An Experimental Study on Scale Effects in Rock Mass Joint Strength

Manuel J.A. Leal Gomes, Carlos Dinis da Gama

Abstract. A series of laboratory tests were conducted on matched rock joint samples, no larger than 16 x 16 cm^2 of section, which were extracted from an artificial joint, having 4.32 m^2 in area, carved in a porphyritic granite block. These tests (1200 pull tests and 200 trials conducted in a sliding machine) involved the systematic levelling of sample middle planes and lead to conclusions that are discrepant with respect to conventional ideas admitted about rock-mass joint mechanics. Those discrepancies are: a) Larger matched samples showed higher strengths in the dilating phase of the sliding tests rather than those from small matched samples; b) Sample shear strengths probably depend on the transverse widths, when *JRC*, *JCS* and σ_n (the average normal stress on the rock mass joint) are high, thus inhibiting the use of stability analysis by common slope stability methods such as Fellenius'; c) At the dilating sliding phases, the mechanics of matched joints is essentially different from that of mismatched joints, as the former brings about inverse scale effects (represented by positive exponential regressions) and the latter involves normal scale effects (represented by negative exponential regressions). The results obtained upon those lab tests do not agree with those reported from *in situ* experiments, as well as the actual behaviour of natural joints. The obtained moderate correlation coefficients do not allow the consideration of these findings as physical laws, nevertheless they do represent certain types of rock mass joint behaviour, or simply useful generic rules. Thus, the subject is full of surprises, as the authors show in text.

Keywords: rock joints, scale effects, dilating sliding phase, matched and mismatched joints, pull-tests, joint strength models, experimental *JRC*.

1. Introduction

Several authors (Charrua Graça, 1985; Cunha, 1990; Bandis, 1990) who contributed to the current state of the art on scale effects in rock joint strength, noted a rather strange progression. Before the Seventies, most authors studying the problem - sometimes using rock joint samples with large areas - found inverse scale effects (that is, increasing average strength values as sample dimensions increase, tending towards an asymptotic value (as explained by the so called representative elementary volume, REV). This behaviour is represented by positive exponential regressions. Probably influenced by the classic experimental works by Barton & Choubey, 1977 and Bandis, 1980, most authors generally reported normal scale effects on joint strength (represented by negative exponential regressions). However, there were also rare exceptions (Swan & Zongqi, 1985; Kutter & Otto, 1990; Giani *et al.*, 1992).

In essence, whether scale effects are normal or inverse is of great importance in assessing the significance of data drawn from small samples testing, which may be very serious when safety of civil and mining works depends on a correct assessment of field conditions. If the scale effect is inverse, data from small samples are on the engineering safe side; if it is normal, they become against workings safety.

However, the problem is not that simple because lithological, morphological and mechanical conditions of small samples are not comparable to those of large samples due to sampling biases. This means that individual small samples cannot represent the weathered and crushed zones of large ones. On the other hand, large discontinuities in nature are commonly mismatched, because shear displacements are more frequent as the joint dimensions increase (Leal Gomes, 1999a), so this fact favours the appearance of normal scale effects. Besides, the undulations of large matched discontinuities have larger amplitudes than those of small samples, where sometimes only the smaller roughnesses are present. But the amplitudes of undulation or roughness provide a favourable contribution to joint strength which is not foreseen by any limit equilibrium model, like Patton's model (Patton, 1966).

Therefore, the problem under analysis is a complex one (Leal Gomes, 2000) for it is necessary to observe many features: the matching or mismatching of rock discontinuities, the presence of weathered and crushed zones, sampling biases, the characteristics of the undulation and roughness of the walls, the test conditions and other aspects that strongly constrain the estimation of the scale effect on the joint mechanical parameters.

In order to understand the integrated behaviour of those multiple effects, numerous experimental tests on samples from a large artificial joint existing in a porphyritic granite from Pontido (Vila Pouca de Aguiar, Portugal) were carried out. They helped to devise the achievement of sev-

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Submitted on February 14, 2008; Final Acceptance on March 2, 2009; Discussion open until April 30, 2009.

eral assertions and essential conclusions in the domain of rock mass joint mechanics.

2. Choice of Test Material

The greatest difficulty in rock discontinuity testing is the acquisition of a sufficient number of samples to obtain representative data, as it is often necessary to reuse the same sample several times in laboratory mechanical tests. During each test there is wearing of sample walls and due to that, successively obtained data are not rigorously based on the same initial test material, which brings about serious interpretation problems.

Bandis (1980) used sample casts in synthetic material of a natural joint but the difficulties of this procedure are well known, for they include the fitting of sample properties to the similarity conditions given by dimensional analysis and the physical acquisition of samples in good conditions. Bandis himself refers to the mismatching ("rocking") of their synthetic samples, which surely had a great influence on their conclusions, as it will be observed. Gracelli (2001) also used casts in synthetic material but not referring the similarity conditions. On the other hand, his experimental study was not dedicated to scale problem analysis, like Bandis' thesis and this paper, which involve other types of questions.

Barton & Choubey (1977) assert that the testing of ten samples having the same size provides reliable strength averages for those dimensions. Harrison & Goodfellow (1993) studying discontinuity roughnesses in granites with Renger discs (Brown, 1981) concluded that their scale effect disappeared for sample dimensions larger than 25 cm x 25 cm. However, the variation of parameters describing roughness (considered the most important factor on scale effect studies of joint strengths at the dilating phase of slides), is mainly due to the resultant vector of normal directions to the discs and of the roughness anisotropy, and cease to be important from a REV around 250 cm^2 (16 cm x 16 cm) of roughness and anisotropy (Leal Gomes, 1998).

The opening of an artificial discontinuity, by introducing chisels in a large block of porphyritic granite having 2.7 x 1.6 x 1.5 m^3 in volume was decided, in an attempt to contribute to the clarification of these matters. These dimensions are close to the sizes of the natural blocks observed near the surface of the Pontido batholith and that artificial joint in particular had about 4.32 m^2 in area. Artificial discontinuities are different from the natural ones because of their better matching, higher roughness, absence of wall weathering and lower hydraulic conductivity (Gale, 1993).

The following samples corresponding to the maximum possible utilization of the available material were extracted: 8 square samples type I (16 x 16 cm^2), 8 rectangular samples type II (16 x 10.7 cm^2), 9 samples type III (16 x 8 cm^2), 9 samples type IV (16 x 5.3 cm^2) and 5 samples type V (10.5 x 8 cm^2). This number of samples is lower than that recommended by Barton & Choubey (1977) but they are still significant, as the small scattering of data shows.

3. Morphology of the Discontinuity Samples

The discontinuity walls of these samples were sound, rough and well mated, having an average *JCS* (joint compressive strength) of 115.4 MPa and a residual friction angle (φ) of 28°, obtained in pull tests with completely smooth and plane surfaces. The rock had an average density of 2.72 g/cm^3 and a Young modulus of 59 GPa, obtained on prismatic samples having 6 cm x 6 cm x 15 cm. It had feldspar megacrystals, up to 2 cm in length, in a quartz, biothite and clorhite matrix.

All the samples were photographed under oblique light, which accentuates the wall relief and roughness, as well as contrasts between crests and valleys. After this operation the contour profiles of all the sample walls were outlined on white paper using a pencil and the corresponding *JRC* was estimated through comparison with the Barton & Choubey (1977) typical profiles.

Prior to testing, prints in smooth tracing paper were made of the actual contact areas between the sample walls in their best fit positions, under an average normal stress in the joint (σ_n) of 10 kPa (before pull tests) and 1.2 MPa (before tests in the sliding machine). The prints were produced by using thin sheets of blue dentist paper introduced with smooth tracing paper between the joint walls. The obtained spots were analysed through image processing by scanning the prints at 400 DPI and leading to histograms of different grey levels. This method proved to be sufficiently objective to allow general quantitative conclusions, while the other referred methods only provided qualitative ideas on sample roughness.

4. Sample Roughnesses

Averages and dispersions of *JRC* parameters obtained through comparison between sample walls and the typical profiles of Barton & Choubey (1977), varying between 8 and 16, did not exhibited scale effects. The main reason for this fact is the great subjectivity of these comparisons, as it was demonstrated by a tendency to focus on the more abrupt aspects of the profiles and of the wall surfaces (Leal Gomes, 1998), which increases the *JRC* obtained by comparisons. On the other hand, the amplification and the reduction of the typical profiles, in order to make those comparisons among profiles of different lengths, is quite invalid. These *JRC* obtained by visual comparison only have a morphological content. In fact, the typical profiles of Barton & Choubey (1977) were obtained by outlining the profiles of their original joint samples, followed by performing pull tests and attributing to them the *JRC* deduced from Barton's model (1990):

$$JRC = \frac{\tan^{-1}\left(\frac{\tau}{\sigma_n}\right) - \varphi}{\log\left(\frac{JCS}{\sigma_n}\right)} \qquad (1)$$

where τ is the peak shear strength.

Therefore, these *JRC* are experimental and have not only morphological meaning but also mechanical contents and are not only roughness parameters but also strength properties. For instance, the experimental *JRC* also depends on the amplitude of roughness, as the typical profiles of Barton & Choubey (1977) demonstrate, increasing their *JRC* as the amplitude of profiles increase. Besides, the mental amplification and reduction of profiles is based on an erroneous principle, asserting that rigorously homothetical changes with the scale of roughness of the original samples of Barton & Choubey (1977) does not change their *JRC*.

This assertion needs experimental demonstration and probably is wrong. Such comparisons also outlook the differences between *JCS* and σ_n of the original samples of Barton & Choubey and the *JCS* and σ_n of the other samples and discontinuities taken in the field. Therefore, the values of *JRC* estimated by comparison only have a geometrical content and so deducting strength parameters from them is not correct.

In this study, *JRC* data obtained by comparison did not detect either the obvious anisotropy in the samples direction, which is visible through the drawing of the sample contours (Fig. 1) or the smaller anisotropy of orientation (for instance, NS direction has two possible orientations, NS and SN), which was shown by subsequent pull tests.

The data distribution of the maximum amplitudes of roughness (R_{max}), which were measured between the highest crest of a sample wall and its deepest valley, suggests not only the increasing of R_{max} as the larger linear dimension of the sample increases, but also that R_{max} does not depend on the smaller sample dimension (Table 1). For instance, the values of average and maximum R_{max} are clearly lower in samples of type V (size 10.5 cm x 8 cm) than in other sample types where differences on R_{max} are nearly always smaller.

But the most important information given by the outline of the sample wall contours was the clear image of shorter dimensions, showing lower roughness values than larger ones, which is contrary to the assertions of most authors (Cunha,1990; Barton, 1990; Bandis, 1990; Pistone, 1990; Maerz & Franklin, 1990), who usually assert that smaller lengths have larger roughness magnitudes.

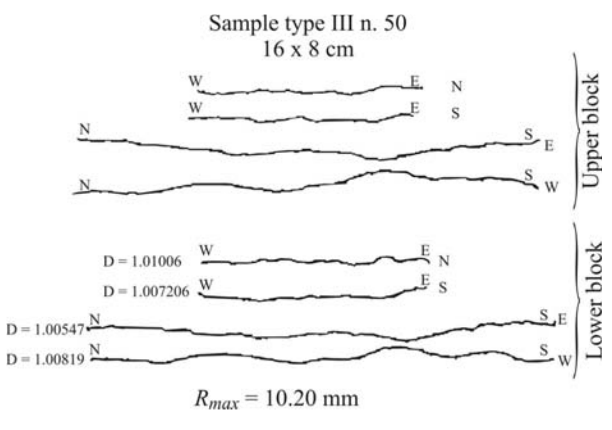

Figure 1 - Contour profiles of sample type III n. 5D.

5. The Problem of Sample Roughness

Patton's model (Patton 1966) asserts that the joint strength in the dilating phase of rock joint sliding is given by:

$$\tau = \sigma_n \tan(\varphi + i) \qquad (2)$$

where *i* is the dilation angle given by the slope of joint asperities. Patton checked experimentally this equation for low normal stresses σ_n .

At UTAD, a series of pull tests were conducted under a σ_n of 0.6 kPa on moulded discontinuities made with Portland cement mortars and river sand. These discontinuities had homothetical triangular asperities presenting slopes around 20°, 30°, 45° and 60° as well as different heights or amplitudes (h) of 0.6, 1.2, 1.8 and 2.4 cm (Fig. 2). Upon the shear testing, Patton's model was verified, except for some slight fluctuations of shear forces attributable to effects of spurious momentums developed during slidings which are not foreseen by Eq. (2)).

Therefore, τ depends on *i* and not on h for regular asperities. However, when the work done by shear forces involved in slides is considered, it was observed that it changes for the same *i* as h increases. Actually, the strengths of these joints having the same *i* but different h are not rigorously described by shear forces but by the strain energies needed for sliding. These energies cannot be measured in the laboratory or in field but may be roughly calculated, so adequate representation of real joint strengths in the dilation phase is not possible.

However, this dilemma probably is mitigated by the less schematic conditions of the asperities in natural discontinuities. A sudden upper wall sliding was observed

Table 1 - Maximum amplitudes of roughness.

Sample type (cm^2)	R_{max} (mm)		
	Average	Maximum	Minimum
I - 16x16	10.72	14.5	8.3
II - 16x10.7	12.72	16.85	10.9
III - 16x8	10.59	15.3	8.3
IV - 16x5.3	10.71	13.3	8.05
V - 10.5x8	9.37	11.5	8.3

(Leal Gomes 1998) in pull tests on samples from the large artificial joint previously mentioned, when having imbricated asperities and several roughness levels (roughness levels are undulations having the same amplitude but either different wave-lengths, or their crests shifted from each other). In the tests with regular homothetical teeth mentioned above, the overcoming by the upper wall of regular asperities was a gradual one.

Therefore, in natural matched discontinuities having irregular asperities with different i, h and morphologies, the amplitude of roughness in the dilating phase has probably implications on the peak shear force, which is accumulated against the asperity faces until their sudden yielding (Leal Gomes 2000; Gracelli 2001). In that case, the higher the asperities are, the larger is the shear force. Therefore, for the same σ_n and morphological i (but different h) there are different values of tan ($\varphi + i$) and i deduced from Patton's model values, so the linear dimensions of amplitude are transformed into dimensionless increases of the dilation angle, and the asperity amplitudes are taken into account by variations of dilation without morphological correspondence.

The above mentioned dilemma is solved, although with loss of physical information, however, intermediate behaviours of difficult evaluation are possible. This approach still demands a better experimental verification, but this principle may be checked with the typical profiles of Barton & Choubey (1977) where higher *JRC* corresponds to profiles having higher amplitudes. These *JRC*, like the experimental *JRC* of this paper, were experimentally deduced from Eq. (1) of Barton's model.

This assertion was presented to point out the use of linear dimensions, like R_{max}, for representing joint strength and not dimensionless parameters, as it is done usually. At present, no strength model includes these linear parameters, including recent approaches such as that of Gracelli's model (Gracelli 2001).

Thus, it was demonstrated that small samples have lower roughness than larger ones, quite the opposite to what usually is admitted by most authors, if and when the middle plane of all samples is levelled. Furthermore, small samples must have necessarily lower roughness than large ones (from the same joint) because the linear parameters related to asperity amplitudes - such as R_{max}, or the average of distances to middle line (CLA), or the standard deviations of roughness amplitudes, RMS (Muralha 1995) or even the dimensionless roughness parameters, like Z_2 (Tse & Cruden 1979), dilation angle (i), R_p (quotient between the length of a profile and its middle line length (Sage *et al.* 1979) and D (fractal dimension) - diminish as the middle planes of smaller and smaller samples are levelled. In Gracelli's model (Gracelli 2001), the parameter A_c which is the potential contact area ratio for a threshold dip angle of asperities is given by:

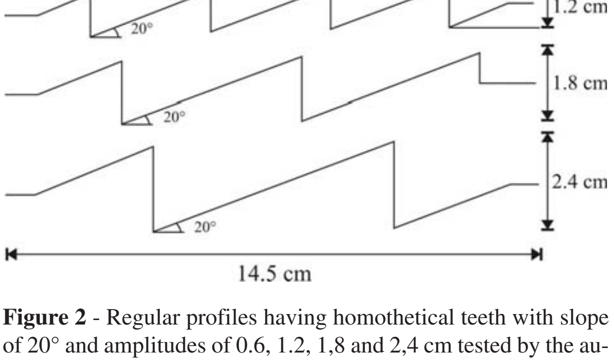

Figure 2 - Regular profiles having homothetical teeth with slope of 20° and amplitudes of 0.6, 1.2, 1,8 and 2,4 cm tested by the authors in UTAD.

$$A_c = A_0\left(\frac{\theta^*_{\max} - \theta^*}{\theta^*_{\max}}\right)^c \quad (3)$$

where A_0 is the maximum possible contact area of the joint walls, θ^* the apparent dip inclination of asperities, $\theta^*_{\max}$ the maximum apparent dip angle in the shear direction and c a roughness parameter calculated using a best fit function, which characterizes the distribution of apparent dip angles over the surface, also denote a roughness reduction as smaller and smaller samples are levelled.

Figure 3 demonstrates that the division of a large sample into small samples, accompanied by their systematic levelling, reduces R_{max} on each small sample with reference to the large sample. And it is easily understood that reducing the asperity slopes in a large sample by dividing it into small samples, which are systematically levelled, if the samples are systematically subdivided into very small dimensions and the middle planes of all samples are levelled, in the limit, as areas tend to zero, leads to obtaining horizontal joint surfaces. To the contrary, in the limit one shall have almost vertical surfaces with the traditional procedure, *i.e.*, by leaving the middle plane position at random.

This is obviously the result of a roughness idea that is very close to a mechanical conception of the problem, where indices like amplitude, wave-length roughness, undulation and asperities slopes are very important. The laboratory tests on matched samples are thus on the safe side of engineering in the dilating phase of slides with reference to the large original natural matched discontinuities, whenever all of them are levelled.

With this procedure, the mechanical and morphological aspects connected with asperity slopes are also affected by subdividing and levelling of samples, resulting in lower morphological indices, lower average dilation angles and even lower *JRC* deduced from Barton's model.

So, previous conceptions may need revision where only the morphological aspects connected with asperity slopes prevail, like the calculation of *JRC* from a fractal dimension (D). Actually, Fig. 1 shows that shorter profiles of

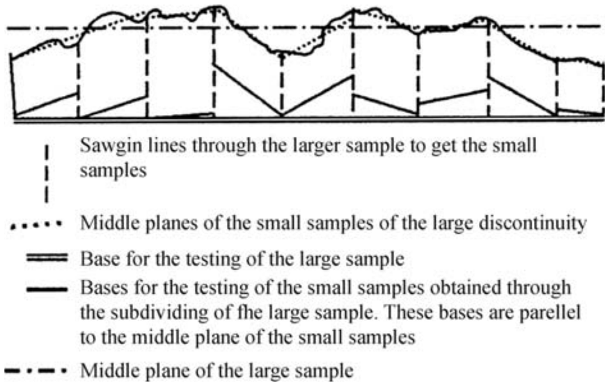

Figure 3 - Subdivision of one large sample into nine small samples and systematic levelling of their middle planes.

the samples 5D seem to have higher fractal dimensions but lower roughness, contradicting the well known statistical regressions such as:

$$JRC = 1000\,(D - 1) \tag{4}$$

For instance, in the direction of the larger contour profiles of the rectangular sample 5D, the experimental value of *JRC* is 10, but in the direction of the shorter profiles it is only 8, but a different *JRC* obtained from the experiments is deduced from Eq. (4).

In Fig. 1, the greater amplitude of roughness of the larger profiles favouring the strength is observed. Actually, these regressions equations like 4) are supported by a traditional view of scale effects on joint strength, involving strength reduction as sample sizes increase and this perspective is supported by tests on mismatched samples. This fact completely changes the scope of considerations by Bandis (1980), who refers the mismatching of their synthetic samples. The model of Peres Rodrigues & Charrua Graça (1985) would be more adequate for them, but not Patton's model. It is remarked that Peres Rodrigues & Charrua Graça's model implies normal scale effects, which are precisely due to sample mismatches.

Hencher *et al.* (1993) repeated Bandis tests on the same synthetic material but they found a scale effect having a maximum value for intermediate dimensions, probably because they did not level the samples and tested different combinations, up slope and down slope, of middle positions of joint samples. The importance of this aspect is more serious when the discontinuity is rougher, because it is equivalent to either add or subtract from *i* a spurious angle which seriously influences higher tan ($\varphi + i$).

Besides that, the partition of a sample is a highly arbitrary operation, as Fig. 4 demonstrates, where only the s surfaces resist, if the larger a) sample is tested from North to South. When that sample is broken in five smaller volumes b), the u surfaces will also be tested and the resulting spurious results will affect the average strength values, which are much different from those of a). At u there is a spurious shear component of σ_n favouring the sliding.

In samples taken from natural discontinuities there are roughnesses and undulations of several ranks or orders that are characterized by their different amplitudes. The lower amplitude is the first order one, having roughnesses and undulations of higher order as h increases. It is more probable to have undulations of higher amplitudes with larger samples, whose slides require greater applied shear forces. It is also still necessary to consider different roughness levels and different types or shapes of asperities.

Therefore, the observation of a discontinuity roughness is a complex task. On this account, to cut a sample off may correspond to the removal of some orders, levels or types of roughness, as Fig. 5 indicates, where AA divides a larger sample into smaller samples having different anisotropy of orientation from the original sample context and where levels and types of roughness were removed with important mechanical consequences.

Bandis (1980) demonstrated that the actual contact areas between joint walls are larger and more distant in large samples, which have larger empty spaces. With small samples the contacts are smaller and more scattered. With samples of the artificial joint removed from the Pontido granite block, it was observed that the percentage of actual contact area (Aef), obtained in accordance with section 3, with reference to the total sample area (Aa or Area) is greater in small samples than in large samples (Leal Gomes 1998, Fig. 6). Therefore, the actual stresses in real contacts between walls (Sigef = σ_n.Aa/Aef) are higher in larger

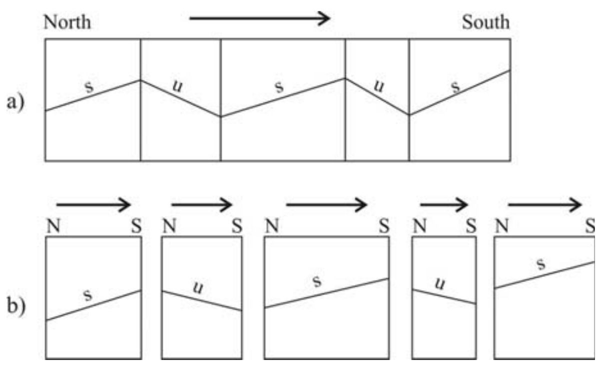

Figure 4 - Conceptual experience about the arbitrariness of subdividing a large sample into small samples.

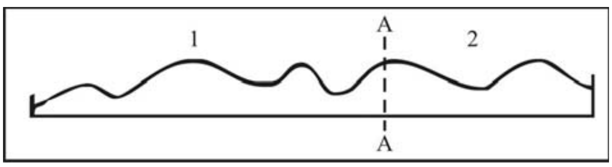

Figure 5 - Division of a sample in accordance with AA into two smaller an asymmetrical samples.

samples, but this difference diminishes as σ_n increases because the bending of walls on larger empty spaces in large samples, bringing their walls in contact and thus increasing Aef, which is easier in those large samples rather than in small samples. In spite of the low correlation coefficients *R* in the Aa vs. (Aef/Aa) plotting, the original variation of Aa *vs.* Aef had $R = 0.48$ (for σ_n of 10 kPa) and 0.66 (for σ_n of 1.2 MPa).

Gracelli (2001) found actual contact areas between their joint sample walls very much higher than those of Fig. 6 (up to 70% or more in fresh tensile joints). Their joint sample walls had an almost perfect matching because they were obtained into small prisms of rock having transverse areas of tens of cm^2, while the samples of the present experimental study were withdrawn from a large artificial discontinuity having 4.32 m^2, created from a 2.7 x 1.6 x 1.5 m^3 granite block. Leal Gomes (2001b) demonstrates that to obtain this joint in the vicinity where the rupture surface passes following the rock imperfections is much greater for the larger volumes of rock than for smaller ones, leaving a great amount of dust and rock fragments between walls in the first case to the detriment of their matching, which does not happen in smaller rock volumes. On the other hand, the features which control the rupture during the production of natural joints are different at two different scales. Therefore, the roughness patterns obtained either in great or in small rock blocks and their morphologies are of difficult correlation.

Concisely, an expeditious observation of the facts demonstrates that the artificial joint samples of Pontido have essentially only one roughness order, with an amplitude around 1 cm and smaller asperities swinging around this roughness. It was verified that sample areas were large enough to contain the greater amplitude of roughness in the whole 4.32 m^2 original artificial discontinuity. Therefore,

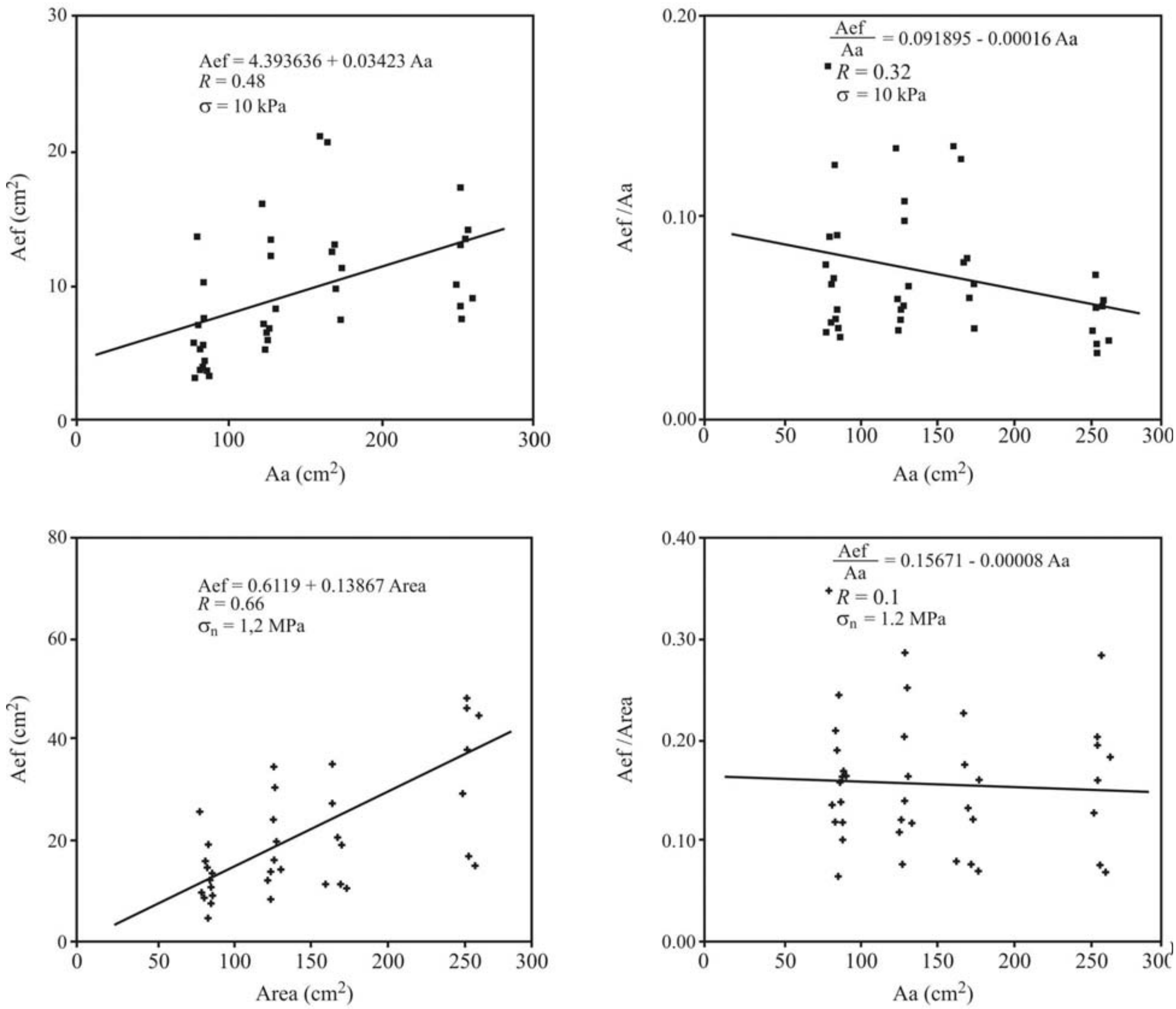

Figure 6 - Graphics (Aa x Aef) and (Aa x (Aef / Aa) for σ_n of 10 kPa and 1.2 MPa. *R* is the correlation coefficient.

an area of 16 cm x 16 cm is probably close to the roughness REV for this artificial discontinuity in granite, as suggested by Harrison & Goodfellow (1993).

6. Pull and Sliding Machine Tests

A total of 1200 pull tests on those joint samples loaded under σ_n of 1 kPa were carried out in two directions, both parallel to the rectangular contour edges. The NS direction was always parallel to their larger dimension (usually 16 cm and 10.5 cm at samples type V) and the EW direction was perpendicular to it. Samples were tested in accordance with NS and SN orientations at the NS direction, and WE and EW orientations at the EW direction. The middle plane of all the joint samples was previously levelled before each test in accordance with the two discontinuity sample lower wall diagonals (Fig. 7). At least three pull tests were carried out for each orientation of each sample, under the weight of the upper block (Fig. 8). The wears in these tests were insignificant or non-existent. The traction wire and the belt around the upper block also were levelled and placed just over the level of the higher protuberance of the sample contour to avoid, as far as possible, inconvenient force momentums.

During the tests it was verified that a lack of attention to these details caused errors of up to 40% with respect to test data obtained correctly. The slides in pull tests were sudden, without meaningful premonitory movements.

The same samples were settled into cement mortar blocks for additional tests in a shearing machine in accordance with SN orientation, after adequate levelling, under σ_n of 0.05, 0.3, 0.6 and 1.2 MPa.

Barton & Choubey (1977) assert that a shear displacement of 1% of the sample length usually was necessary to reach peak conditions. Total displacements of 6 mm under the last σ_n level of 1.2 MPa trebled the recommended value to enable comparison among samples after their final wears were reached. Under lower σ_n levels, the displacements were halted as soon as the peak conditions were reached, preventing excessive wears of joint sample surfaces.

The wears caused by the tests with the sliding machine were assessed through new pull tests in accordance with all orientations (NS, SN, WE and EW). It was verified that at SN orientation a strength loss of 70% occurred with a loss of 40% for *JRC*, but strength and roughness were reasonably preserved in accordance with the other orientations (Fig. 9). For instance, at WE orientation, 5.3 cm type IV samples maintained 93% of their original *JRC*, so they were also tested in the sliding machine under the same σ_n levels of 0.05, 0.3, 0.6 and 1.2 MPa, in accordance with this WE orientation to check tendencies of scale effects (Fig. 10).

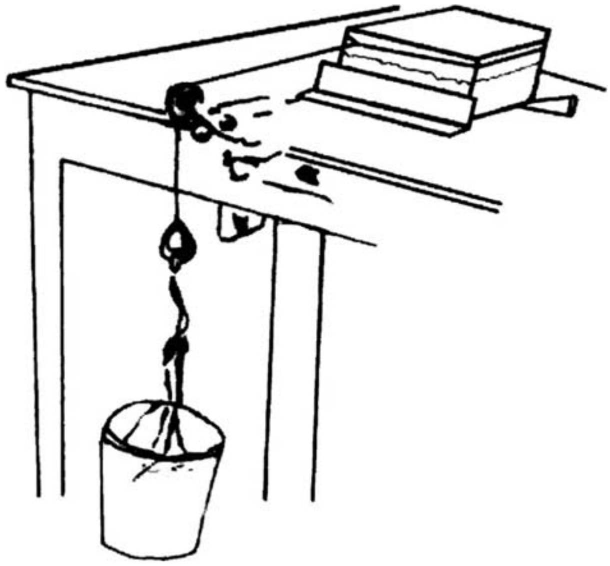

Figure 8 - Pull test apparatus. The sliding of upper block was caused pouring lead grains into the bucket.

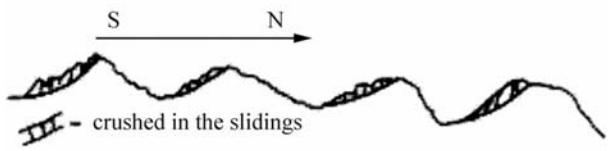

Figure 9 - Damage of roughness in shearing machine at SN orientation, but preservation of roughness in agreement with other orientations.

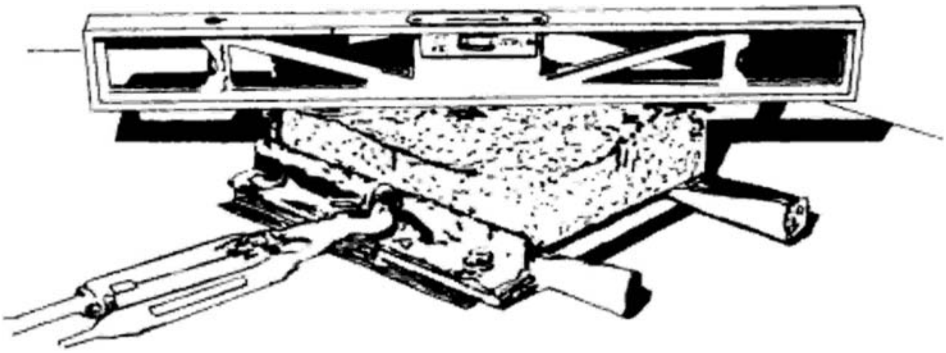

Figure 7 - The levelling of the middle plane of the samples was made with a level introducing wedges under the lower block.

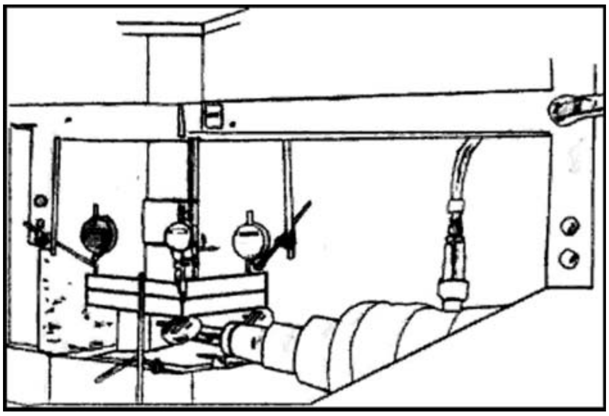

Figure 10 - Sample type IV assembled into the shear machine for a WE shear test.

7. Test Data

In pull tests, the predominance of inverse scale effects was observed when Barton's model was used. Data of Fig. 11 show the increase of roughness and strength at EW direction (WE orientation plus EW orientation) as sample areas (Aa) and lengths increase.

Figure 12 refers to pull tests at SN direction as the transverse dimension to slides (or widths) increase. A slight normal scale effect was observed, but the correlation coefficient *R* was very low. The Student correlation test for 95% of confidence demonstrates that the resulting correlation is random and was not due to a genuine scale effect.

Figure 13 contains all pull test data at the four stipulated orientations including the sample type V values and a clear inverse scale effect is observed.

Figure 14 shows the decrease of anisotropy of direction which tends to zero as sample areas and symmetry increase. The REV of this anisotropy is reached for 16 cm x 16 cm dimensions in these pull tests.

Figure 15 (a) represents the anisotropy of orientation (*JRC* NS - *JRC* SN) along the NS direction. Figure 15 (b) shows the anisotropy of orientation (*JRC* WE - *JRC* EW) for the WE direction. Figure 16 presents the evolution of the average of these two anisotropies of orientation.

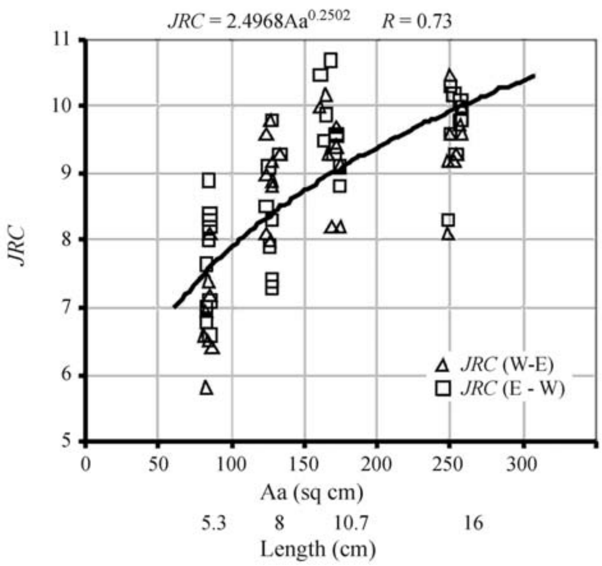

Figure 11 - Graph ((Aa and length) x (*JRC* (EW). Sample widths of 16 cm.

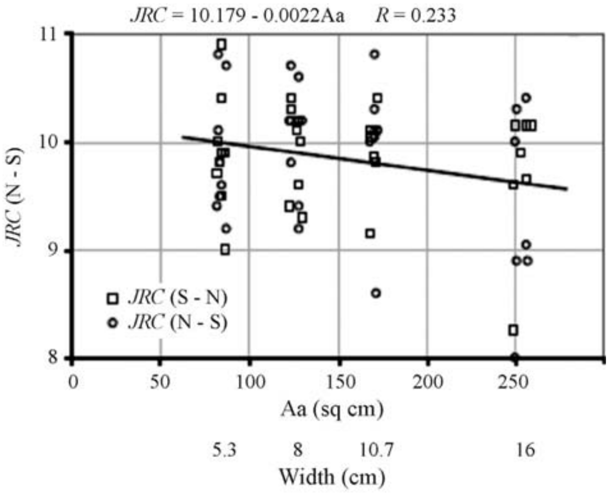

Figure 12 - Graph ((Aa x *JRC* (NS)). Sample lengths of 16 cm.

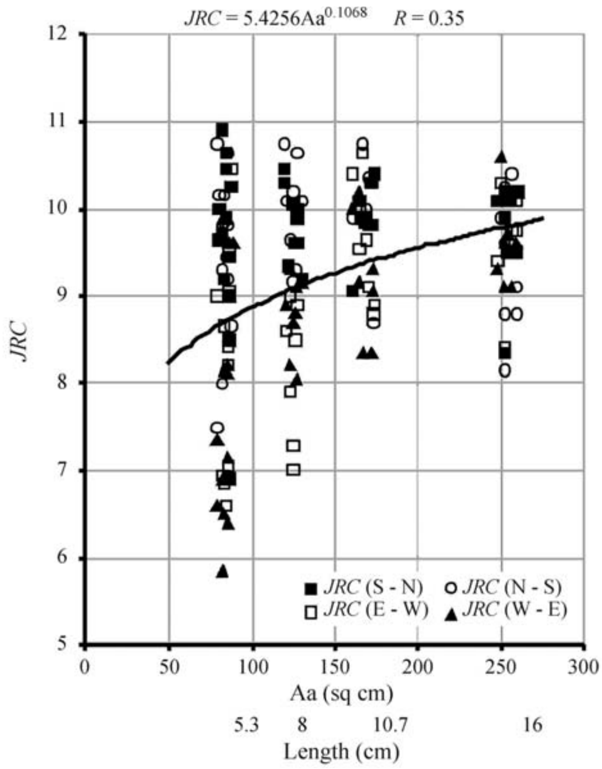

Figure 13 - Graph (Area x *JRC* (NS direction plus EW direction of all the samples)). The graph includes samples type V.

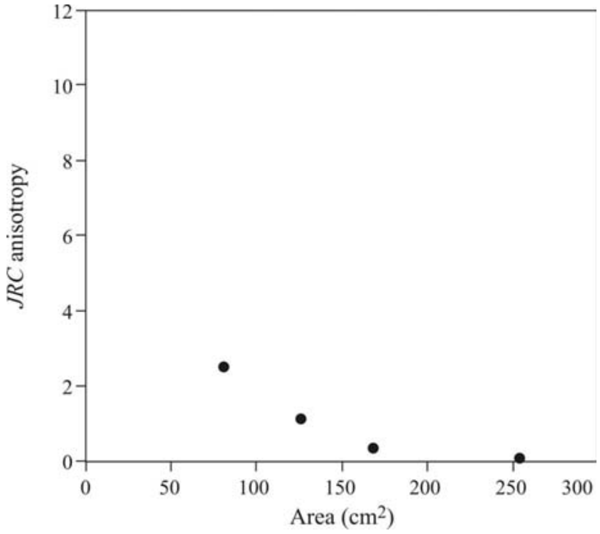

Figure 14 - Graph (Area x (*JRC* NS - *JRC* EW)). Anisotropy of direction of *JRC*.

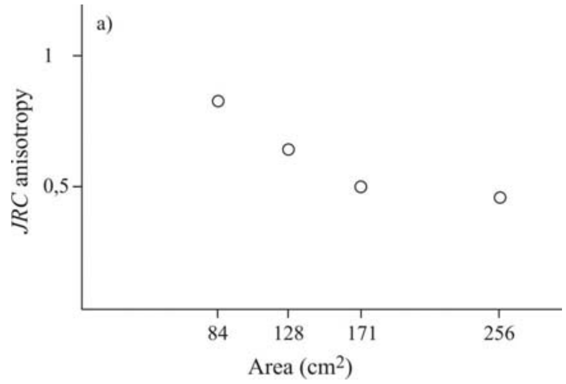

Figure 16 - Evolution of (*JRC* EW anisotropy + *JRC* NS anisotropy)/2.

These last diagrams also show the reduction of anisotropies of orientation as sample dimensions and symmetry increase. Unlike the anisotropy of direction, their REV are not zero, remaining around 0.5 *JRC* units for areas larger than 250 cm^2.

Figure 17 refers to sample shear tests at SN orientation under σ_n levels of 0.05, 0.3, 0.6 and 1.2 MPa. The reduction of peak shear strength (τ) as the transverse dimension to sliding direction (the perpendicular widths) increases from 5.3 up to 16 cm is observed. These normal scale effects are accentuated as σ_n increases.

In spite of the low correlation coefficient in the curve corresponding to 0.3 MPa, the correlation coefficients of the other curves are moderate and this graph suggests the close dependence of shear strength on the width of tested samples.

Muralha & Cunha (1990), whose joint samples were obtained in schistose rock probably with lower *JRC* and *JCS* than the present samples, did not obtain this τ dependence on the widths. These facts seem to point out the increase of this effect of sample width on the shear strength as *JRC*, *JCS* and σ_n increase.

Lower strength for worn samples type IV at WE orientation than at SN orientation, were found in the sliding machine tests. Inverse scale effects probably tend to vanish as σ_n increases, but these tendencies are not clear and explained.

The shear machine was not very rigid, so gauge readings near peak conditions were difficult to obtain. The peculiar shape of the samples may cause some suspicions of spurious influences on data because of shape effects, but this preoccupation is unsubstantiated. The adoption of these unusual sample shapes actually brought out some behaviour types, facilitating the interpretation of the phenomena, without loss of generality.

8. Discussion of Scale Effects on Rock Joint Strength in Accordance with the Experimental Work

It was already observed the decreasing of joint roughness as sample sizes diminish by cutting them when the

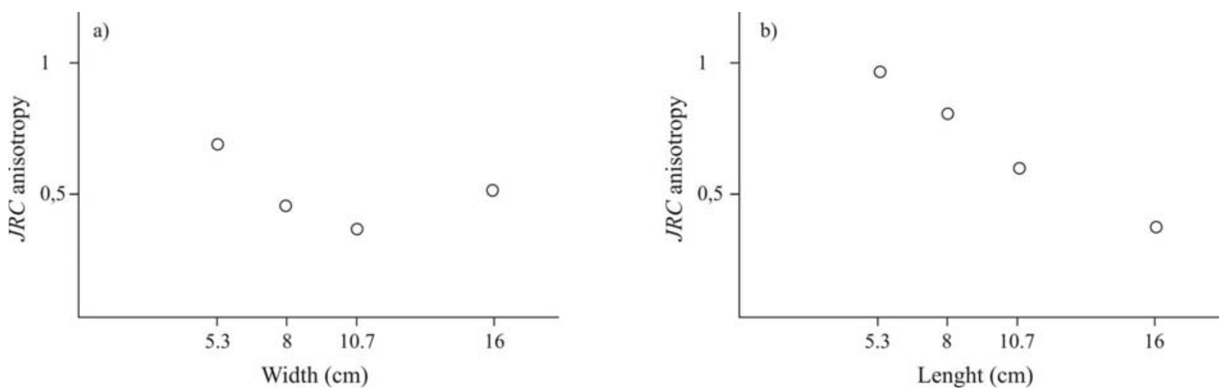

Figure 15 - Anisotropy of orientation of *JRC* at NS direction (sample length of 16 cm); b) Anisotropy of *JRC* for the EW direction (sample width of 16 cm).

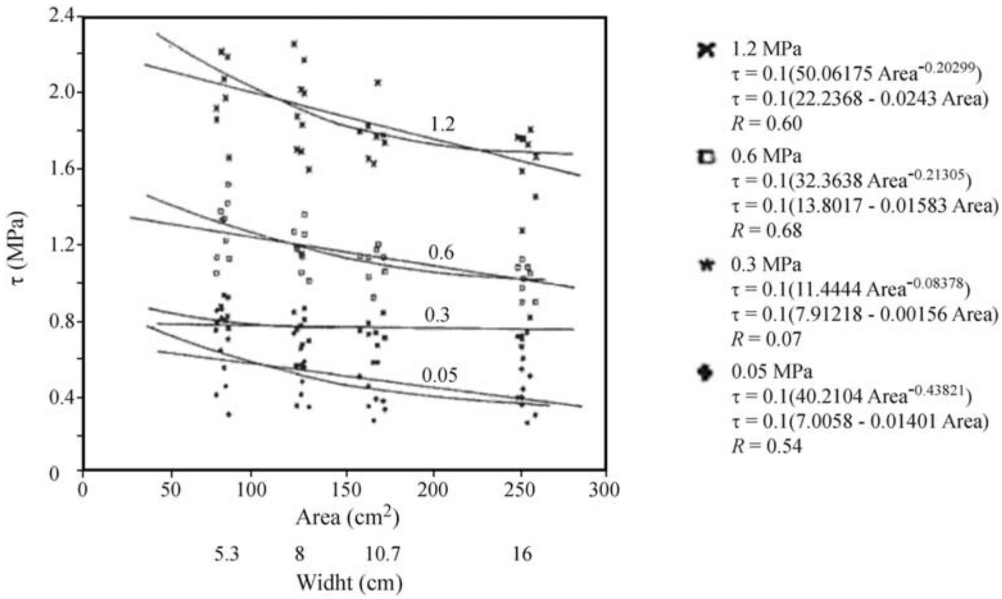

Figure 17 - (Area and width x τ) for s_n of 0.05, 0.3, 0.6 and 1.2 MPa. Sample length of 16 cm.

middle plane is levelled. At the dilating phase of the slidings, if the roughness was reduced the sample strength also decreased. Apart from this reason for the appearance of inverse scale effects in these tests, there are two other possible complementary mechanisms having the same effect. Actually, it is possible that φ will diminish as σ_n tends to zero, contrary to Patton's (1966) assumption, such as for very high σ_n, as σ_n increases. Basic friction angle of silicate rocks may decrease to 10° as σ_n tends to zero (Hencher *et al.*, 1993), while for mid σ_n, φ remains around 30°. The gathered test data about this matter show a great scattering but that possibility is not discarded. The ignorance of φ evolution as σ_n tends to zero, may only be understood because this vicinity is hardly involved in real geotechnical problems. The dilation contribution in this same vicinity may not exist or be lower than *i* but it is only completely mobilized when there is a minimum value of σ_n.

An increasing τ / σ_n (and not a constant one) for low σ_n values was admitted (Leal Gomes, 1999b), contrary to Patton's model. Figure 6 suggests higher Sigef in larger samples becoming greater (Sigef.(Aef / Aa) . tan (φ + *i*)), that is, the shear strength. This mechanism should lose its importance as σ_n increases (Fig. 6) because the slope of the diagram Aa vs. (Aef / Aa) and therefore of Aa vs. Sigef values is reduced for high σ_n values, when another evolution for tan(φ + *i*) appears.

The other complementary mechanism is less controversial and supported on the knowledge of the average peak displacements (d_p) obtained in tests under a σ_n level of 0.05 MPa (Table 2).

The mean shear strengths are not exactly inversely proportional to d_p. They show otherwise a clear inverse magnitude order with respect to d_p and by analysing the curved paths of the top block (assuming they are circular) they show a small average curvature radius C = 0.139 m. This is valid under the condition that such a radius C path is observed when the sample's top border overthrow the lower border asperities, in the type IV samples along the WE edge, which is smaller (5.3 cm size) than the SN edge (16 cm size).

The sliding of samples type I (16 cm) was done with a C of 3.869 m and samples type IV slides at SN orientation (16 cm) with the largest C of 5.028 m. This analysis was performed upon the readings in gauges.

Actually, the upper block in longer samples needs to overcome the whole asperity heights in its translating movement, whereas, despite our samples being mated, a rounder movement of the upper block over the asperities occurred in short samples, like WE orientation of samples type IV, causing larger peak displacements but lower strengths. Samples of type I, which are wider, show greater d_p and lower τ than samples type IV at SN orientation, due to their greater wealth in roughness levels, which becomes rounder the overcoming of asperities.

Actually, Fig. 18 shows the increase of general roughness symmetry and reduction of anisotropy as two or more

Table 2 - Average peak displacements (d_p) and average curvature radius (C) of upper block sliding trajectories.

Sample (cm^2)	Orientation	dp (mm)	τ (MPa)	C (m)
16 x 5.3	SN (16 cm)	0.19	0.6	5.028
16 x 16	SN (16 cm)	0.24	0.46	3.869
5.3 x 16	WE (5.3 cm)	0.6	0.2	0.139

roughness levels are laterally juxtaposed, indicating that the larger the samples, the greater are the number of these juxtapositions. Due to this effect, the anisotropy of mated samples decreases in Figs. 14, 15 and 16 as sample sizes increase, and the slides are rounder, having lower strength as the transverse dimension to sliding, that is, the sample widths, vary from 5.3 to 16 cm.

Due to all these reasons, in the dilating phase of slides, sound, fresh and mated discontinuities must have inverse scale effects, vanishing as σ_n increases, because then the dilating character of slides, which begin to occur with asperity cut, is lost.

However, there are not reasons to admit *a priori* that scale effects on joint strength become normal ones only because the scale effect on *JCS* is eventually normal. That fact has little influence, because the differences among transverse dimensions of asperities to be cut are not important enough, either in large or in small samples. Besides, it is necessary to bear in mind that the measured scale effects on uniaxial compression strength of some rocks, mainly porphyritic like Pontido granite, are inverse (Leal Gomes, 2001a).

It is deduced from this exposition that, if discontinuities are well-mated, the average slopes of different roughness levels must be added to reach their strength, so the roughness slope i_1 swinging around the undulation of higher order must be added to its slope i_2 and the corresponding factor in Patton's model is given by tan $(\varphi + i_1 + i_2 + ...)$.

Thus, large samples having higher undulation orders, must have greater strengths than small ones, where there only exists small roughness. Therefore, these small samples are on the safe side of engineering. Besides, there is the amplitude of the undulation effect, not foreseen by Patton's model favouring the large sample strengths, where several undulations of higher amplitude may be found. Clear inverse scale effects on τ of matched discontinuities (and these samples of the 4.32 m^2 artificial joint of Pontido are matched) result from these facts. However, the panorama is rather different when the discontinuities are mismatched, as in the Bandis (1980) samples (Fig. 19), because of the imbrications of small asperities, which do not partially or wholly intervene in slides cannot be taken into account. In this case, the consideration of only the average slope of large undulations is necessary, which is usually gentler than roughness slopes. On the other hand, contributions of amplitude will also be much reduced with reference to a situation of complete matching, since the walls are shifted to each other. Peres Rodrigues & Charrua Graça's model (1985) is the appropriate model for these conditions, not Patton's. An extremity of the upper wall of the samples leans on the lower wall and the upper wall turns around the more conspicuous asperity, that is, the irregularity being the hardest to overcome, that is named as the meaningful irregularity for that model.

Figure 19 - Mismatched joint. The roughness slope is i_1, the undulation slope is i_2, the amplitude of undulation is a_1 and the amplitude contribution for strength at a mismatched discontinuity is only a_2.

Contrary to Patton's model, in Peres Rodrigues & Charrua Graça's model the movement of upper wall is not parallel to the lower wall and dilation angles are clearly lower than in Patton's model. These two authors postulated that the median of heights of that meaningful irregularity (H) relates to the sample area (A) in accordance with a function lnA(H^2). If L is the sample length and the distribution of the meaningful irregularity is uniform on it, the median of the dilation angle is H/(L/2), where L/2 is the median of the positions of this irregularity on the joint lower wall. It is easily understood that the increase of heights of meaningful irregularity (and therefore of dilation angles) is much slower than the area increase. Therefore, this model (Fig. 20) favours the appearance of normal scale effects on dilation angle and on strength.

Experimental data is available for showing that mismatched joints have normal scale effects and matched joints present inverse scale effects (Kutter & Otto 1990) completely corroborating the considerations of this paper.

Therefore, the *in situ* observation of joint wall matching is the fundamental rule to program sliding tests. Only residual parameters must be taken into account if their mismatching overcomes the peak conditions and these residual parameters are little or not affected by scale effects. Peres Rodrigues & Charrua Graça's model must be used whenever peak conditions are not reached and when there are mismatchings. Actually, these authors demonstrate the excellent correlation between their model and Bandis' tests (1980) on mismatched samples exhibiting the so called "rocking" effect, considering that Bandis obtained normal scale effects. It is necessary to consider all dilation angles corresponding to several roughness and undulation orders and also of their amplitudes (which are not clearly taken into account by any known strength model) if the joints are matched. In these cases, Patton's model is usually used.

Even so, it may be observed in the field that shear displacements are clearer at joints as discontinuity sizes in-

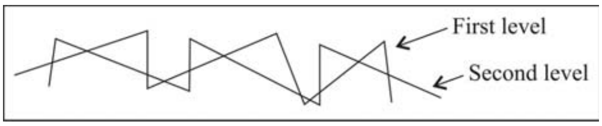

Figure 18 - Two different roughness levels laterally juxtaposed increased the symmetry of the sample.

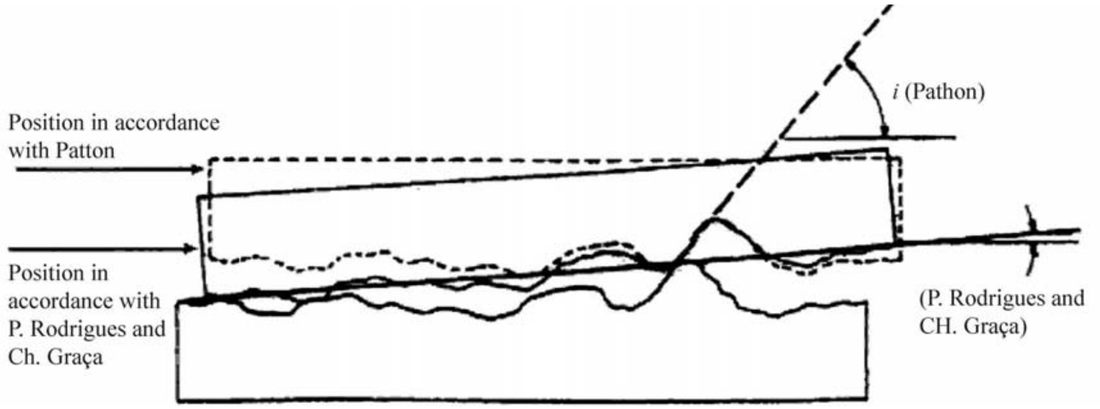

Figure 20 - Peres Rodrigues & Charrua Graça's sliding model (1985).

crease. It may be even asserted that shear displacements are always present in large crustal features. It is known that simple joints may have not only tensile origin but also shear or mixed origins and there are also frequently mismatched discontinuities. The situation is made worse by weathering and crushed zones.

Nevertheless, the problem is put on the unsafe side of engineering countless times because, despite the care in levelling the middle joint planes, the small samples from these mismatched joints are put into their best wall matching before the tests in sliding machines (the principle of adding the dilation angles applies here). If, for *in situ* tests, large samples are matched, inverse scale effects with small sample testing are obtained and the small samples will be on the safe side of engineering, but shear displacements are very probable for features having large areas, as the discontinuities are mismatched and that principle is not applicable. Thus, Peres Rodrigues & Charrua Graça's model is more adequate in such cases and so, normal scale effects correspond to these mismatched *in situ* conditions. Probably small sample tests, *in situ* tests and mainly, the conditions of discontinuities included in rock masses, are not comparable.

Therefore, the *in situ* observation of features matching is essential for the assessment of the significance of large and small tests. Mismatched roughnesses and undulations are partially inoperative for shear strength.

The results of Mac Mahon (1985) may only be understood within this scope, where he studied several joint slides by back analysis and found normal scale effects. He also concluded that small roughnesses had no influence in slides, with fillings and weatherings of those features probably only partially explain his results.

9. Conclusions

In spite of the obtained moderate correlation coefficients obtained in this experimental work, it allowed some essential rules to be highlighted. Many doubts about joint mechanical behaviour are solved by simple geometric considerations on the matter. Neglecting this principle may cause inadequacies in further rock joints test programs if some details of the testing execution are disregarded.

The interest of investigating the behaviour of small joint sample tests depends on the kind of scale effect that is sought, as they are on the safe side of engineering, if scale effects are inverse. Patton's model must be used if the rock mass joints are sound and matched. The advantage of the proposed test procedure, involving the levelling of joint middle planes, is to have demonstrated that small sample tests in dilation sliding phases are on the safe side of engineering. Mean amplitude and slope of roughness are reduced as sample sizes diminish, when joints are levelled. But mismatched samples obey Peres Rodrigues & Charrua Graça's model and the corresponding scale effects on strength are normal.

Many ideas and experimental regressions about joint mechanics must thus be reviewed because they do not fit the effects of a systematic levelling of sample middle planes on the roughness geometry in a dilating sliding phase.

Small samples may not be physically comparable with rock mass features from which they were withdrawn, depending on their dimensions, their matching or mismatching, the test techniques, their middle plane position, their weathering and crushed zones and on the sampled orders and levels of roughness and undulation.

Additionally, other important suggestions and conclusions applicable to matched and sound discontinuities, particularly if they have horizontal middle planes, were deduced from these tests. The following ones are pointed out:

Probably the maximum amplitude of roughness depends on the larger dimension of the joint and little or nothing on the smaller one. Samples having smaller linear dimensions have lower roughness amplitude and slope.

The anisotropy of roughness (anisotropies of direction and of orientation) increases as dimensions and plane symmetry of joint samples decrease. There is a general increase of roughness symmetry and lower anisotropy as sample areas and their geometrical symmetry increase.

Average roughness increases as areas and dimensions of levelled samples increase (inverse scale effect).

The curvature of sliding trajectories has an obvious influence on the strength and on peak displacement. Longer mated samples have greater strength (and smaller peak displacement) when there are only the same undulation orders.

Sample strengths increase as the transverse dimensions to the sides (or widths) are reduced. The assessment of joint stability by the slices method is not appropriate because that effect puts them on the unsafe side of engineering. This effect worsens as σ_n, *JRC* and *JCS* increase. There is the possibility of the limit of this effect to be the REV of roughness anisotropy (Leal Gomes, 2002). More experimental work in this area is necessary to clarify this aspect.

As discontinuity scales increase (large joints, faults) the effect of previous shear displacements is clearer. Large active faults probably had overcame their peak conditions. Even so, they may have some dilation from their completely mismatched irregularities, which must be added to strength residual parameters in order to obtain their shear strength (Leal Gomes, 2001c).

The interest and significance of tests on small samples is very difficult to judge within the domain of mismatched joints. Therefore, there are situations where such tests are not advisable and, in these conditions, only the large *in situ* tests lead to reliable results.

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