fig. 3). Such facets are considered active or contributing. It is assumed that this mechanism also prevails under high normal stress.

The model scans all facets starting from the steepest ones in order to identify all the facets that will contribute to the shear resistance of the discontinuity. This is achieved via a loop on a parameter noted β^*, which is decreased in increments of 0.1° from an initial value equal to the highest apparent dip ($\max\{\beta_{app\_i}\}$). At each iteration, all facets whose apparent dip is larger than or equal to β^* are considered active. Once all the active facets are identified, the local force acting on the active facets (f_{local_i}) in the z direction is calculated as:

$$f_{local\_i} = \frac{F_{macro}}{N_{cf}} \tag{2}$$

where F_{macro} is the vertical force exerted on the whole discontinuity, and N_{cf} is the total number of contributing facets at a given increment of β^*.

Then, the forces required to slide over the active facets and shear them at their base are computed as:

$$f_{sliding\_i} = f_{local\_i} \times \tan(\phi_b + \beta_{app\_i}) \tag{3}$$

$$f_{shear\_i} = A_{ip} \times (c + \sigma_{local\_i} \times \tan(\phi)) \tag{4}$$

where β_{app_i} is the apparent dip of facet i, ϕ is the friction angle of the material, c is the cohesion, ϕ_b is the basic friction angle, A_{ip} is the area of the facet projected on the xy plane and σ_{local_i} is the local vertical stress acting on facet i (equal to f_{local_i} - given by Eq. (2) - divided by A_{ip}). At each iteration, the model checks which of $f_{sliding\_i}$ and f_{shear_i} is the largest. If $f_{sliding\_i} > f_{shear\_i}$ then the facets are sheared and their apparent dip is reduced to the current value of β^*, a process that mimics progressive shearing.

Another iteration now takes places with β^* reduced by 0.1°. At this stage, the local forces $f_{sliding\_i}$ and f_{shear_i} are both initialized and the comparison of local shearing and sliding forces applies again.

The iterations stop when, for all active facets under analysis, it takes less force to slide upon the facets than to shear them, i.e. when $f_{sliding\_i} \le f_{shear\_i}$. At this stage, the final peak force is computed as the total contribution of all active facets (only frictional at this stage):

$$f_{peak} = \sum_{i=1}^{N_{cf}} f_{sliding\_i} = \sum_{i=1}^{N_{cf}} f_{local\_i} \times \tan(\phi_b + \beta_{app\_i}) \tag{5}$$

where $f_{sliding\_i}$ is the local horizontal force required to slide over active facet i and N_{cf} is the total number of active facets for a given value of β^*. The peak shear strength τ_{peak} is simply the peak shear force over the total discontinuity area.

The same strength parameters than those chosen in 1 were used here: the apparent cohesion c is 4.74 MPa, the friction angle ϕ is 58.1° and the base friction angle ϕ_b is 35.3°. These parameters were identical for all simulations and pertain to the mortar used to create the replicas tested in 1.

2.3. Random field model

A random field model creates correlated data that follow a given statistical distribution.[31] In this new method to predict shear strength, synthetic surfaces are created from the statistics of the seed trace. More specifically, the model creates a field of surface heights associated to a given grid of (x,y) data. The heights (noted z) are assumed to follow a Gaussian distribution, with a mean and a standard deviation corresponding to those of the seed trace. The degree of correlation between two random data is expressed via the coefficient of correlation ρ, which is assumed to be an exponential function of the distance between two points (d):