Scale Effects in Rock Masses 93, Pinto da Cunha (ed.) © 1993 Balkema, Rotterdam, ISBN 90 5410 322 1

Scale dependent shear strength of rock joints

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ABSTRACT: The results of a systematic series of direct shear tests on model joints at different scales are reported and compared with the results of Bandis (1980). Considerable scatter is found between tests and between repeat tests on models of the same section of joint. Similar scatter is found in the shear strength of planar surfaces. The broad-scale behaviour observed by Bandis, such as the relatively brittle behaviour of small samples, is confirmed and explained in terms of the mobilisation of textural friction and dilational strength. In contradiction to the conclusion of Bandis, on correction for dilation, no scale dependence of frictional strength is found.

1 INTRODUCTION

In the literature on shear strength of rock joints there is considerable discussion on the applicability of strength parameters obtained from direct shear tests on small samples to the strength of full scale discontinuities in the field. Bandis (1990) and Cunha (1990) present useful reviews.

Intuitively, a reduction of shear strength with increasing length of discontinuity surface is expected due to a reduction in effective roughness (Fecker & Rengers, 1971) although others have suggested that the opposite may be true (Swan & Zongqi, 1985). The evidence for systematic and consistent scale effects is not conclusive; there are examples reported of both increasing and decreasing shear strength with increasing size of sample.

Using plaster based models, a systematic study of scale effects on shear strength of single joints was carried out by Bandis (1980) as summarised by Bandis et al (1981). His results show a remarkably clear scale effect in which shear strength reduces with increased joint length. He suggested that the reduced strength could be partly accounted for by a reduced dilation angle as might be expected but was also partly attributable to a reducing *asperity failure* component with increasing length of sample. The asperity failure component was defined as that component of strength that remains after the *basic friction angle* and *geometrical component* (dilation angle) have been accounted for.

Empirical relationships for adjusting Joint Roughness Coefficient (JRC) and Joint Compressive Strength (JCS) with length of joint, which have been derived largely from the results of Bandis, are now widely used in numerical modelling of rock mass behaviour (Barton & Bandis, 1990).

In explanation of the scale dependence of the asperity failure component, firstly it was noted that the area of wear apparently increased with length of sample. Then, recognising that there is evidence that uniaxial compressive strength decreases with size of sample, it was argued that the contribution to shear strength from the larger areas of wear would be less proportionally than the contribution from the smaller areas of wear for smaller samples. However the evidence for increased area of wear with size of sample was not well documented and in any case depends upon the accuracy of very difficult measurements. More importantly, it does not follow that the factors responsible for the apparent scale effect in compressive strength testing (probably increasing numbers of flaws with size) would be equally relevant to the deformation and ploughing of asperities during direct shear.

Bandis does not give sufficient detail to allow full re-analysis on a sample by sample basis. This is partly because of the limitations of the manual data collection system employed but also because the majority of data have been presented as cumulative averages for tests at any particular scale.

For these reasons the series of tests reported here has been carried out. The aim has been to test samples similar to those tested by Bandis (1980) whilst following his methods as closely as possible but using the more sophisticated data collection system now available at the University of Leeds. Analysis of individual tests has been carried out using recently developed methods (Hencher & Richards, 1989). Testing was carried out using the original purpose-built shear box designed and used by Bandis.

2 METHOD

Samples were prepared following the method outlined by Bandis (1980) in which impressions were taken of natural joints using Vinamould and then casts formed using model material. The models were then subdivided to provide samples of a range of sizes. Due to limitations of time and considerable difficulties encountered in making true and acceptable impressions of sandstone surfaces, a single joint surface of Carboniferous Limestone was used for this test programme as described in detail by Toy (1993). Representative profiles are presented in Figure 1.

Repeatability as well as detailed behaviour of individual samples was investigated in this study. Although only a single rock joint was modelled, six of the largest size models were tested, three times in a forward direction and three times in the reverse direction. Quartered samples were each similarly tested six times. The smallest samples (12) were only tested once each in a forward direction. Some tests on the roughest small samples were repeated using better support after noting damage at their trailing edges which was thought to have given rise to anomolously low strengths.

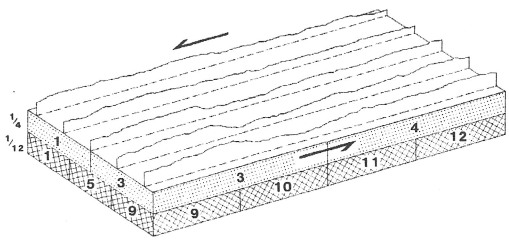

Figure 1 Joint profiles indicating sample positions and sizes

The model material was prepared as described by Bandis (1980) using a mixture of silver sand, barytes, calcined alumina, plaster of Paris and water. Great care was taken to ensure that particle size distributions of each component were as originally specified. Samples were cured in an oven and normally tested within 90 minutes of removal from the oven. The model material is white, brittle, very weak and friable. The material can be powdered readily between the fingers.

It should be noted that, despite considerable care in their construction, model halves would never match precisely; various degrees of rocking were noted. It is considered that this may have been an important contributing factor in the variability in shear behaviour reported later. Similar difficulties were noted and investigated by Kutter & Otto (1990)

All tests were carried out at the same single normal stress used by Bandis (24.5 kPa) and at a shear rate of 0.4 to 0.45mm/min.

Displacements were monitored by LVDTs; three were used to measure vertical displacement and to monitor tilting. All data were collected via an analogue/digital interface into a microcomputer at one second intervals. Large and medium samples were sheared for approximately seventeen mm, the small samples for twelve mm.

Data were transferred to the spreadsheet Microsoft Excel and then analysed to account for dilational effects following the methods outlined by Hencher & Richards (1989). The horizontal displacement over which the instantaneous dilation angle is

3.2 Results for different scales

In Figure 3 the full range of results for shear stress (uncorrected) are plotted against horizontal displacement for models at different scales, all tested in a forward direction. The smallest samples had the widest range of morphology (roughness) and also both the highest and lowest peak strengths of all tests irrespective of scale. The medium sized samples showed the second largest variation and the largest samples showed the smallest variation.in both morphology and peak strength. It should of course be noted that all of the tests on the large samples were essentially on the same model (1 model, 3 tests in the forward direction) and the scatter for medium samples was for twelve tests on only four models (4 models, 3 tests in the forward direction). The range for small samples is for twelve tests, each on fresh replicas.

For comparison, the results obtained by Bandis (1980) from tests on models cast

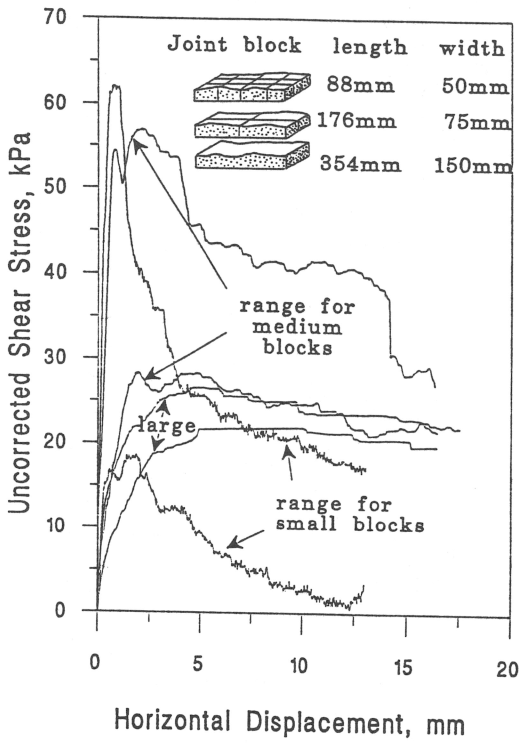

Figure 3 Strength envelopes for tests at different scales

from a similar bedding surface through limestone are presented in Figure 4. These curves represent cumulative averages of the results from 18, 6, 4 and 1 test respectively from the smallest to largest model sizes.

It can be seen that the broad shapes of the averaged results of Bandis are similar to the strength envelopes from the tests reported here. The observations of Bandis that peak strength occurs at smaller strains and that peak dilation angle is generally higher for smaller samples are confirmed.

A possible explanation for both of these findings is that the centres of gravity of small, rough samples which are allowed to tilt will rotate through shorter radii than will longer surfaces as they dilate above a given asperity height. As a result peak dilation will tend to occur more rapidly for shorter samples. Furthermore, the essentially frictional resistance contributed from textural interlocking can be expected to be mobilised over small strains irrespective of the size of sample. Therefore, for smaller samples, these two prime processes can be expected to reinforce to provide a sharp, early peak followed by clear reduction to some lower strength. In contrast, for the larger samples, this reinforcement does not occur because the longer radii of rotation lead to more gradual (and reduced) dilation.

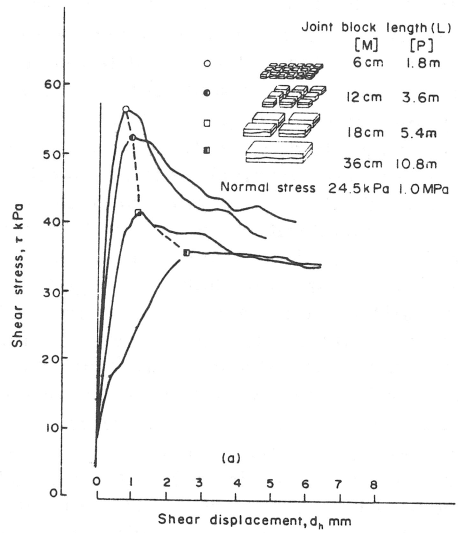

Figure 4 Cumulative mean shear stress-shear displacement curves of model No. 1 (Bandis et al, 1981).

calculated can be varied and must be selected by judgement. If too short a strain interval is used (say 0.005mm) then reading errors become high leading to a high degree of scatter. However, if too long an interval is used for calculation then detailed behaviour may be missed.

3 RESULTS

3.1 Individual tests

Data were plotted in several ways and fairly typical examples of one style of graph are given in Figure 2. Each of the three graphs a, b and c in Figure 2 is from a single test on one of the quarter-size models (no. 4 in Fig.1), tested with the same direction of shearing. Each model is a replica of the others so that a fresh sample can be used for each repeat test. Measured (uncorrected) shear stress to normal stress ratio (μ) is plotted against horizontal displacement. Plotted on the same graph is dilation versus horizontal displacement and the ratio of shear to normal stresses (μ_{corr}) corrected with respect to work associated with dilation or contraction (Hencher & Richards, op cit) also against horizontal displacement. In Figure 2a it can be seen that the sharp peak uncorrected stress ratio is mirrored by the dilation curve and that on correction for the effect of dilation the stress ratio is essentially constant throughout the test, (μ_{corr} = 0.8 to 1.0).

In the majority of tests, the correction for dilation accounts for much of the variability in measured shear strength. Nevertheless there is considerable variation between repeated tests. The results of tests on replicas of the model, shown in Figure 2b and c, differ from that of the first test shown in Figure 2a. It can be seen that for the second test the shape of the peak shear strength ratio curve is similar to that in the first but with a different peak value (μ = 1.4 rather than 1.65); in the third test (Figure 2c) the shape is quite different and the peak value lower still. The dilation angle in the early part of the third test was also much reduced. Corrected stress ratios are similar for the three tests (μ_{corr} = 0.8 to 1.0) but the repeatability is not precise.

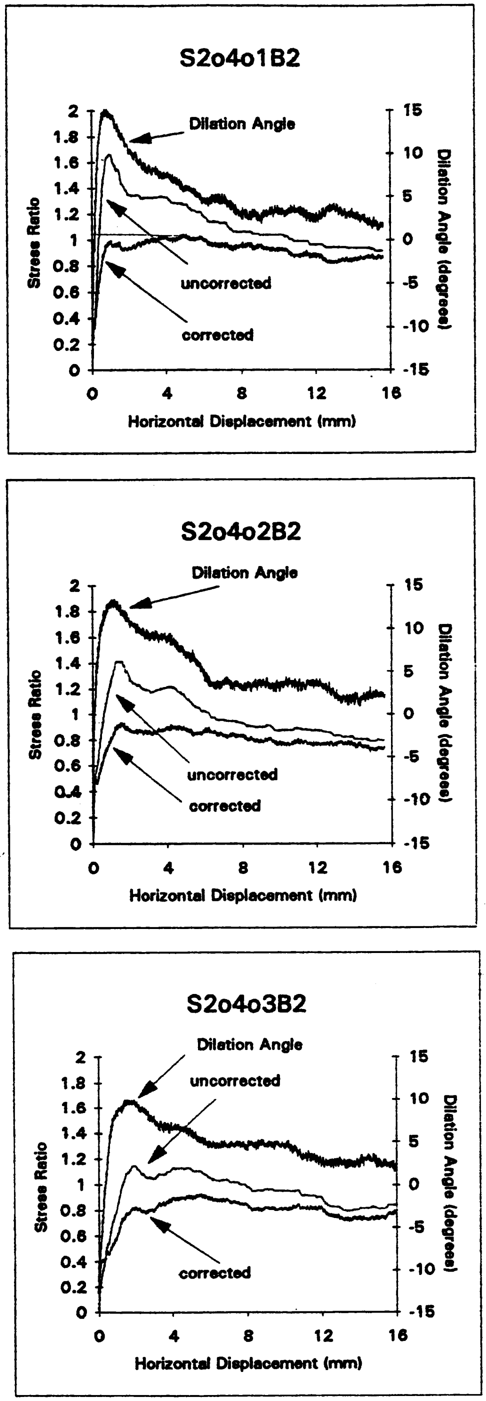

Figure 2 Results from shear tests on quarter size sample # 4, in a forward direction

Consequently, by the time peak dilation is reached the textural friction has already been fully mobilised and is reducing. This would lead to more "plastic" behaviour as observed both here and by Bandis. Aspects of this geometrical effect on behaviour were investigated recently by Tse (1991) using idealised models of single asperity geometry and employing the same shear box as for this study.

The other major conclusions of Bandis et al (1981) have not been clearly confirmed by the tests reported here. Mean peak strengths and standard deviations for different scales, both as measured (uncorrected) and corrected for dilation are listed in Table 1. In terms of peak strength, of all tests the smallest samples gave both the highest and the lowest strengths (ϕ = 36 to 69°). The medium blocks gave strengths ranging from ϕ = 48 to 67°and the large ranging from ϕ = 43 to 46°. Again it must be emphasised that the results for large samples are for 3 repeat tests on essentially the same model and therefore some considerable reduction in the degree of scatter is to be expected. In terms of mean peak strength the medium blocks were the strongest.

3.3 Corrected strengths

Hencher & Richards (1982, 1989) show that a constant frictional strength is normally revealed when corrections are made for incremental dilation during direct shear tests on real rock joints of similar mineralogy and surface texture but variable roughness. The corrected strength represents the frictional resistance of effectively planar (non-dilational) joints of those particular surface characteristics. Such corrected values may be higher or lower than the friction angle derived from a saw cut sample of the same parent rock type (the basic friction of Barton & Choubey, 1977).

Barton (1990) argues that, following the work of Bandis (1980) and his conclusions regarding the "asperity component" of friction, part of the corrected strength from tests on real joints will be scale-dependent. However, this scale dependency of asperity component is challenged by the close correspondence between mean corrected strength values of both the smallest and largest samples found in this study and listed in Table 1.

However, it is also the case that the corrections do not yield a single corrected strength for all samples, as would be expected for real rock joints according to Hencher & Richards (op. cit.) A possible explanation for the variability in corrected shear strength comes from a study of basic frictional behaviour.

3.4 Basic friction

The analysis carried out by Bandis and published in Bandis et al. (1981) was based on the assumption that shear strength is derived from a basic frictional resistance supplemented by the effects of asperity deformation, shear and overriding. Basic friction was taken to be the frictional resistance between planar surfaces and represented a constant lower bound in the equation for shear strength. It was considered measurable by testing a surface

Table 1 Mean strength and dilation data from tests at different scales

BLOCK SIZE	UNCORRECTED peak friction		DILATION ANGLE at peak τ		CORRECTED peak friction	
	mean	st.dev	mean	st.dev	mean	st.dev
LARGE (3x1) [a]	44.9	3.3	9.2	0.2	35.7 36.1 [b]	3.6 2.6 [b]
MEDIUM (3x4) [a]	56.6	5.6	13.9	4.4	43.8 42.2 [b]	2.3 4.0 [b]
SMALL (1x12) [a]	51.6	9.7	14.5	4.2	36.9	6.4

NOTES : [a] number of repeat tests (eg 3) on number of different models (eg 1)
[b] data includes those for tests on same models but in reverse direction

to the residual stage. However, frictional resistance between planar surfaces can be extremely variable, depending upon the degree of flatness, the textural roughness, the development and nature of flour and other debris and, especially for natural joints, their mineralogy. Coulson (1971) demonstrated the importance of slight roughening of saw-cut surfaces on frictional resistance and Hencher (1976, 1977) showed how the angle of sliding of a saw-cut surface of sandstone, for example, could vary between 12 and 32° according to the degree of wear and presence or absence of rock flour. At best the strength measured for a particular planar surface can be taken as a convenient reference value which may be repeatable.

It is possible that the true basic (lowest) friction for discontinuities in most silicate rocks is of the order of 10 degrees and that all additional strength for planar or rough surfaces is derived by asperity deformation, ploughing and other processes which depend on the textural finish. In reality, the matter is even more complex in that extremely smooth surfaces of rock may have even higher strengths than rougher surfaces, as found for materials such as glass (Hardy and Hardy; 1919).

Bandis (1980) derived a basic friction angle of 32° from tests on planar surfaces of model material cast against glass plates and, noting the correspondence to the reported basic (residual) friction angles of many saw-cut surfaces through sedimentary rocks, considered this acceptable. Full test data were not presented so that the degree of scatter in the series of tests is not known.

Several workers at the University of Leeds have used the Bandis model material for testing programmes; some used a slightly stronger material in which all components were kept the same except that dental plaster was used in preference to plaster of Paris (Papaliangas, 1986, Stiakakis, 1987). Some scatter in the shear strength of planar surfaces prepared in different ways was found and therefore further tests were carried out for this study.

Toy (1993) prepared samples in three different ways: saw-cut, saw-cut and then sanded flat and cast against glass. Tests on individual samples gave essentially constant strengths for the full range of shear

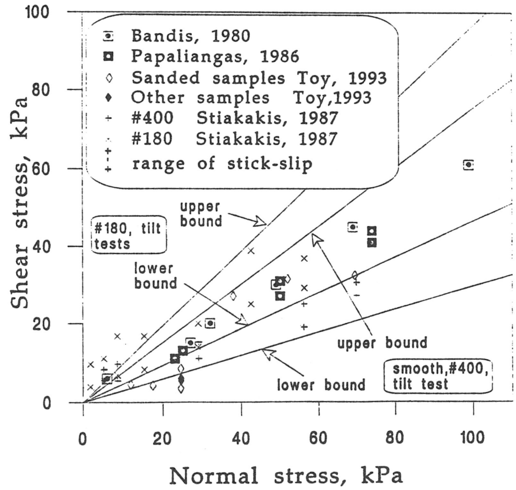

Figure 5 Shear strength of flat samples of plaster based model material

displacement but the scatter in frictional resistance between tests was enormous, with the range from as little as 9° up to a high of 45°. Similar variability had been noted for the stronger material by Stiakakis (1987) both in tilt tests and in direct shear tests which all showed stick-slip behaviour. Strengths from these and other tests are presented in Figure 5. Papaliangas (personal communication) has recently repeated some tests and found values in direct shear to be consistent with his previously reported, well constrained results for the stronger, less friable material prepared in a uniform manner.

The explanation for such observed behaviour is not simple but clearly relates to the nature of the model material which comprises hard clasts in a soft plaster matrix. The porosity is high, the material very friable and surface finish can vary between relatively smooth and plaster-rich to friable and granular. For such a material there is a range of potential shear mechanisms that can be envisaged, from ploughing and interlocking of grains to rolling friction. Toy suspects that the variability he noted for sanded surfaces was related to the degree to which dust was blown with compressed air from the surfaces.

Whatever the explanation it must be concluded that, depending upon the mechanisms involved during shear, a wide range of "basic frictional parameters" are possible for planar surfaces of the model material and therefore there must be severe implications for any conclusions which are based on the assumption of a single basic friction angle without due regard to the conditions during shearing.

3.5 Residual strength

The lowest ("residual") strengths measured in each model test at different scales provide further evidence and confirmation of the importance to shear strength of surface finish and shear mechanism.

- o Of the 6 large shear tests, none gave residual strengths below the 32° basic value of Bandis (1980).
- o Of the 24 medium size tests, more than 20 gave residual strengths above 32°, 1 gave a corrected strength of between 25 and 32° and 2 gave values between 20 and 25°.
- o Of the 12 smallest samples, all corrected residuals were below 32°, 7 were below 20° and several of these below 10°.

The explanation for these results is not obvious. Possibly, rolling friction played a major role in reducing strength at the relatively large number of contact points observed in the tests on small samples. This suggestion would be compatible with Toy's opinion that the wide variability in test results on planar, sanded surfaces related to the degree to which flour was blown from the surfaces prior to testing.

4 SUMMARY AND CONCLUSIONS

- o The testing programme was undertaken to investigate the mechanisms contributing to the scale effects found by Bandis (1980) and reported in Bandis et al. (1981).
- o This study was intended to pay particular regard to the validity of the conclusion that an *asperity failure* component was a) identifiable and b) scale dependent
- o Many difficulties were encountered in preparing samples and especially in obtaining reasonable moulds of porous sandstones.
- o A common problem was that halves of models fitted imprecisely and therefore tended to move ("rock").
- o Investigations of the *basic friction angle* of planar surfaces revealed extremely wide scatter.
- o The finding of Bandis (1980) that small samples tend to reach peak strength at lower strains than longer samples was confirmed.
- o The clearly defined scale effects reported by Bandis (1980) and Bandis et al (1981) have not been confirmed.
- o The conclusion that an *asperity failure* component is scale dependent is not confirmed.
- o The model material employed by Bandis and used in this study has severe limitations for accurately and consistently simulating shear behaviour of most rocks.

ACKNOWLEDGEMENTS

The financial support for J. Toy from the Natural Environment Research Council and from Geoffrey Walton Practice during his Msc studies is gratefully acknowledged.

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