A GEOMETRICAL APPROACH FOR THE ESTIMATION OF SCALE EFFECTS IN ROCK JOINT BEHAVIOUR

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ABSTRACT
It is well known that the shear strength and deformability of rock joints are affected by scale, particularly joints with rough surfaces under low to moderate normal stresses. The estimation of the scale effects on joint behaviour is done with an approach based on measurements of the asperity angles of the joint surfaces. The approach also makes use of a recently developed constitutive model for rock joints, called CSDS, which models the behaviour of rock joints in the pre-peak and post-peak strength regions. The approach is validated with results taken from the literature.

RÉSUMÉ
La résistance au cisaillement et la déformabilité de discontinuités rocheuses présentent des effets d'échelle. Ces effets sont surtout marqués pour les surfaces rugueuses sous contraintes normales faibles et modérées. L'estimation des effets d'échelle sur le comportement des discontinuités est réalisée par une approche basée sur des mesures de l'angle des aspérités de la surface des discontinuités. L'approche utilise un modèle constitutif récemment développé appelé CSDS qui peut représenter aussi bien le comportement des discontinuités en phase pré-pic que post-pic. L'approche est ensuite validée à l'aide de résultats tirés de la littérature.

1. INTRODUCTION

In many situations, the mechanical behaviour of rock masses are much more dependent on the mechanical properties of the joints as opposed to those of the intact rock. For fractured rock masses, failure mechanisms are often governed by translational shear along existing joints. The understanding of joint shear mechanisms is thus a basic tool for a comprehensive description of the complex mechanical behaviour of rock masses. Recently, a new model for rock joints, the CSDS model (Complete Stress-Displacement Surface), has been developed (Simon 1999, Simon et al. 1999). This model is very representative of the behaviour of rock joints in the pre-peak and the post-peak strength regions.

In current practice, the properties of rock joints on a large scale are determined either by in situ testing of large volumes or estimated from laboratory experiments on small samples without consideration of the effects of the size of the sample. Several researchers (e.g. Barton and Choubey 1977, Bandis et al. 1981, Barton et al. 1985, Muralha and Pinto da Cunha 1990) have shown that the strength and deformability of rock joints depends on the size of the tested sample. The variation of properties with size is known as the scale effect. The joint size may affect the shear strength, peak shear displacement, shear stiffness, and peak dilation angle of non-planar joints (e.g. Indraratna and Haque 2000). The size dependence of joint behaviour is governed to a large extent by surface characteristics such as roughness and wall strength (Barton et al. 1985). A key factor is the effective asperity size (Bandis et al. 1981). Thus, a reliable method is needed for extrapolating laboratory data to larger scales that would be representative of in situ characteristics.

2. THE CSDS MODEL FOR ROCK JOINTS

2.1 Shear stress - shear displacement relationship

The CSDS model has been developed to fully describe the behaviour of rock joints in pre-peak and post-peak phases (Simon 1999, Simon et al. 1999). It can be written as follows for the shear stress - shear displacement relationship:

$$\tau = a + b\,exp(-c\,u) - d\,exp(-e\,u) \qquad [1]$$

where τ is the shear stress (MPa), u is the shear displacement (mm) and a through e are model parameters, which must satisfy the conditions $c < e$ and $a, b, c, d, e > 0$. These parameters can be determined from the following relationships:

$$a = \tau_r \qquad [2]$$

$$b = d - a \qquad [3]$$

$$c = 5 / u_r \qquad [4]$$

Parameters d and e can be obtained by solving the following equations:

$$\frac{d\,e\,u_r}{5\,(d - \tau_r)} - exp\left[u_p\left(e - \frac{5}{u_r}\right)\right] = 0 \qquad [5]$$

$$d = \frac{\tau_p - \tau_r\left[1 - exp\left(-\frac{5u_p}{u_r}\right)\right]}{exp\left(-\frac{5u_p}{u_r}\right) - exp\left(-eu_p\right)} \qquad [6]$$

In these equations, τ_r is the residual strength, τ_p is the peak strength, u_p is the displacement at peak strength and u_r is the displacement at the onset of τ_r. Equations 5 and 6 must be solved simultaneously to evaluate the values of parameters d and e from a given τ - u curve. These can be solved by standard iterative methods. When solving Equation 5, which has two roots for e, the larger value is used to satisfy the condition $c < e$. More details on the development of these equations can be found in Simon (1999) and Simon et al. (1999).

From the above equations, it can be seen that all parameters can be determined from four joint characteristics, which are the peak and residual shear strengths (τ_p, τ_r) and the corresponding displacements (u_p, u_r). Here the displacements (u_p, u_r) are considered to be independent of normal stress σ_n.

The residual shear strength is usually given by a Coulomb criterion without cohesion:

$$\tau_r = \sigma_n \tan \phi_r \qquad [7]$$

where ϕ_r is the residual friction angle on the joint surface. The peak shear strength τ_p can be obtained using any existing peak strength criterion. Simon (1999) and Simon et al.(1999) have used the well-known LADAR (Ladanyi and Archambault 1970) criterion as modified by Saeb (1990). The peak shear strength is then given by:

$$\tau_p = \sigma_n (1 - a_s) \tan (i + \phi_r) + a_s S_r \qquad [8]$$

where (Ladanyi and Archambault 1970):

$$i = \tan^{-1}\left[\left(1 - \frac{\sigma_n}{\sigma_T}\right)^{k_2} \tan i_0\right] \qquad [9]$$

$$a_s = 1 - \left(1 - \frac{\sigma_n}{\sigma_T}\right)^{k_1} \qquad [10]$$

$$S_r = S_0 + \sigma_n \tan \phi_0 \qquad [11]$$

In the above equations i_0 is a parameter that represents the initial angle of asperities. σ_T is a transitional stress (often taken as the uniaxial compressive strength C_0, as suggested by Goodman 1976). k_1 and k_2 are material constants for the LADAR model. Ladanyi and Archambault (1970) determined experimentally that k_1 = 1.5 and k_2 = 4.0. a_s is the ratio of the projected sheared asperity surface area to the joint surface area at peak strength. S_r is the shear strength of the rock asperities with S_0 the corresponding cohesion and ϕ_0 the friction angle.

2.2 Normal displacement - shear displacement relationship

To describe the normal displacement (v) to shear displacement (u) relation, an exponential formulation has also been used. This relation can be expressed as (Simon 1999, Simon et al. 1999):

$$v = \beta_1 - \beta_2 \exp(-\beta_3 u) \qquad [12]$$

where β_1, β_2 and β_3 are model parameters. The values of these parameters are given by:

$$\beta_1 = u_r \left(1 - \frac{\sigma_n}{\sigma_T}\right)^{k_2} \tan i_0 + \frac{\sigma_n V_m}{k_{ni} V_m - \sigma_n} \qquad [13]$$

$$\beta_2 = \beta_1 - \frac{\sigma_n V_m}{k_{ni} V_m - \sigma_n} \qquad [14]$$

$$\beta_3 \cong \frac{1.5}{u_r} \qquad [15]$$

where V_m is the maximum closure of the joint and k_{ni} is the initial normal stiffness of the joint.

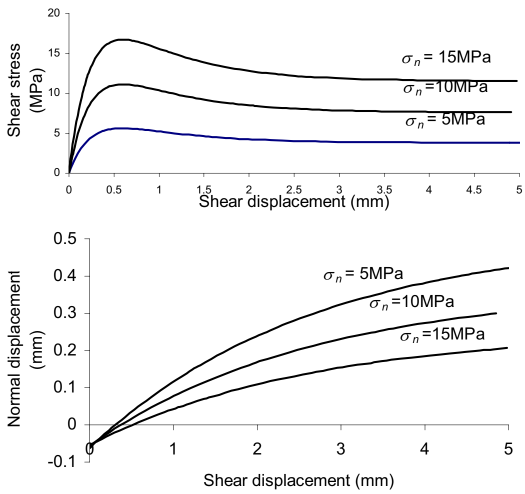

Figure 1. Typical curves obtained with the CSDS model.

Figure 1 shows curves obtained with the CSDS model. The CSDS model can very accurately predict the pre-peak behaviour and the stress reduction associated with the softening behaviour of joints under constant normal stress. This model has been applied to several sets of test data obtained from the literature and the results indicate that it is representative of the behaviour of rock joints (Simon 1999, Simon et al. 1999). The model can also predict rock joint behaviour under constant normal stiffness conditions. Simon et al. (2000) showed that the constitutive relations used to model discontinuities can have a significant influence on mining-induced stresses around an underground stope, especially when segments of the discontinuity are loaded beyond their peak strengths. The need for adequate constitutive relations to describe the stress reduction in the post-peak region becomes more relevant in the light of these results. The CSDS model can also be used to estimate the post-peak behaviour of intact rock (Simon et al. 2003).

3. SIMULATION OF SCALE EFFECTS WITH THE CSDS MODEL

3.1 Observation of scale effects in rock joint mechanical behaviour

The problem of scale effects in rock joint behaviour has been studied by several authors (e.g. Bandis et al. 1981, Barton and Bandis 1982, Pinto da Cunha 1991; Muralha and Pinto da Cunha 1992, Ohnishi et al. 1993), mainly by performing direct shear tests on different sized replica casts from various natural joint surfaces. The results indicate significant scale effects on both the shear strength and deformation characteristics. Increasing block size or length of joint leads to a gradual increase in the shear displacement at peak strength, an apparent transition from a brittle to plastic mode of shear failure, and a decrease in the peak dilation angle. The joint surface somehow appears smoother at larger scales (Rasouli and Harrison 2001). Scale effects are more pronounced in the case of rough, undulating joint types; whereas they are virtually absent for planar joints.

The peak shear strength of rock joints is a strongly scale-dependent property. The shear strength decreases non-linearly with joint length and tends to become asymptotic. Roughness is a dominating aspect at lower stress levels, while ϕ_r is of great importance at higher stress levels. Normal stiffness is not expected to be strongly scale-dependent along the discontinuity, but shear stiffness is evidently scale dependent. In shear tests at different scales conducted with normal stiffness control, the increase in the normal stress was less pronounced at larger scales due to reduced dilation. Scale effects should therefore be even more pronounced in stiffness controlled tests than in constant normal stress tests (Barton 1990).

3.2 Influence of scale on key model parameters

Among the four parameters used for the shear stress - shear displacement relationship in the CSDS model, the peak shear strength τ_p and the corresponding shear displacement u_p are much affected by scale effects. The residual strength τ_r on the other hand is more or less insensitive to scale effect, so ϕ_r can be considered as independent of scale according to Bandis (1990). As for the shear displacement at residual shear strength u_r, it is relatively insensitive in the CSDS model and is considered here to be independent of scale.

In the CSDS model, the LADAR (Ladanyi and Archambault 1970) criterion is used for the prediction of the peak shear strength τ_p (Eq. 8), which takes into account the basic friction of joint surface, dilatancy, and the shearing of asperities. In this criterion, the most scale-dependent parameters are i_0 and S_0. Parameter a_s, the ratio of the projected sheared asperity surface area to the joint surface area at the peak strength, may also vary as a function of joint size (Pratt et al. 1974; Yoshinaka and Yoshida 1993). However, experimental investigations performed by Re et al. (1997) have shown that the contact area to total area ratio only decreases very slightly with increasing joint surface size. Thus, in this study, parameter a_s is considered independent of scale. For the normal displacement - shear displacement relationship in the CSDS model, the parameters mostly influenced by scale effect are the initial asperity angle i_0 and the transitional stress σ_T (taken equal to the uniaxial compressive strength C_0). The rock joint characteristics which are used in the CSDS model are listed in Table 1. Scale relationships need to be established for the scale dependent parameters.

Table 1. Joint characteristics used in the CSDS model.

scale dependent	scale independent
i_0	ϕ_r
u_p	u_r
S_0	a_s
C_0	

3.3 Evaluation of scale effects using joint roughness geometry

Rengers (1970) measured asperity angles of natural joint surfaces over a range of sizes from 0.01 to 1000 cm using a variable focus microscope, a profilometer, and terrestrial photogrammetry. Corresponding to each selected step size, there was a distribution of roughness angles. For example, corresponding to step size $L = 1L_0$, the surface contained angles $\alpha_{1,A}$ through $\alpha_{1,F}$ (see Figure 2). Similarly, step $L = 2L_0$ contained angles $\alpha_{2,A}$ through $\alpha_{2,E}$ varying over a smaller range and so on for $L = 3L_0$, $4L_0$ etc. Rengers plotted those angles which corresponded to given values of L and constructed envelope curves, assuming that the steepest surface angle of contacting mating blocks regulates dilatancy during shear with over-riding asperities. The envelope of positive angles governs forward shearing while the envelope of negative angles governs backward shearing. Rengers (1970) found that the asperity angle varies inversely with the step size L.

The effective roughness mobilised upon shearing of joints of different lengths appears to be responsible for scale effects in rock joints (Bandis 1990). Scale effects on the shear strength may be caused by the influence of intermediate scale roughness of a wavelength not usually encountered in laboratory testing. Roughness of smaller scale acts only as interference and is sheared-off even at moderate stress levels. On the other hand, the intermediate scale roughness controls the dilation potential of a joint, as shearing through can only occur at much higher stress levels. The intermediate scale roughness largely determines the displacement needed to mobilise peak shear strength, which apparently increases with increasing joint length (Bandis 1993). It is postulated that the dimension of effective roughness, or the reasonable step size L for asperity angle measurement is proportional to the joint length l.

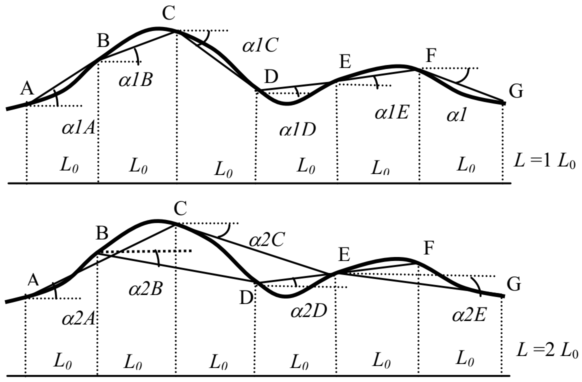

Figure 2. Example of roughness angle measurement (adapted from Goodman 1976).

3.4 A geometrical approach for scale effect on the initial asperity angle

- Measurement of initial asperity angle

Figure 3 is a joint profile taken from Bandis (1980). It was digitized so the geometrical asperity angles i_0 can be measured as

$$i_0 = a\tan\left(\frac{h}{L}\right) \qquad [16]$$

where L is the selected measuring step size, and h is the relative height between two measurement points on the joint surface of a width L.

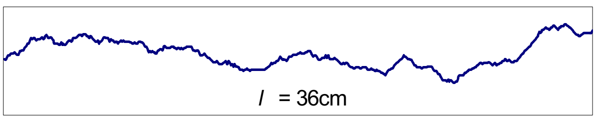

Figure 3. Profile of a rock joint (taken from Bandis 1980).

Using the same procedure as Rengers (1970), several asperity angles have been obtained along the joint surface. Envelopes were obtained as L changes from 0.7mm to 20mm. The mean envelope (for mean absolute value of the positive and negative geometric asperity angles, $i_{0\text{-}max}$) is plotted in Figure 4.

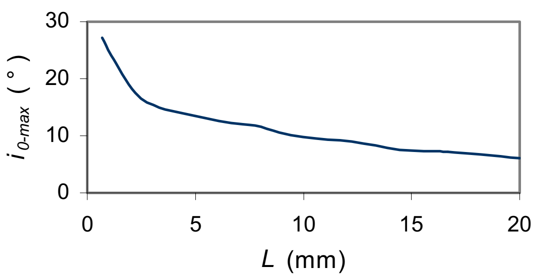

Figure 4. Envelope of geometric asperity angle.

- Determination of measuring step size

In the following, the step size L is considered to be proportional to the joint length l. Then, once the ratio L/l is fixed, there exists a corresponding L for each joint length l. To illustrate the approach, results of peak shear strength (under a normal stress σ_n of 24.5kPa) obtained by Bandis (1980) with different joint lengths are used. These results of peak strength $\tau_p(l)$ can be converted to a τ_p - L relationship and plotted on a graph of the envelope of asperity angle ($i_{0\text{-}max}$ *vs* L), as in Figure 5. Since the peak shear strength is directly related to the value of the asperity angle, by comparing the two curves, a ratio of L/l (corresponding to the mobilised effective roughness) can be determined. Figure 5 illustrates the values of τ_p and $i_{0\text{-}max}$ for L/l = 5.55%, which result in a correlation coefficient R^2 of 0.954 between τ_p and $i_{0\text{-}max}$. Varying the value of L/l, a graph of the correlation coefficient R^2 can be plotted as in Figure 6. For this example, the best correlation is obtained for L/l = 1.85%, with R^2 = 0.999. Thus, it has been determined that a step size of 1.85% of l for asperity angle measurement can be used for this case.

- Scale effect model for initial asperity angle

Using a value of L = 1.85% of l, the curve $i_{0\text{-}max}$ - L is then converted to an $i_{0\text{-}max}$ - l relationship as shown in Figure 7. It reflects the scale effect on $i_{0\text{-}max}$. A mathematical relationship can be set up to simulate this scale effect. According to laboratory test results, when the joint is rougher, the scale effect is more important (Bandis et al. 1981, Omnishi et al. 1993, Yang and Chen 1999). Inspired by Barton and Bandis (1982), a scale effect model for a joint roughness coefficient (see Eq. 21), the following equation is proposed to model the scale effect of $i_{0\text{-}max}$:

$$i_{0-max}(l_n) = i_{0-max}(l_0)\left(\frac{l_n}{l_0}\right)^{-\alpha\, i_{0-max}(l_0)} \qquad [17]$$

where l_0 is the basic joint length (from laboratory measurement), l_n is the length involved, $i_{0\text{-}max}(l_0)$ is the value of $i_{0\text{-}max}$ for $l = l_0$, and so as $i_{0\text{-}max}(l_n)$ for $l = l_n$. α is a parameter to be determined. In this equation, the exponent is function of roughness. Parameter α is obtained by fitting the converted curve $i_{0\text{-}max}$ - l (measurement) with Equation 17. Taking l_0 as 6 cm and its corresponding measured value of $i_{0\text{-}max}$, the values of $i_{0\text{-}max}$ for l_n = 12, 18, 24, 30, 36 cm for a given value of α can be estimated with Equation 17. As shown in Figure 7, for different values of α, a correlation coefficient is obtained for the measured and modelled values of $i_{0\text{-}max}$. The best correlated value is obtained for α = 0.017 (with a correlation coefficient of 0.995).

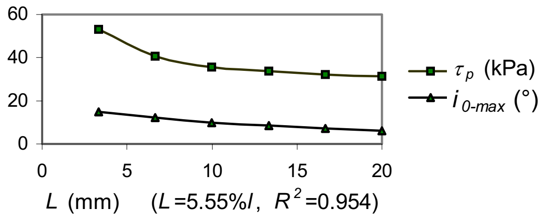

Figure 5. Correlation of geometric asperity angle envelope with peak shear strength.

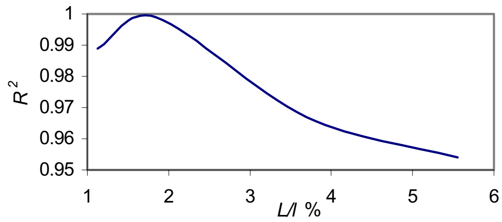

Figure 6. Evaluation of correlation coefficient with L/l.

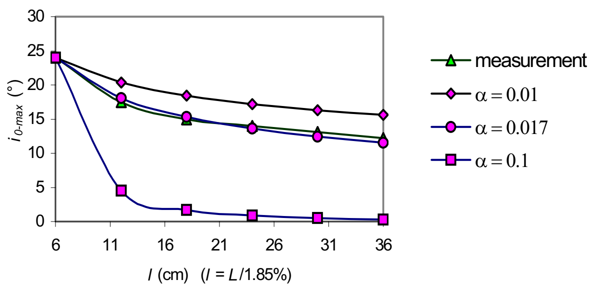

Figure 7. Determination of parameter α.

For the initial asperity angle i_0 used in the CSDS model, it is postulated that there is a linear relation between $i_{0\text{-}max}$ and i_0:

$$i_{0-max} = \eta \cdot i_0 \qquad [18]$$

where η is a material parameter independent of scale (as verified in the next section). Introducing Equation 18 in Equation 17, the scale effect model for the initial asperity angle i_0 is obtained as follows:

$$i_0(l_n) = i_0(l_0)\left(\frac{l_n}{l_0}\right)^{-0.017\ i_{0-max}(l_0)} \qquad [19]$$

where $i_0(l_n)$ is the value of i_0 for $l = l_n$, and $i_0(l_0)$ is the value of i_0 for $l = l_0$.

3.5 Scale effects on the other CSDS model parameters

Table 1 lists the four scale dependent parameters in the CSDS model. Equation 19 presents the effect of scale on the initial asperity angle i_0 used in the CSDS model. For the scale effect on shear displacement u_p, the relationship used is the one proposed by Barton and Bandis (1982):

$$u_p = \frac{l_n}{500}\left(\frac{JRC_n}{l_n}\right)^{0.33} \qquad [20]$$

with

$$JRC_n = JRC_0\left(\frac{l_n}{l_0}\right)^{-0.02 JRC_0} \qquad [21]$$

where JRC_0 and JRC_n are the laboratory and field joint roughness coefficients, respectively.

For an unweathered rock joint, the joint compression strength JCS equals the uniaxial compressive strength C_0 of the rock (Barton and Choubey 1977). Therefore, the scale effect on C_0 can be presented by the scale effect model of the joint compression strength JCS in Barton and Bandis (1982) as:

$$JCS(l_n) = JCS(l_0)\left(\frac{l_n}{l_0}\right)^{-0.03\, JRC_0} \qquad [22]$$

where $JCS(l_n)$ is the value of JCS for $l = l_n$, and $C_0(l_n) = JCS(l_n)$; $JCS(l_0)$ is the value of JCS for $l = l_0$, and $C_0(l_0) = JCS(l_0)$.

For the cohesion S_0, using the value of $C_0(l_n)$ in the Mohr-Coulomb criterion, we get:

$$S_0(l_n) = \frac{C_0(l_n)(1 - \sin\phi_r)}{2\cos\phi_r} \qquad [23]$$

The scale effects on rock joint behaviour are represented with the CSDS constitutive model using values obtained with Equations 19, 20, 22 and 23. In practice, once the laboratory test sample ($l = l_0$) is prepared, the parameter $i_{0\text{-}max}$ of the sample joint can be measured geometrically with the measuring step L = *1.85% of* l. The other parameters are obtained from laboratory testing. The scale dependent parameters (see Table 1) of the joint at different lengths ($l = l_n$) can be estimated with the scale effect relationships and its behaviour can be predicted with the CSDS constitutive model, as will be shown in the following section.

4. VALIDATION AND APPLICATION

4.1 Validation for asperity angle relationship

Figure 8 presents results of laboratory tests performed by Bandis (1980) on rock joints of different lengths under a constant normal stress (σ_n = 24.5kPa). This figure shows the measured normal displacement - shear displacement (v - u) for the joint surface profile of Figure 3. The material was a mixture of silver sand, calcined alumina, barytes and Paris plaster with water. The sample joint lengths were 6 cm, 12 cm, 18 cm and 36 cm, respectively. The joint length of 6 cm is taken as the basic measurement (l_0 = 6cm).

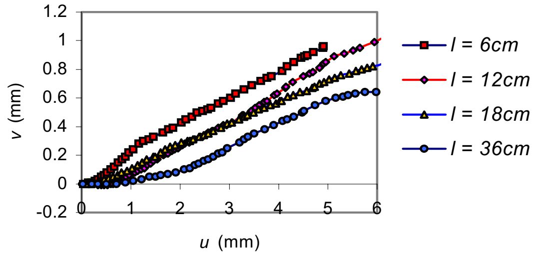

Figure 8. Measured dilation curves (from Bandis 1980).

Parameters for the basic joint length take the following values: uniaxial compressive strength C_0 = 2.0 MPa, basic friction angle ϕ_b = 32° ($\phi_r = \phi_b$), peak shear strength τ_p = 50.4 kPa and the corresponding shear displacement u_p = 0.9 mm (Bandis 1980). The residual shear strength is calculated to be $\tau_r = \sigma_n \tan\phi_r$ = 15.31 kPa. The residual displacement u_r was not obtained in the test so the value of u_r can not be determined from the test results. However, it can be back calculated with the CSDS model by curve fitting. To do so, an iterative approach is taken where the value of u_r is modified so the point m shown in Figure 9a (which was the maximum value obtained in the test) would fit the value predicted with the CSDS model (Eq. 1). This led to a value of u_r = 31.7 mm. The asperity angle i_0 for the basic joint length l_0 is determined by fitting the dilation results with the CSDS model for the normal displacement - shear displacement relation. The value calculated was $i_0(l_0)$ = 11° (Fig. 9b). The profile of the joint was analysed and the value of $i_{0\text{-}max}(l_0)$ measured with L = 1.85% of l_0 was 24°.

The scale effect relation for i_0 (Eq. 19) is used for the other joint lengths, which gives $i_0(l$=12 cm) = 8.3°, $i_0(l$=18 cm) = 7.0° and $i_0(l$=36 cm) = 5.3°. Eq. 22 leads to values of $C_0(l$=12 cm) = 1.41 MPa, $C_0(l$=18 cm) = 1.15 MPa and $C_0(l$=36 cm) = 0.81 MPa. The normal displacement - shear displacement relations for the other three joint lengths with the same normal stress can then be predicted with the CSDS model. As shown in Figure 10, they are in good agreement with the laboratory measurements. This indicates that the assumption that the parameter η (used in Eq. 18) is independent of scale is acceptable.

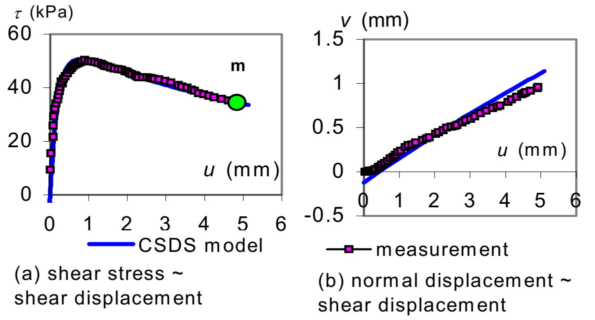

Figure 9. Simulation of the basic measurements (l_0 = 6cm) (from Bandis 1980) with the CSDS model.

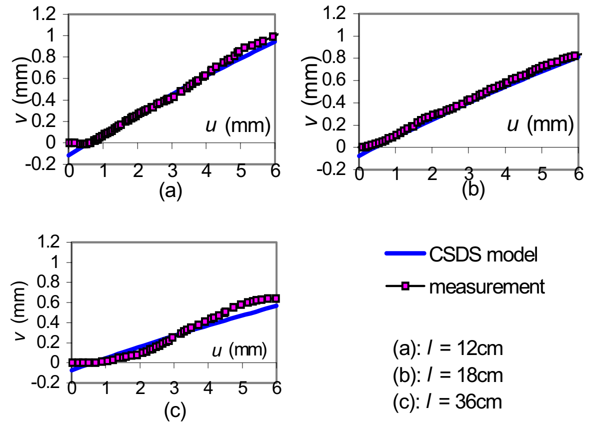

Figure 10. Measured (from Bandis 1980) and predicted dilation curves for different joint lengths.

4.2 Shear stress - shear displacement prediction for the results of Bandis (1980)

To predict the complete shear stress - shear displacement curves for different joint lengths with the CSDS model, other parameters must also be determined. The joint roughness coefficient for the basic joint was JRC_0 = 16.8 (Bandis 1980). The values of parameter u_p are calculated with Equation 20, and u_p = 1.14 mm, 1.42 mm and 2.27 mm for l = 12 cm, 18 cm and 36 cm, respectively. For the estimation of the peak shear strength, the LADAR criterion is used. According to the measured value of τ_p for basic joint length l_0, the value of a_s is equal to 0.05 for this joint.

The CSDS model can reproduce the shear stress - shear displacement relation for the basic test (l = l_0) as shown in Figure 9 fairly well. Using the proposed approach, the CSDS model can predict the shear stress - shear displacement relationship for the other joint lengths of l = 12, 18 and 36 cm, as illustrated in Figure 11. As can be seen, the CSDS model provides good correlation with the measured $\tau - u$ curves.

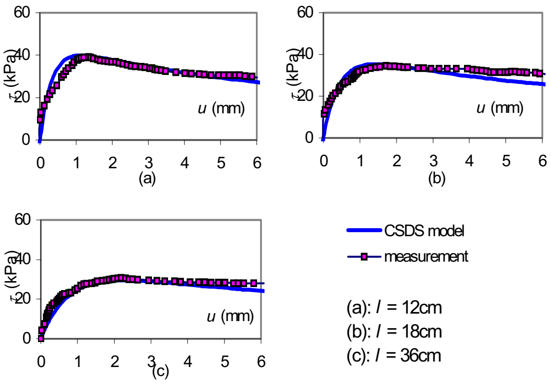

Figure 11. Measured and predicted shear strength - shear displacement curves for different joint lengths (data from Bandis 1980).

4.3 Application to the laboratory tests of Ohnishi et al. (1993)

Ohnishi et al. (1993) have performed a series of experiments to investigate the peak shear strength scale effects of natural and artificial joints. Several specimens were cast using the same joint surface with cement mortar. Direct shear tests were performed on the specimens cast with irregular surfaces. The sample joint lengths were 8 cm and 12 cm, and the normal stress applied was 2.0 MPa. The joint length of 8 cm was taken as the basic laboratory test size (l_0 = 8 cm).

First, the CSDS model parameters for the basic test are determined. Shear stress experiments were carried out for specimens with a diamond saw cut smooth surface. The mean basic friction angle for this cast cement mortar material is ϕ_b = 33° (Ohnishi et al. 1993). Results gave a peak shear strength τ_p = 2.80 MPa, and a peak shear displacement u_p = 0.91mm. From Eq. 20, the joint roughness coefficient obtained is JRC_0 = 15.4. The joint compression strength is determined as JCS_0 = 50 MPa (equal to C_0). The value of parameter a_s was estimated to be 0.071 for this specimen. Here again, the residual strength was not attained during the test and the same procedure was used to estimate the value of u_r (Fig. 12a), which gave a value of 39.7 mm. The residual shear strength was calculated as $\tau_r = \sigma_n \tan\phi_r$ = 1.56 MPa (with $\phi_r = \phi_b$). With the dilation measurement of the basic test, the initial asperity angle $i_0(l_0)$ in the CSDS model was estimated at 12° (Fig. 12b). It can be seen from Figure 12 that the CSDS model simulation correlates well with the laboratory measurement for the basic test.

Next, the scale dependent parameters for the length of 12 cm were obtained using the scale effect model. With a measuring step L = 1.85% of l_0 = 1.5 mm, the joint profile was measured as described in Section 3 and the maximum geometrical asperity angle $i_{0\text{-}max}$ obtained was 26.7°. The scale dependent parameters for the length l = 12cm were calculated as follows: i_0 = 10°, C_0 = 41.5 MPa, and u_p = 1.14 mm.

The joint shear strength - shear displacement and the dilation - shear displacement relations for joint size l = 12 cm were then predicted with the CSDS model as shown in Figure 13. By comparison with the measurements, it can be seen that the CSDS model can predict the behaviour of the joint fairly well.

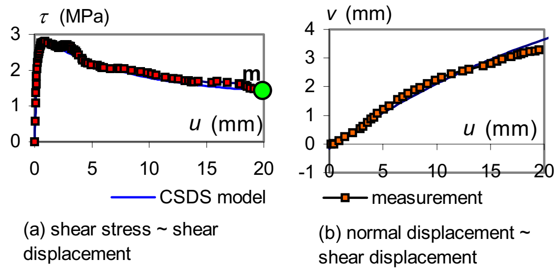

Figure 12. Simulation of the basic measurements (l_0 = 8cm) of Ohnishi et al. (1993) with the CSDS model.

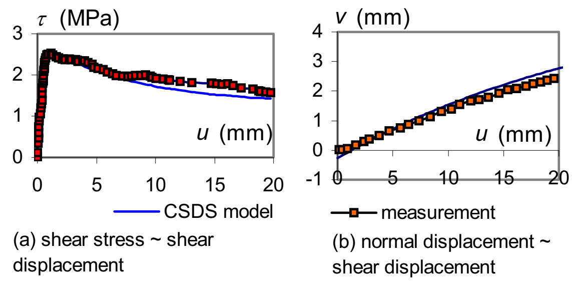

Figure 13. Measured (Ohnishi et al. 1993) and predicted results for joint length l = 12cm.

5. CONCLUSION

Several shearing characteristics of rock joints, such as the shear strength, shear stiffness, and joint wall compression strength are strongly scale-dependent. Thus, any constitutive model for the shear behaviour of rock joints should take into account scale effects. Based on the fact that the effective roughness mobilised upon shearing of joints of different lengths is responsible for the scale effects of rock joint behaviour, a geometrical approach was proposed to simulate the scale effect of the asperity angle of the joint surface. With a suitable measuring step L, which was determined to be approximately 1.85% of the joint length l, the geometrical asperity angle of rock joint surface is measured. It is verified that the effective geomechanical asperity angle is proportional to the geometrical asperity angle. Using existing laboratory measurements of shear strength for different joint lengths, a scale effect model is established for the effective geomechanical asperity angle. This model uses the physically measured geometrical asperity angle to represent proportionality between roughness and scale effect.

With the physical approach presented herein, the scale effect for the asperity angle and the Barton and Bandis scale effect model for parameters u_p and JCS (or C_0), scale effects can be taken into account in the CSDS rock joint constitutive model. Applications of the CSDS model with scale effects on laboratory shear test results for different joint lengths showed that the CSDS model can adequately represent the mechanical behaviour of rock joints. It was shown that the proposed scale effect model with physical approach is satisfactory for the estimation of scale effects on the behaviour of rock joints and fractured rock masses.

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