A DEM approach to rock joint strength estimates

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ABSTRACT

Structural defects such as joints or faults are inherent to almost any rock mass. In many situations such defects have a major impact on slope stability as they can control the possible failure mechanisms. Having a good estimate of their strength then becomes crucial. The roughness of a structure is a major contributor to its strength through two different aspects, the morphology of the surface (or the shape) and the strength of the asperities (related to the strength of the rock). In the current state of practice, roughness is assessed through idealised descriptions (Patton strength criteria) or through empirical parameters (Barton's JRC). In both cases, the multi dimensionality of the roughness is ignored.

In this study, we propose to take advantage of the latest developments in numerical techniques. With 3D photogrammetry and/or laser mapping, practitioners have access to the real morphology of an exposed structure. The derived triangulated surface is then introduced into the DEM code PFC3D to create a synthetic rock joint. The recent one development of the Smooth Joint Model (SJM) allows to get rid of the artificial roughness introduced by the particle discretization. Shear tests are then performed on the synthetic rock joints. Amongst the benefits of the methodology is the possibility offered by DEM to reproduce the progressive degradation of the asperities upon shearing and analyse structures of different scales without introducing any empirical relation.

INTRODUCTION

The presence of discontinuities is inherent to almost any rock mass and is a major contributor to strength and deformation of rock structures (natural or engineering). The shear strength of those discontinuities not only controls structurally controlled failures but also dramatically influences the shear strength of the rock mass (Lambert [1]). In slope stability analysis, it is crucial for practitioner to have a best estimate of their shear strength. Direct shear tests on rock joints have been performed in the lab and have quickly enhanced the influence of roughness on the mechanical behaviour of discontinuities (Barton [2]). Barton proposed assessing roughness with an empirical parameter, Joint Roughness Coefficient or JRC, from which the shear strength of the discontinuity can be established. Initially estimated by visual comparison with standard roughness profiles, correlations between JRC and various statistical parameters or fractal dimension have been established (Tse and Cruden [3] ; Carr and Warriner [4]). More recently the use of laser scanner and photogrammetry to define the surface topography and estimate the roughness have been described (Hans and Boulon [5] ; Grasselli [6] ; Poropat [7] ; Haneberg [8]). The dependence of shearing on the location and distribution of the three dimensional contact area has been demonstrated (Gentier et al. [9]) and new constitutive relations have been developed based on a general description of roughness (Grasselli and Egger [10]). Laser scanning and 3D photogrammetry techniques have been applied in the field (Fardin et al. [11]) for large scale surface measurements. Asperity shape and distribution on a discontinuity can now be measured with a great detail and potentially incorpored in any analysis. However with the complexity of the interaction between the two walls of a discontinuity, a complete analytical formulation is a hard task and many authors have used numerical tools to assess the shear strength of discontinuities. DEM simulations have been presented as they offer a provision for asperity degradation (Cundall [12] ; Nicot et al. [13]). However the discrete nature of the medium can introduce an artificial roughness to the discontinuity, especially for coarse discretizations. The recent development of a new contact model “Smooth Joint Model” (Pierce et al. [14]) in PFC3D where particles are allowed to slide past one another without over-riding one another has been a major breakthrough to represent discontinuities as planar surfaces. In this study we propose to develop a synthetic rock joint where a digital representation of a surface is introduced and described as a series of SJM.

DEM SIMULATIONS OF CONSTANT NORMAL STRESS SHEAR TESTS

The Discrete Element Method

The commercially available PFC3D [15] software package was used for the three-dimensional Discrete Element Method (DEM) simulations presented here. Rock is represented as a bonded particle assembly using parallel bonds to create a synthetic material. Such assemblies have proven their ability to reproduce typical behaviour of rock-like materials (Potyondy and Cundall [16]). For the scope of this study, a granite (as studied by Grasselli [6]) has been considered whose properties are given in Table I. The micro-properties have been calibrated accordingly and the emergent bulk properties of the synthetic material are given in Table I.

Table I - Target (Lab.) and calibrated (Cal.) bulk properties of the granite

		Lab.	Cal.
Uniaxial Compressive Strength, UCS	[MPa]	172.5	170.8
Young’s Modulus, E	[GPa]	48.4	48.6

Description of the Interface

The interface morphology used in the simulations is based on natural discontinuity in granite studied by Grasselli [6]. The surface is 140 × 140 mm^2 and the maximum amplitude of the asperities is around 9 mm. Figure 1 shows a general view of the surface. The 3D surface has been triangulated with a sampling interval of 1.4mm. The coefficient Z_2 (root mean square of the first derivative of the profile) has been estimated performing statistical analysis on several profiles along the shear direction (X). A value of the Joint Roughness Coefficient (JRC) can be derived from Z_2 using empirical correlations (Tse and Cruden [3]). The triangulated surface exhibited a JRC of 10.4.

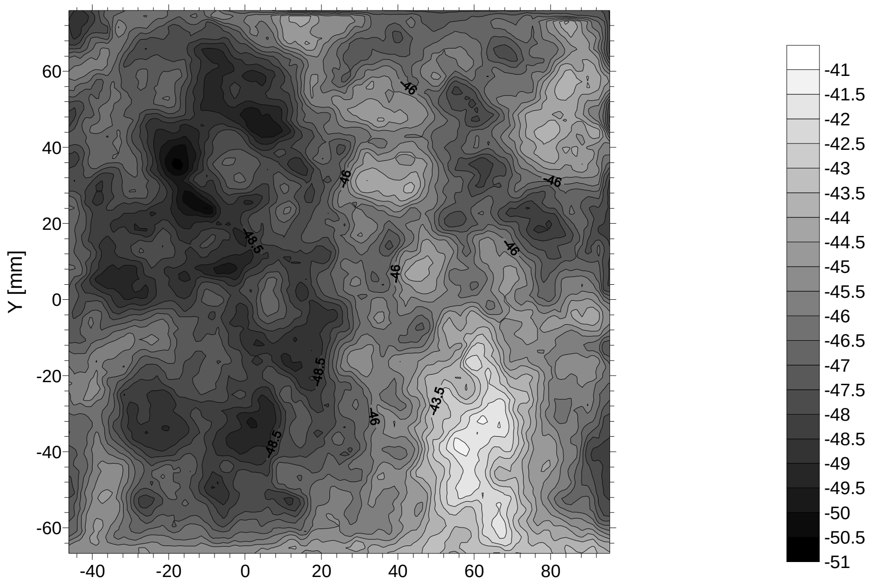

Figure 1 - Representation of the granite surface. All dimensions in mm.

A Synthetic Rock Joint Model

The numerical rock joint consists of a 140mm x 140mm x 50mm (respectively X,Y,Z) parallelepiped particle assembly as shown in Figure 2. It contains 98345 particles having a radius ranging from 0.5mm (in the vicinity of the interface) to 2.4mm. The discontinuity is purely frictional (friction angle of 20°) and is introduced as a series of triangles. Each contact intersecting a triangle is assigned a “Smooth Joint Model” (SJM) (Pierce et al. [14]), whose orientation matches the orientation of the triangle. The SJM was used to prevent the local roughness from depending on the particle discretization. Dark and clear patches in Figure 1 correspond to depressions and peaks respectively on the surface. They appear on a cross-section of the specimen (Figure 2) as part of the upper wall and lower wall respectively. Visual comparison of Figure 1 and Figure 2 enhances a good agreement in their locations.

The specimen is firstly subjected to a compression along axis Z (Figure 2) and then to a shearing along axis X at constant normal stress. Displacements along Z are restrained. The sum of contact forces on the periphery of the upper half are used to compute the average normal stress and shear stress on the interface whereas normal and tangential displacements are monitored averaging particle displacements on the periphery of the lower half (Z displacements and X displacements respectively).

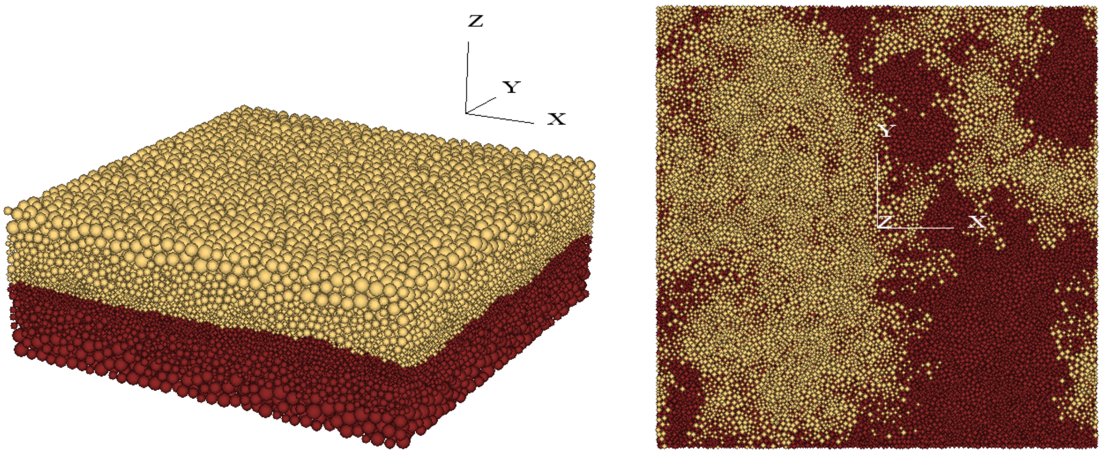

Figure 2 - Visualization of the synthetic rock joint sample. Upper wall in orange and lower wall in brown. Full 3D view on the left and lower half section on the right.

Mechanical Behaviour of the Discrete Interface

Numerical shears tests under constant normal stress have been performed on the synthetic rock joint for three values of normal confinement (0.5MPa, 1MPa, 1.5MPa). Figure 3 (a) and (b) show the evolution of shear stress and normal displacement with shear displacement. It can be seen that the classical elasto-plastic response of rock joints is well captured. The mobilised shear stress increases to a peak value as roughness is mobilised and then decreases due to asperity degradation. The peak value defines the shear strength of the synthetic rock joint (the higher the normal stress, the higher the shear strength). Peak dilation angles have been measured as the slope of the normal displacement vs. shear displacement curve at the peak of the shear stress (Figure 3). As shown in Figure 3, dilation decreases as normal stress increases.

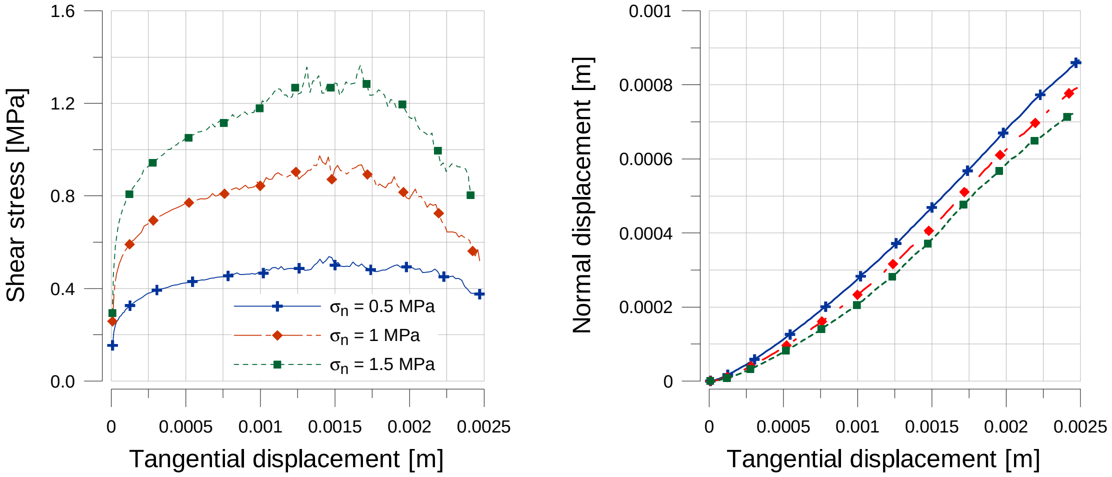

Figure 3 - Stress-strain curves of direct shear tests under constant normal stress (ranging from 0.5 MPa to 1.5 MPa) on a 140 x 140 mm^2 surface. a) Shear stress versus tangential displacement. b) Normal displacement versus tangential displacement.

The numerical shear tests performed under increasing normal stress define the strength envelope of the model from which a Barton failure criterion [17] can be expressed. In Barton's formulation the shear strength is expressed as a function of the Joint Roughness Coefficient (JRC), Joint Compressive strength (JCS) and friction ϕ_b (1):

$$\tau_p = \sigma_n \cdot \tan\left(JRC \cdot \log_{10}\left(\frac{JCS}{\sigma_n}\right) + \phi_b \right) \tag{1}$$

Where τ_p is the peak shear stress and σ_n the normal stress.

A best fit of Barton's failure criterion can be seen on Figure 4. The obtained values for JRC, JCS and ϕ_b are 10.43, 172MPa and 20.6° with a coefficient of determination R^2 close to 1. The JRC value from the back analysis is in good agreement with its counterpart of the surface introduced in the simulations suggesting that the effect of roughness on the mechanical behaviour is well captured. The base friction angle ϕ_b in equation (1) corresponds to the friction angle of a perfectly planar discontinuity. Once again the obtained value corresponds to its counterpart in the smooth joint model (20°).

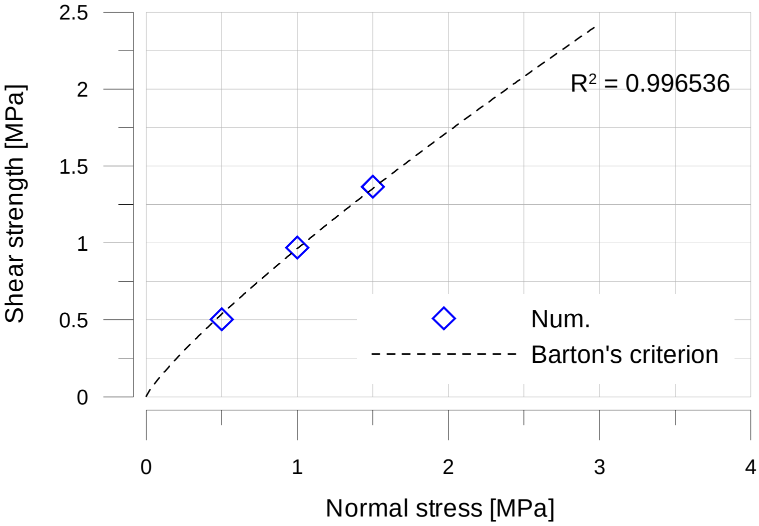

Figure 4 - Failure criterion for the numerical model with a best fitted Barton criterion (Equation 4 with JRC = 10.43 and ϕ_b = 20.6°)

SCALE DEPENDENCY OF JOINT CONSTITUTIVE BEHAVIOUR

Bandis et al. [18] have identified three contributors to rock joint strength: a basic frictional component, the geometry (or morphology) of the discontinuity (shape of the asperities) and asperity failure (the strength of the asperities) (Figure 5).

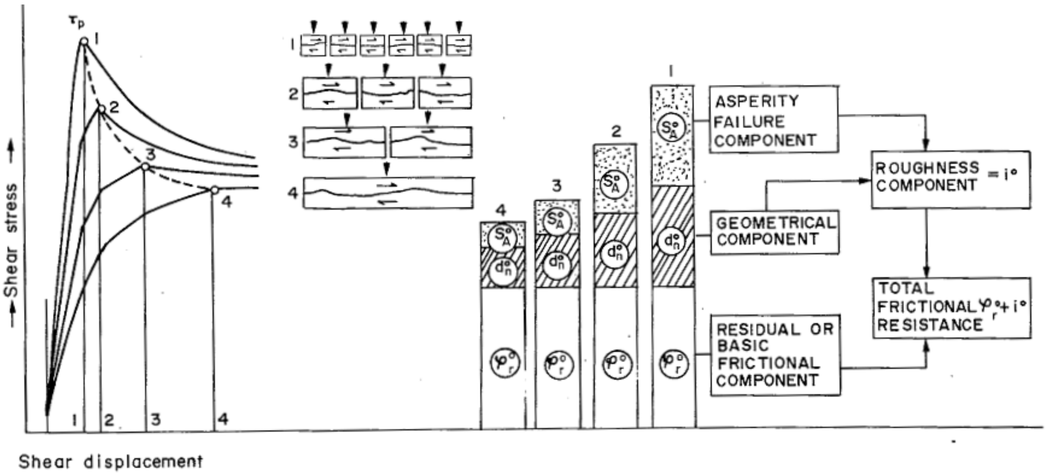

Figure 5 - Scale effects in the shear strength components of non-planar defects (Bandis et al. [18])

Geometry and strength of asperities are the basis of the roughness component. While basic friction appears to be scale independent and can be estimated on lab scale experiments, the roughness component is highly scale dependent. Roughness decreases as scale increases. Numerous studies have been carried out trying to quantify the scale dependence of joint strength from which empirical relations have been proposed (Barton and Bandis [19]):

$$JRC_n = JRC_0 \cdot \left(\frac{L_n}{L_0} \right)^{-0.02\,JRC_0} \tag{2}$$

$$JCS_n = JCS_0 \cdot \left(\frac{L_n}{L_0} \right)^{-0.03\,JRC_0} \tag{3}$$

Scale dependence has been addressed in this study performing numerical shear tests on samples of different sizes. Two smaller scales have been tested, 70 x 70 mm^2 and 46.7 x 46.7 mm^2, splitting the initial surface into respectively 4 and 9 sub-samples. Direct shear tests under a constant normal stress of 1.5MPa have been performed on each of the 4 + 9 newly created samples. Figure 6 shows peak shear stress (mean value and variability) versus sample size for all the tests. The results from the numerical simulations exhibit a clear reduction of the strength with the sample size. As can be seen in Figure 6, the general trends follows strength reduction as predicted by equations (2) and (3).

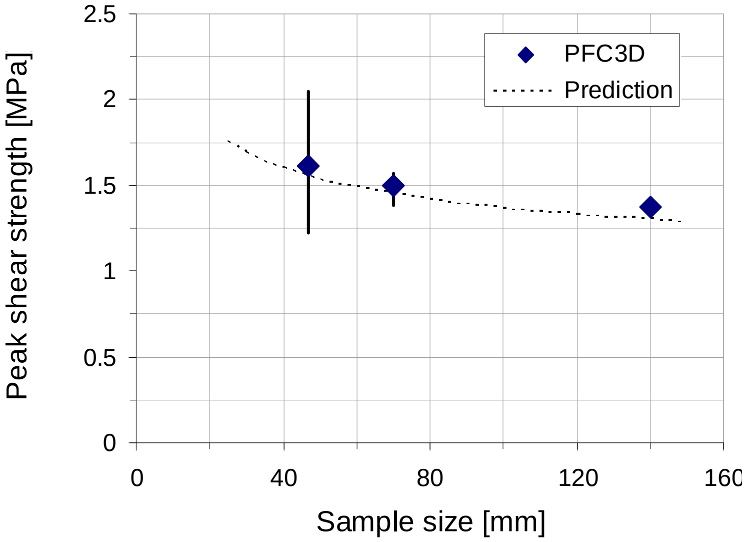

Figure 6 - Variation with joint size of peak shear strength from numerical simulations (diamonds) and predicted by equations (2) and (3) (dashed line). Diamonds represent the mean value for each size and error bars the variability (minimum and maximum).

SIGNIFICANCE FOR LARGE SCALE DISCONTINUITIES

Because of the scale dependency observed in the mechanical behaviour of discontinuities, their properties should be assessed at the relevant scale. In a rock mass, the scale of the discontinuities ranges from meters to hundreds of meters (and more)

Extending lab methods where scale is usually restricted to meter and below, for field estimates introduces some difficulties that need to be assessed.

Effect of Surface Sampling Interval

As mentioned previously in recent years several methods have been developed to characterise surface roughness of rock discontinuities from laser scanning [5-6] or 3D photogrammetry imaging [7-8]. These techniques applied to remote characterisation in the field of large scale structure often need a compromise between scanned area of the discontinuity and surface resolution. Degradation in the resolution (or in the sampling interval) leads to a reduction of the measured roughness (Yu & Vayssade [20]; Fardin et al. [21]). In this study, several triangulated surfaces have been extracted from the initial 3D surface with a sampling interval ranging from 0.57mm to 2.95mm and heir JRC values have been derived from the statistical parameter Z_2 (Figure 7). As expected the measured JRC drops from 11.55 to 9.55. Synthetic rock joint samples have been generated using the various triangulated surfaces and the same particle discretization. Any difference observed in the behaviour can thus be attributed to the sampling degradation. Direct shear tests under a constant normal stress of 1.5MPa have been performed. The variation of peak shear strength τ_p and peak dilation angle ψ_p with sampling interval can be seen in Figure 8. A clear reduction in the shear strength and the dilation behaviour is observed for sampling higher than 1.5mm corresponding to the reduction of the triangulated surface roughness. However for sampling intervals smaller than 1.5mm such trend cannot be observed as both strength and dilation exhibit little variation with sampling intervals. The additional information coming from a higher surface resolution is erased by particle resolution (average particle diameter in the vicinity of the surface is 1.82mm). Modelling rock joints with a high surface resolution certainly requires a fine particle discretization.

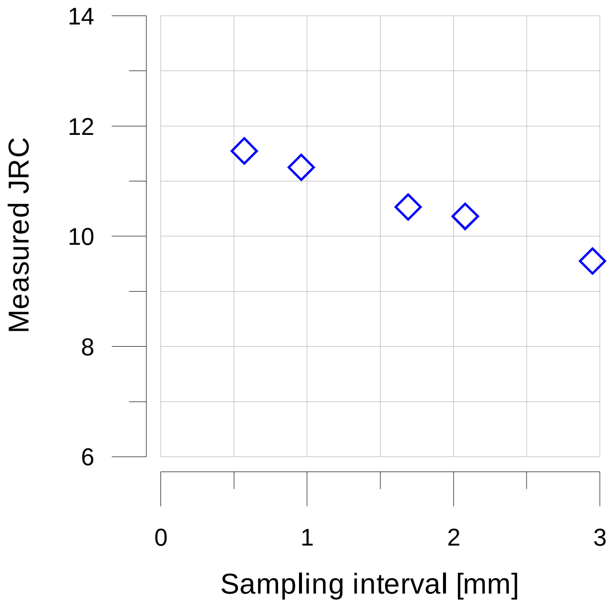

Figure 7 – Variation of the Joint Roughness Coefficient (JRC) with the surface sampling interval.

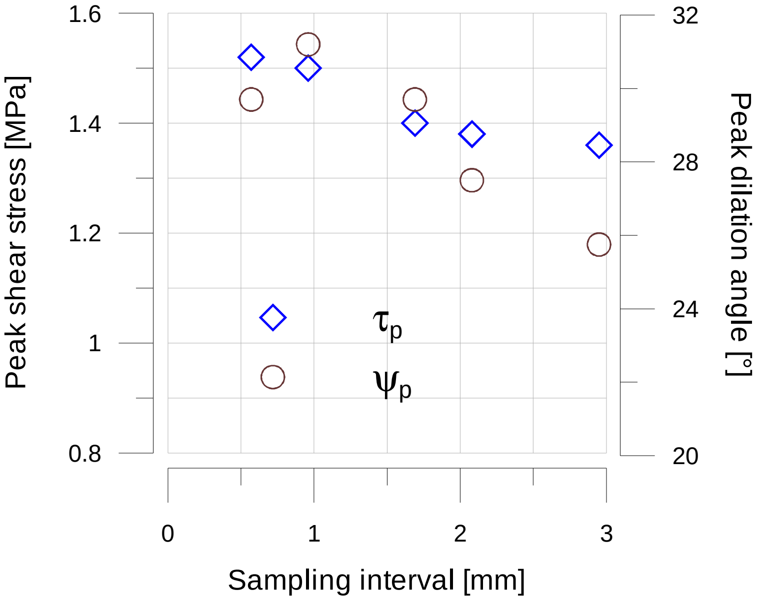

Figure 8 - Peak shear strength τ_p and peak dilation angle ψ_p vs. sampling interval

Effect of Particle Size

With the current computer limitations, testing large scale discontinuities (metres and above) would require the use of larger particles. As mentioned in the previous section, a fine particle resolution is required to capture the full complexity of roughness. The discontinuity surface can be artificially smoothed down as particle size increases, especially when particles become larger than the smallest asperities. In order to address this problem direct shear tests under constant normal stress (1.5MPa) have been performed on 70 x 70 mm^2 samples using different particle size distributions, with a minimum radius ranging from 0.335mm to 0.866mm. The shape of the size distribution and the size of the refinement zone around the discontinuity have been kept unchanged.

Figure 9 shows the peak shear stress for the different simulations. For an average particle radius higher than 0.914, a clear reduction in the peak shear stress is observed. Whereas the shear strength for samples with a radius lower than 0.914 appears to be rather independent of the particle size. Thus, particle size distribution should be fixed accordingly to the resolution of the surface (or sampling interval). The use of bigger particles will artificially reduce the roughness of the discontinuity and lead to an underestimation of the strength of the discontinuity. Interestingly, the average diameter below which the mechanical response of the model becomes independent of the particle resolution is slightly higher than the sampling interval of the surface (1.4mm).

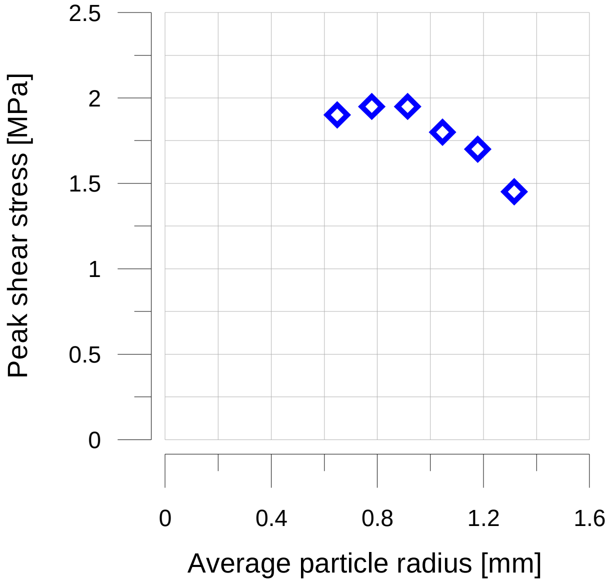

Figure 9 - Evolution of peak shear stress with average particle radius of the refinement area. 70 x 70 mm^2 sample.

It is widely accepted in the community that 2 orders of asperities have to be taken into consideration when considering joint roughness and thus joint strength. Second order asperity exhibits high angle and narrow base length (or wave length) in opposition to first order asperities that have lower angles and longer base length.). The behaviour of rock joints is controlled primarily by the second order asperity during small displacements and the first order asperity governs the shearing behaviour for large displacements. Barton [2] first stated that at low normal stress levels the second order asperity controls the shearing process. With increasing normal stress, the second order asperity is sheared off and the first order asperity takes over as the controlling factor. Fardin et al. [20] have suggested that a resolution of 0.2mm in the roughness measurement was required to correctly capture the second ordered asperities whereas a resolution of 20mm seems sufficient to capture first order asperities. Yang et al. [22] obtained similar conclusions using analytical decompositions. An extrapolation of the previous observations would suggest that using a minimum particle radius of 20mm, a maximum joint surface of $10m^2$ could be modelled with a standard computer. However, only the effect of first order asperities would be captured in an appropriate way. Results should be restrained to situations where first order asperities appear to be the controlling factor. In other situations, results should carefully be questioned.

CONCLUSION

Strength of large scale discontinuities is a fundamental input in almost any rock slope stability analysis. In the current engineering practice, discontinuity strength can be assessed directly, performing direct shear tests, or through empirical parameters such as JRC. In both cases, the strength estimate is performed at the laboratory scale. As roughness and strength are scale dependent, practitioners eventually resort to empirical relations to scale-up the strength to field level. Recent developments in roughness measurement in the field and improvements of numerical softwares offer new perspective to large scale strength estimates. A DEM approach was developed to generate a synthetic rock joint with a real morphology that is able to mimic the mechanical behaviour of a discontinuity. Direct shear tests under constant normal stress have been performed and the mechanical response of the model has been analysed. The effect of roughness was consistently captured throughout the simulations, for various normal stress and various apparent roughness. Both peak strength and dilation of the models were in relatively good agreement with predictions from Barton's failure criteria. The scale dependency exhibited by the model could be predicted by standard empirical relations. With the current computational limitations regarding reproduction of the effect of the second order asperities at a very large scale, limitations have been discussed that would require an alternative approach.

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