

Chapter 76

EFFECTS OF BLOCK SIZE ON THE SHEAR BEHAVIOR OF JOINTED ROCK

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ABSTRACT

The descriptive term "rock mass" encompasses individual block dimensions ranging from centimeters to many tens of meters. Strength and deformability vary both qualitatively and quantitatively as a result of this size range. A key issue is therefore the appropriate size of the test sample. A large body of test data was reviewed to determine the influence of block size on the displacement required to mobilize peak strength. It is shown that the shear strength and shear stiffness reduce with increased block size due to reduced effective joint roughness, and due to reduced asperity strength. Both are a function of the delayed mobilization of roughness with increasing block size. A method of scaling shear strength and shear displacement from laboratory to in situ block sizes is suggested. It is based on the assumption that size effects disappear when the natural block size is exceeded. This simplification appears to be justified over a significant range of block sizes, but is invalidated when shearing along individual joints is replaced by rotational or kink-band deformation, as seen in more heavily jointed rock masses. Recent laboratory tests on model block assemblies illustrate some important effects of block size on deformability and Poisson's ratio.

INTRODUCTION

The wide range of natural block sizes found in nature has a strong and obvious influence on the morphology of a landscape. The contrast in natural slope angles and slope heights sustained by a ravelling "sugar cube" quartzite and a monolithic body of granite suggests that block size may be a controlling factor when compressive strength and slake durability are high in each case. In a tunnel, the contrast in behavior may produce more than an order of magnitude change in costs

per meter. It is clear that the strength, the deformability and the mode of deformation (ravelling versus elastic) are strongly controlled by relative block size.

The mode of deformation cannot, however, be exclusively tied to block size. The loaded volume *relative* to block size, and the level of stress *relative* to the yield stress will each tend to control the mode of deformation. The above factors illustrate the difficulty that often arises in selecting the appropriate sizes of test sample. Usually, a jointed laboratory size sample will be small compared to the natural block size, and very small compared to the loaded volume in situ. Size effects will then be evident. On occasion, large size cores may be recovered which include a representative number of interlocked blocks, giving presumably a fair approximation to the strength and deformation behavior of a heavily jointed rock mass.

JOINT SAMPLE SIZE EFFECTS

Major through-going joint sets or individual discontinuities often dominate the stability and deformability of engineered structures in rock. Attempts to sample and test these surfaces are less successful than generally appears. This is because the size of the test sample often determines the magnitude of the strength data obtained.

Examples of joint sample size effects are illustrated in Figures 1 and 2. These shear tests were performed at such low normal stress (self-weight) that no shearing of asperities occurred. The marked difference in strength is strictly a function of different effective joint roughness. The small samples have the necessary degree of freedom to rotate slightly and "feel" the smaller, steeper asperities, while the monolithic blocks register only the flatter slopes of the major asperities, as clearly shown by Bandis et al (1981).

The combined effect of reduced effective roughness and increased individual contact areas causes a marked change in the shape of shear stress-shear displacement curves as sample size is increased. These effects are illustrated graphically in Figure 3. Extensive laboratory testing by Bandis (1980) suggests that the widely different shape of these illustrative strength-displacement curves is in no way exaggerated for the case of rough or moderately rough joints. However, smooth planar joints indicate only limited effects when sample size is increased.

A convenient way of interpreting the above size effects is to express shear strength in terms of its components. The peak drained friction angle (ϕ') developed by a rock joint can be expressed as:

$$\phi' = \phi_r + i \quad (1)$$

where ϕ_r = the residual friction angle of a smoothed surface

i = total roughness component

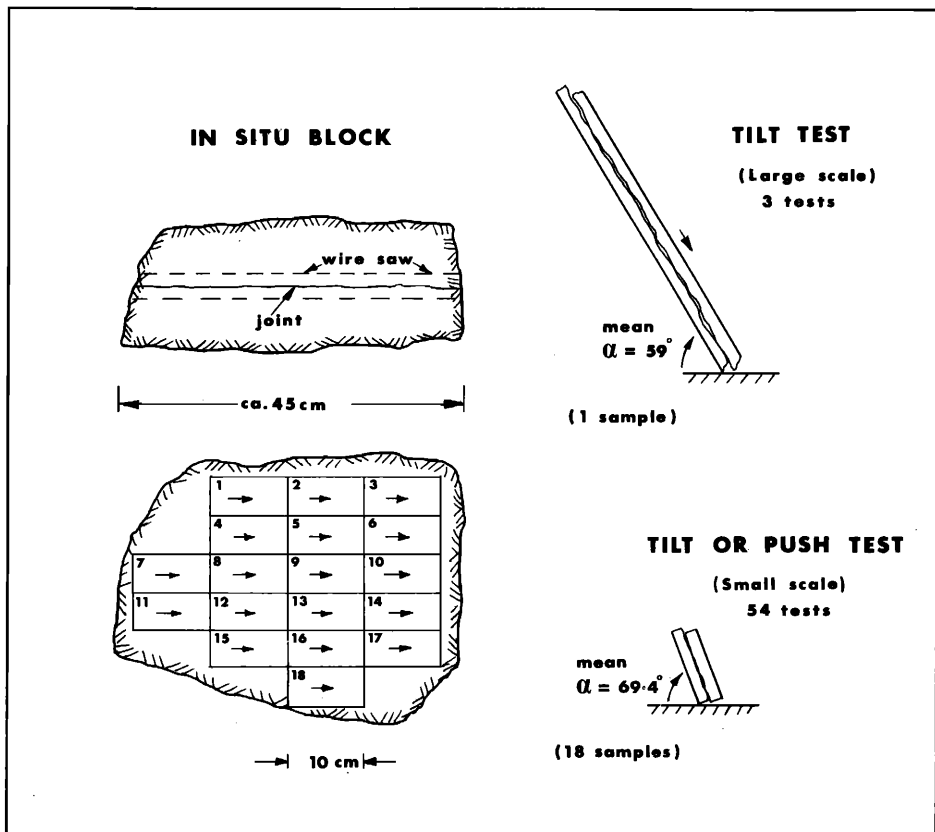


Figure 1. Tilt (self-weight sliding) tests of a natural joint in granite illustrate the exaggerated shear strength obtained when joint samples are too small. (Barton and Choubey, 1977).

The total roughness component (i) can be broken down as follows:

$$i = \text{JRC} \log (\text{JCS}/\sigma_n') \quad (2)$$

where JRC = joint roughness coefficient

JCS = joint wall compression strength

σ_n' = effective normal stress

The joint wall compression strength can be measured with a Schmidt hammer (Barton and Choubey, 1977) while the joint roughness coefficient can be calculated by rearrangement of equations 1 and 2:

$$JRC = \frac{\phi' - \phi_r}{\log (JCS/\sigma_n')}$$

(3)

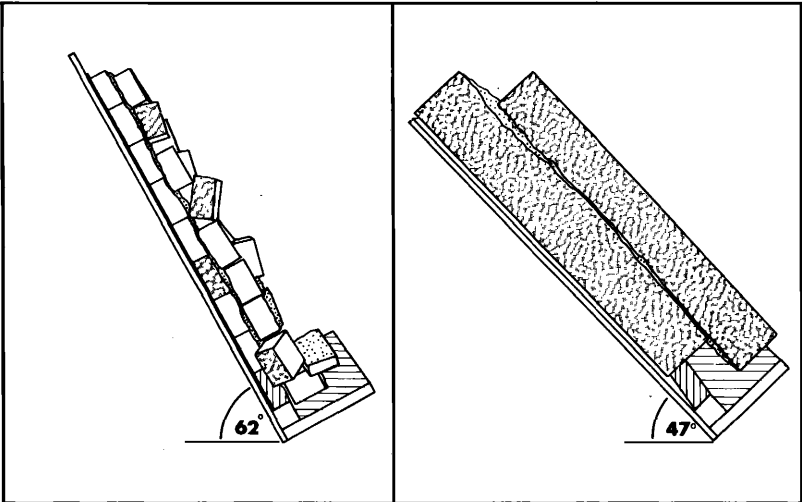


Figure 2. Contrasting shear strength of a large monolithic joint sample and an assembly of smaller blocks, each fabricated with the same batch of model material, and cast against the same joint surface. (Bandis et al. 1981).

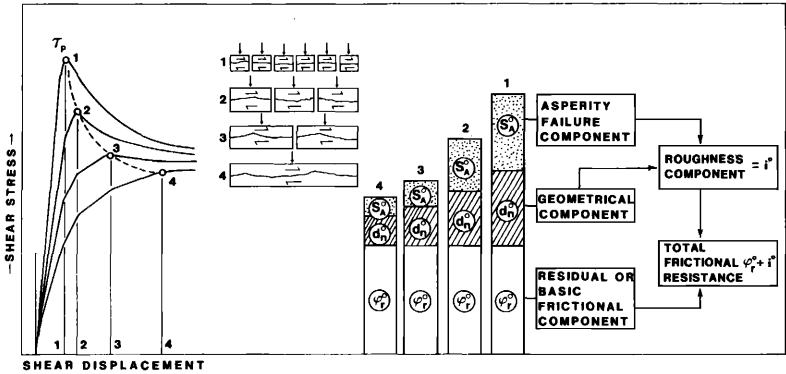


Figure 3. Increases in joint sample size cause the three fundamental changes in behavior; i.e. reduced asperity strength, reduced dilation, and increased displacement to mobilize peak strength. (Bandis et al. 1981).

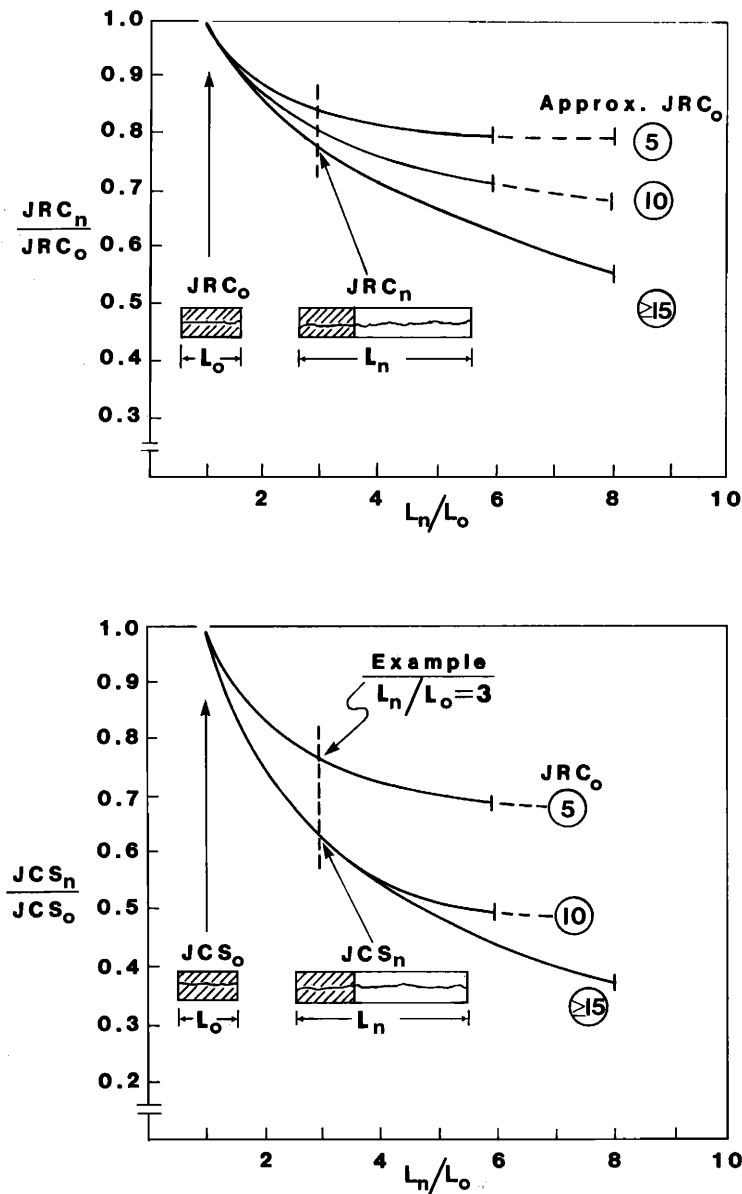


Figure 4. An approximate method for reducing joint roughness and wall strength parameters, to allow for size effects between laboratory and in situ sample sizes. (Bandis et al 1981).

Typical parametric values for a moderately rough joint in slightly weathered granite would be as follows: $\phi_r = 25^\circ$, JRC = 10 and JCS = 100 MPa. An effective normal stress of 1 MPa would give a value of (ϕ') equal to 45° , while 10 MPa would give 35° .

Extensive size effects testing reported by Bandis et al (1981) suggest that both JRC and JCS reduce with increasing block size. Experimental data available at present are summarized in Figure 4. Greatest reductions in these parameters occur with the roughest joint surfaces due to the marked change in size of the individual contact points between opposed asperities.

SHEAR DISPLACEMENT SIZE EFFECTS

The block size effects discussed above are basically the result of the reduced degrees of freedom as block size is increased. The inability of a large block to slightly rotate and register all scales of roughness results in the situation depicted in Figure 5.

The parameter $\delta(\text{peak})$ increases significantly as block size is increased. A wide ranging survey of laboratory and in situ test data, numbering approximately 650 tests, is summarized in Figure 6. For convenience, the data was grouped into three size categories: laboratory (30-300mm); in situ (300mm-3m); and novel (3m-12m). Table 1 summarizes mean values and number of tests for three categories of surface. The data has been expressed in a manner that minimizes the size effect, since all $\delta(\text{peak})$ values are normalized by sample length. Nevertheless, significant size effects are evident.

TABLE 1
Summary of Mean Peak Shear "Strains" for
Joints and Clay-Filled Discontinuities

TYPE OF SAMPLE	LAB. SCALE (30-300mm)	IN SITU (0.3-3.0m)	NOVEL (3-12m)	ALL SIZES
(1) Filled discontinuities	1.31% (56)	0.55% (94)	0.13% (5)	0.81% (155)
(2) Rock joints	1.28% (224)	0.72% (71)	--	0.98% (295)
(3) Model joints	--	1.04% (96)	0.58% (66)	0.86% (162)

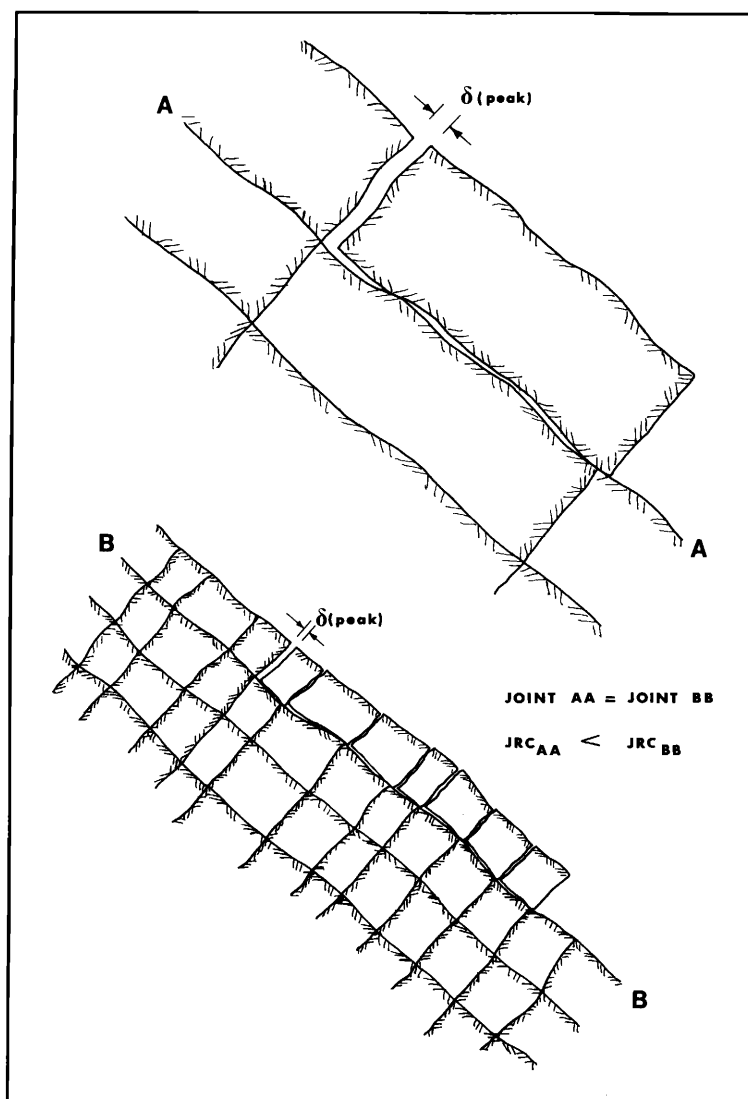


Figure 5. An illustration of the block size dependence of $\delta(\text{peak})$, the shear displacement to mobilize peak strength.

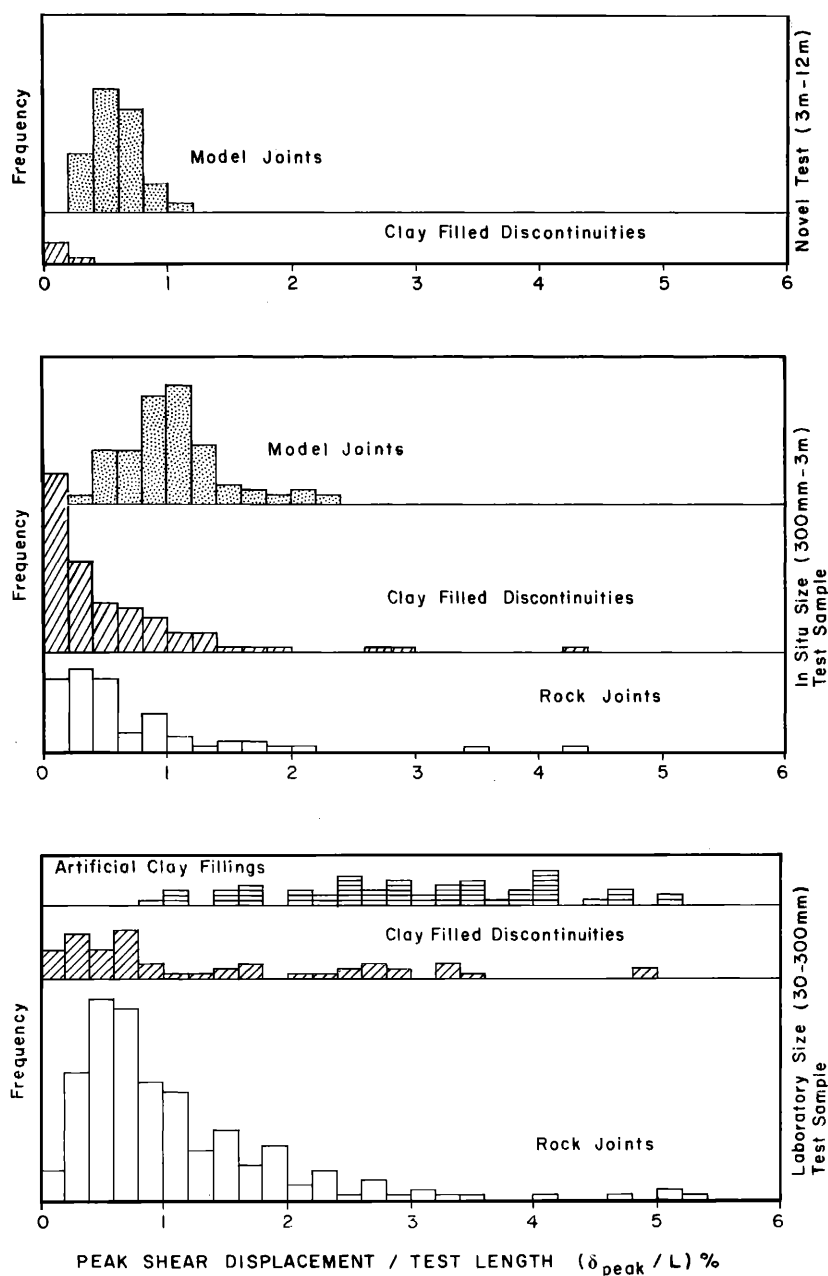


Figure 6. Distribution of $\delta(\text{peak})$ as a function of sample length for rock joints, clay-filled discontinuities and model joints.

Figure 7 illustrates the apparent consistency in displacements observed in shear tests that involve *loading* in shear, and earthquake slip magnitudes which involve *unloading* in shear. An analysis of the data indicates that the following equation gives a reasonable approximation to the observed values:

$$\delta = \frac{L}{500} \cdot \left(\frac{JRC}{L} \right)^{0.33} \quad (4)$$

where δ = slip magnitude required to mobilize peak strength, or that occurring during unloading in an earthquake

L = length of joint or faulted block (meters)

JRC = joint roughness coefficient (>0)

Example 1. Laboratory Specimen. Assume: JRC = 15 (rough), $L = 0.1\text{m}$
Equation 4 gives $\delta = 1.0\text{mm}$

Example 2. Natural Jointed Block. Assume: JRC = 7.5, $L = 1.0\text{m}$
Equation 4 gives $\delta = 3.9\text{mm}$

Example 3. Earthquake Fault. Assume: JRC = 0.5 (near-residual),
 $L = 100\text{km}$
Equation 4 gives $\delta = 3.6\text{ meters}$

The above examples of size effects illustrate that equation 4 gives an acceptable degree of accuracy for most practical applications. The implication that (δ) is smaller when surfaces are smoother or closer to residual (JRC $\cong 0$) also appears to be consistent with observations.

SHEAR STIFFNESS SIZE EFFECTS

Increased block size has been shown to:

increase $\delta(\text{peak})$

reduce JRC

reduce JCS

The combined effect is to noticeably reduce the peak shear stiffness (K_s) which was defined by Goodman (1970) as:

$$K_s = \frac{\sigma_n' \tan \phi'}{\delta (\text{peak})} \quad (5)$$

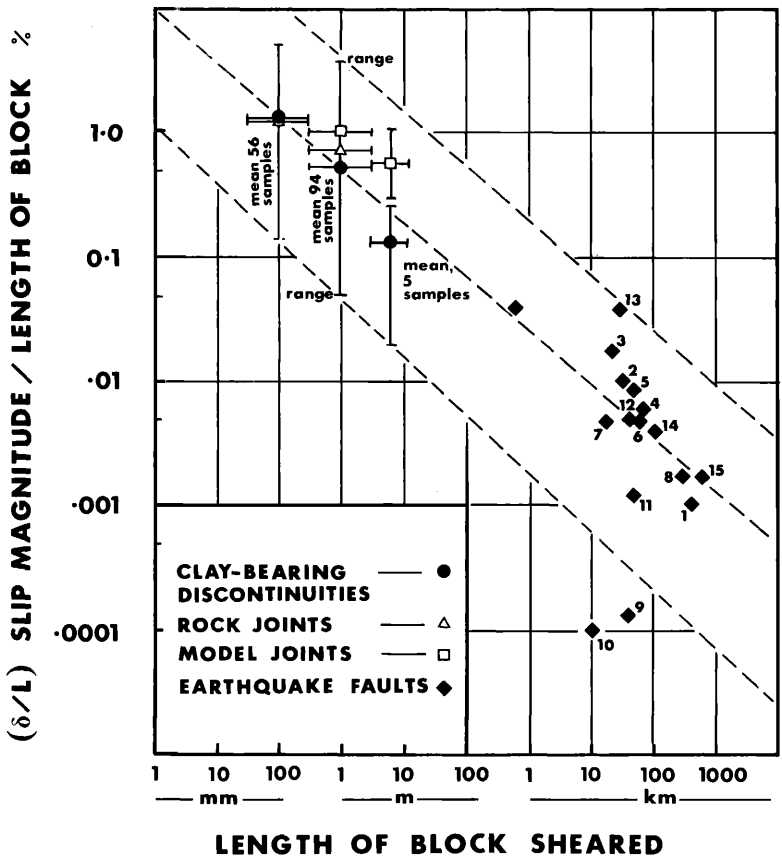


Figure 7. Slip magnitudes required to mobilize peak strength show a consistent effect of block length. Extrapolation to data for earthquake slip magnitudes (after Nur, 1974) suggests consistent trends between loading and unloading shear stiffness.

A useful approximation to K_s is given by rearrangement of equations 1, 2, 4 and 5:

$$K_s = \frac{\sigma_n' \tan [JRC \log (JCS/\sigma_n') + \phi_r]}{\frac{L}{500} \cdot \left(\frac{JRC}{L}\right)^{0.33}} \tag{6}$$

Measured values of K_s derived from a wide ranging review of test data are shown in Figure 8, each as a function of block size. The stippled lines representing normal stress levels were located using the mean

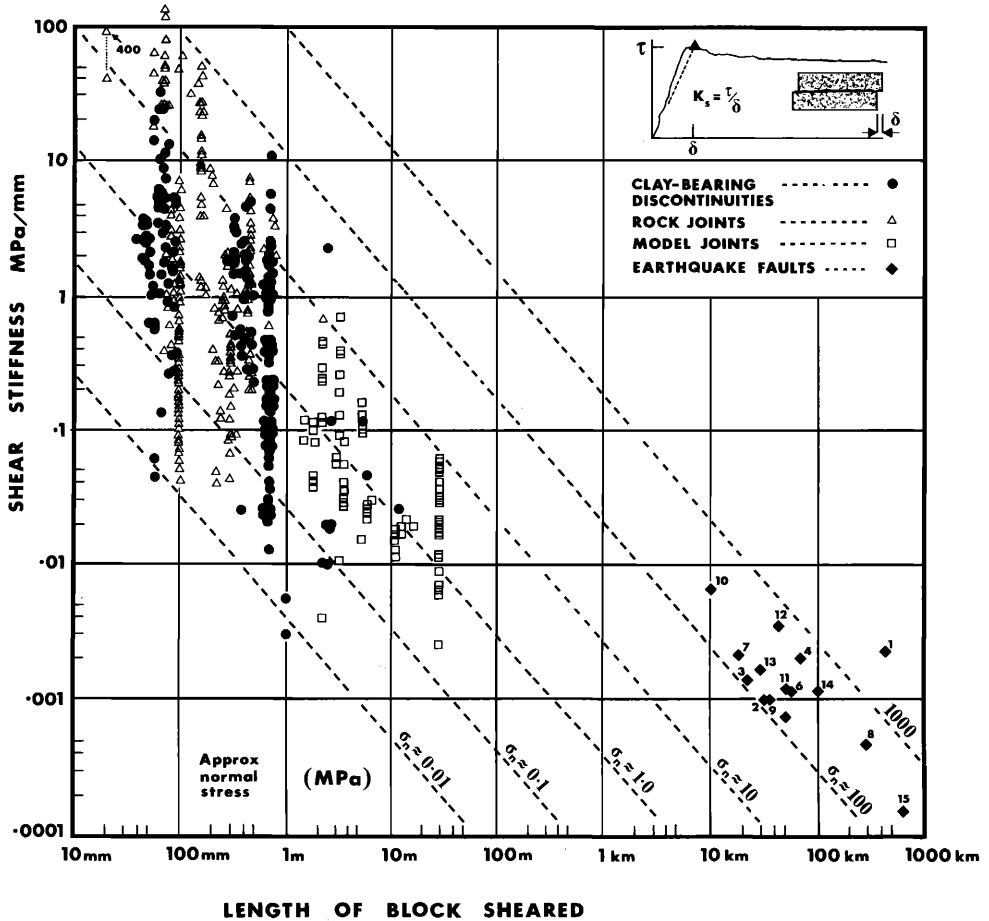


Figure 8. Laboratory and in situ shear stiffness data reported in the literature indicate the important influence of block size. Comparison is also made with the average values of stiffness derived for earthquake events, as reviewed by Nur (1974). The normal stress diagonals have been extrapolated linearly outside the range of typical test sizes of 100mm-1 meter.

values of JRC, JCS and ϕ_r obtained from the 137 shear tests on rock joints reported by Barton and Choubey (1977):

$$\text{JRC} = 8.9$$

$$\text{JCS} = 92 \text{ MPa}$$

$$\phi_r = 27.5^\circ$$

$$L = 0.1\text{m}$$

The most frequently measured value of $\delta(\text{peak})$ was 0.6mm, giving a peak shear stiffness value of 1.7 MPa/mm under a normal stress of 1 MPa. The gradient of the normal stress lines was derived from the best fit relationships to the data shown in Figure 4.

$$\text{JRC}_n \approx \text{JRC}_o \left(\frac{L_n}{L_o} \right)^{-0.02 \text{ JRC}_o} \quad (7)$$

$$\text{JCS}_n \approx \text{JCS}_o \left(\frac{L_n}{L_o} \right)^{-0.03 \text{ JRC}_o} \quad (8)$$

These equations were derived from shear tests over a ten-fold range of block sizes, and linear extrapolation outside the size range 100mm - 1 meter has been assumed when drawing the effective normal stress diagonals in Figure 8. It will be noted that the earthquake fault stiffnesses (mean values from Nur, 1974) are bracketed by the effective normal stress diagonals 100-1000 MPa (1-10 Kbars).

Tentative application of equations 6, 7 and 8 over a two order of magnitude range of block sizes shown in Figure 9 suggests a gradual flattening out of the normal stress diagonals with increasing block size. Tentative scaling of the same data to earthquake fault sizes indicates normal stress levels closer to the range 5-20 MPa (50-200 bars). This is conveniently close to the effective normal stress levels operating at depth in the vicinity of the San Andreas fault (Zoback et al. 1980).

It will be noticed that the stiffness of the rough, competent joint and that of the weaker, smooth joint (Figure 9) converges when either the stress level, or block size is increased. The above method of estimating peak shear stiffness for rock joints is specifically directed at clay-free discontinuities. When clay is present, preventing (to a greater or lesser extent) rock-to-rock contact, the peak shear stiffness tends not to be so size-dependent, and is also somewhat less stress dependent, due to the low shear strength (Infanti and Kanji, 1978).

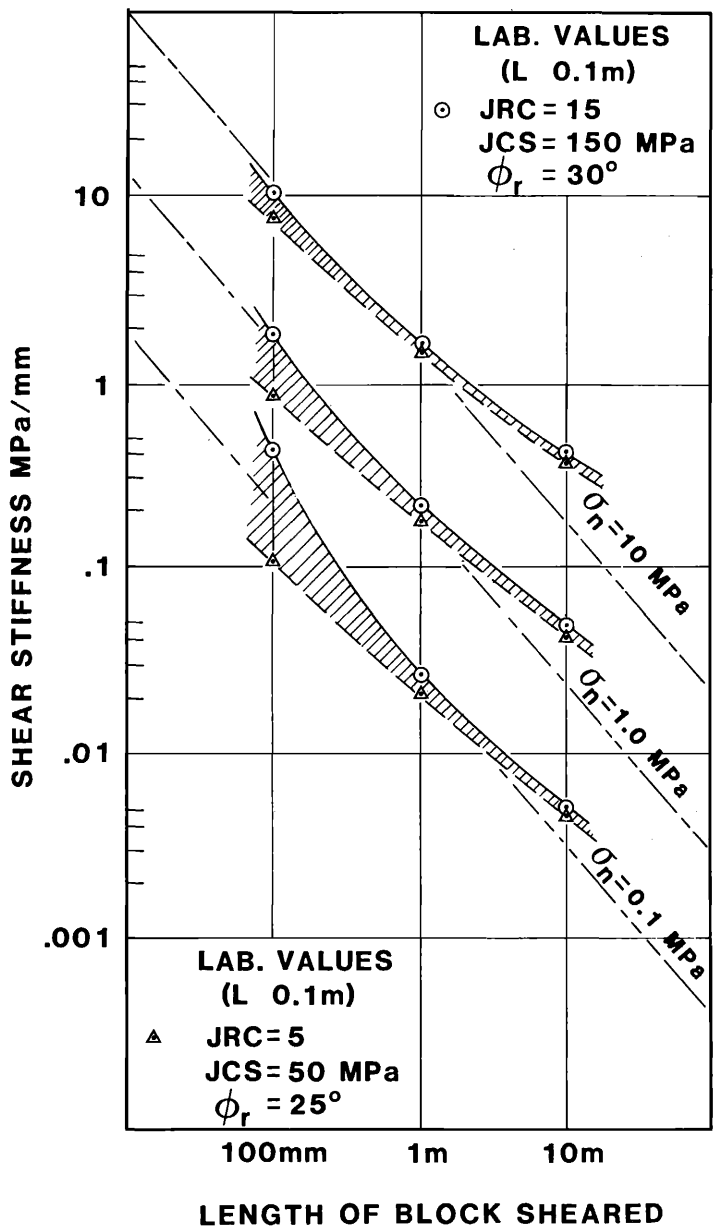


Figure 9. Application of equations 6, 7 and 8 to the scaling of typical laboratory test data. The diagonal normal stress lines match those in Figure 8.

SIZE EFFECTS IN BLOCK ASSEMBLIES

It has been shown earlier that joint properties are size-dependent when shear displacement is involved, due to the displacement-dependence of strength mobilization. However, the size dependency may apparently die out in an assembly of rock blocks when a "sample" exceeds the natural block size. Figure 10 shows schematically that, for unchanged roughness, the smaller the block size, the higher the shear strength of an assembly of blocks. The spacing of joints intersecting a potential shear plane also defines the distance between potential "hinges" in the assembly. The slightest block rotation allows the finer features of roughness to be felt as opposed to sheared over, hence the scale effect.

The biaxial samples depicted in Figure 10 were each fabricated with the same weak, brittle model material. Joint sets were formed using the same guillotine (Barton and Hansteen, 1979). Joint angles were the same in each case. Thus, the only difference was the joint spacing. Assembly No. 1 consisted of 4000 blocks; No. 2, 1000 blocks, and No. 3, 250 blocks. Joint spacing was doubled and quadrupled to produce these totals.

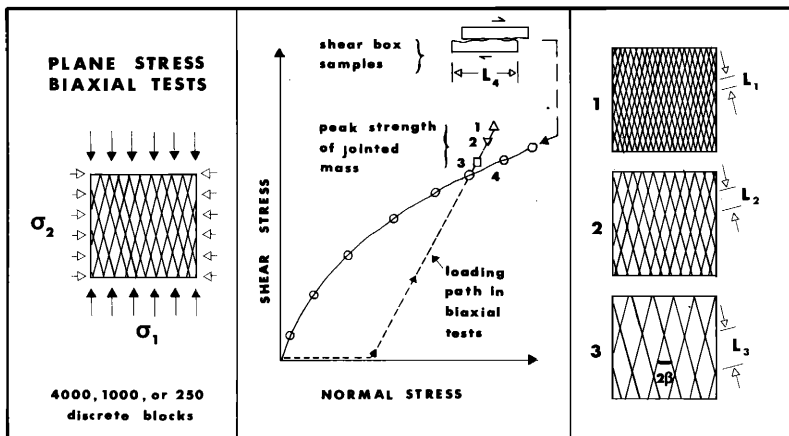
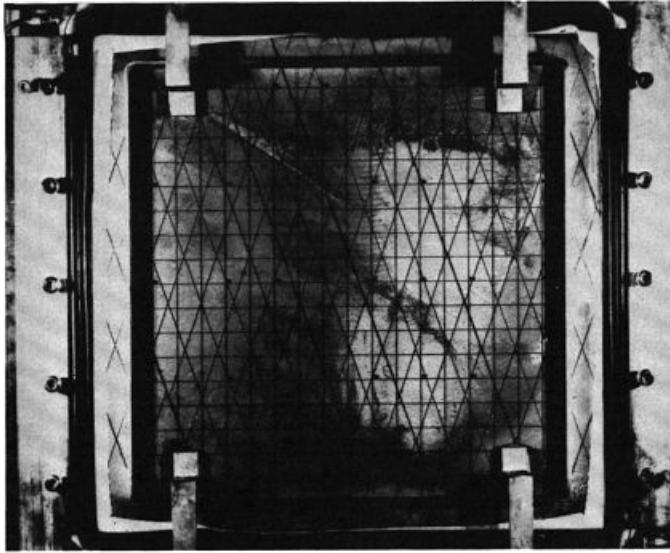


Figure 10. The size of individual blocks in a jointed assembly determines the shear strength of the assembly.

Sample Nos. 2 and 3 failed by shear along several of the primary continuous joints when the mobilized roughness JRC had reached values of 25.1 and 21.6 respectively. Higher differential stress was required to fail assembly No. 1, and failure did not occur by shear parallel to the weakest joint set. The contrasting failure modes are illustrated in Figure 11. Several tests were performed on assemblies of the smallest size blocks, using both diamond and square shaped

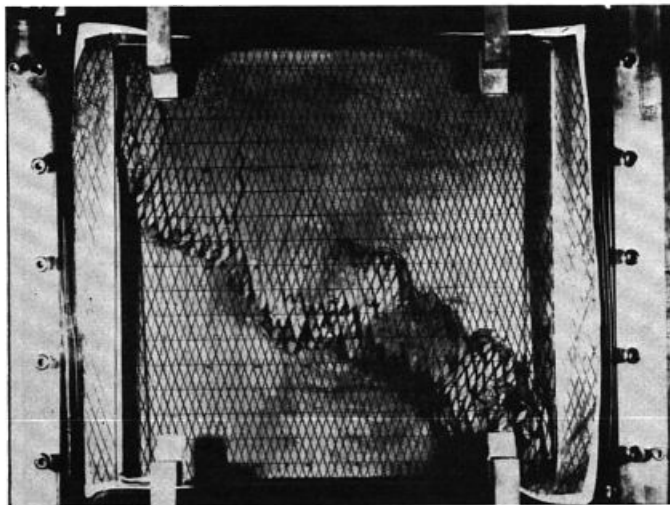
blocks. In each case, failure occurred by rotation of blocks within a "kink" band at least eight blocks wide. Sequence photographs of such a development are given in Figure 12.



Test IV

$$\downarrow \sigma_1 = 1.75$$

$$\leftarrow \sigma_2 = 0.2$$



Test III

$$\downarrow \sigma_1 = 1.9$$

$$\leftarrow \sigma_2 = 0.2$$

Figure 11. Block assemblies with large relative block size fail by shear along the weakest (continuous) joint set. All the assemblies with the smallest block sizes failed by rotation within a "kink" band.

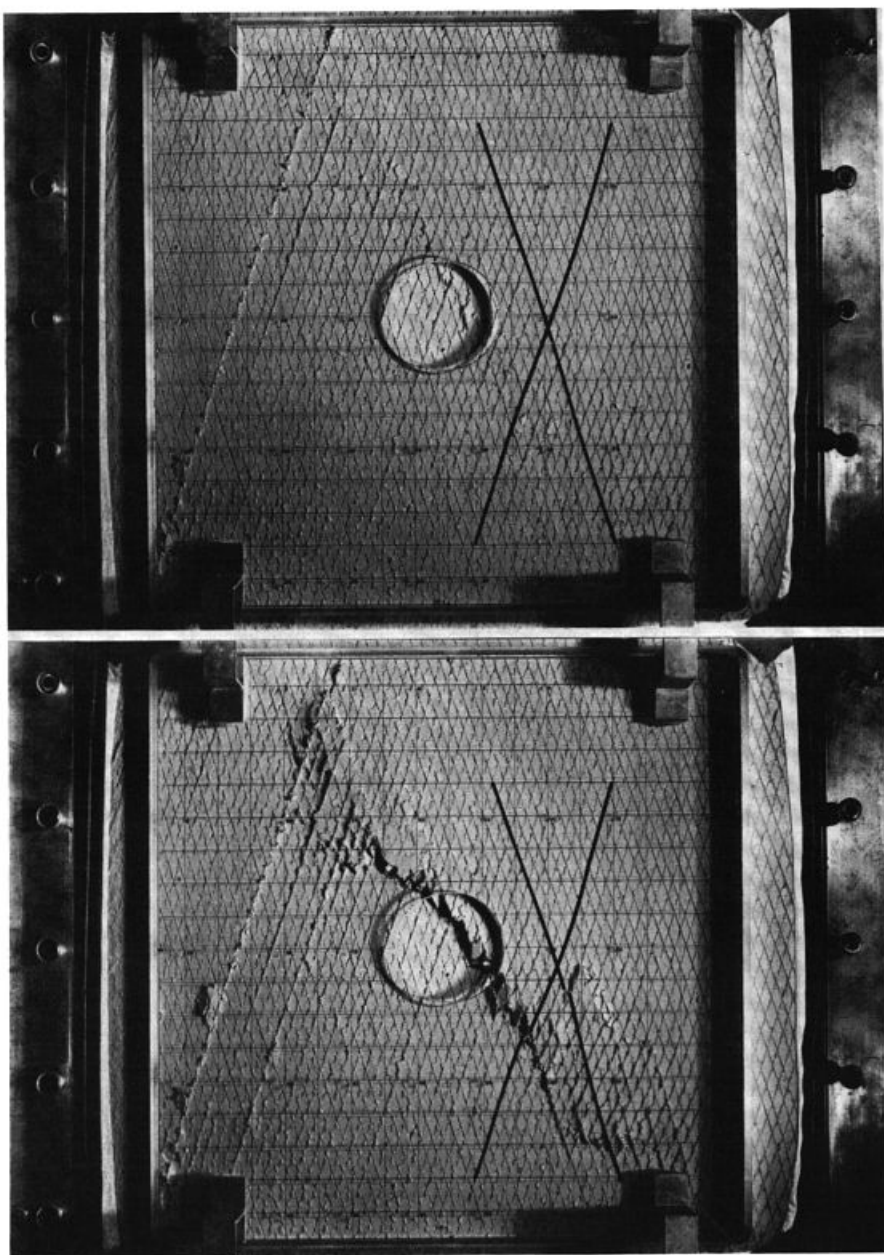


Figure 12. Sequence photographs illustrating the development of a rotational "kink" band concurrently with in-plane joint shear.

It appears that a fundamental change in deformation and strength behavior occurs when the number of blocks per loaded area exceeds some limit. Rotational modes of deformation have been observed in model studies by Ladanyi and Archambault (1972), and by Hayashi and Kitahara (1970). In 1974, Goodman made the following comments on the subject: "Rotational friction is important in view of the low shear strengths associated with instability by buckling and kinking of layers or rows of joint blocks. Unfortunately, our appreciation and understanding of these phenomena is only just beginning". These comments appear equally valid today.

Triaxial compression testing of jointed models reported by Baecher and Einstein (1981) indicate that both strength and deformation moduli decrease logarithmically with numbers of joints. The reported tests were performed with just one set of joints perpendicular to the major principal (axial) stress. As pointed out by these authors, changing scale may change the relative importance of the various possible failure mechanisms. In addition, changing the shape of blocks and the angle between joint sets may result in failure modes other than those commonly considered, especially when confining stresses are low or zero (Brown, 1970).

SIZE EFFECTS ON POISSON'S RATIO

An attempt to investigate the onset of different failure modes with different block sizes is shown in Figure 13. The axial and lateral strains were recorded using a photogrammetric technique. The most obvious difference in behavior is the ratio of axial to lateral strain, or Poisson's ratio. The stiffer, large-block assemblies deform by in-plane joint shear, and this results in rapid increases in Poisson's ratio due to the combined effect of joint shear and dilation caused by over-riding of roughness. The relatively moderate build-up of Poisson's ratio in the heavily jointed assembly (Figure 13) is probably a function of the large amount of axial consolidation that can be accommodated by numerous joints, before significant shear is apparent. At a later stage of loading when shear failure is imminent, Poisson's ratio is seen to increase up to, and beyond 1.0. An example of physical measurements of this phenomenon is shown in Figure 14.

Large increases in Poisson's ratio due to joint shear have been observed in model studies by Muller and Packer (1965), John (1970), and Barton and Hansteen (1979). They have also been measured in large-scale in situ block tests on jointed rock by John (1961), Lögters and Voort (1974), and Barton and Lingle (1982).

APPROPRIATE TEST SIZE

It is apparent from these tests on assemblies of blocks that the size of individual blocks controls both the shear strength of the

assembly, and its deformation characteristics. It appears reasonable to assume that a test on one jointed block will give nearly the same result as a test on two adjacent blocks, if the pair of blocks are "hinged" (i.e. cross-jointed) so that the necessary freedom for rotation is present. If this is true, then a significant rock mechanics test size for jointed media will be the natural block size as depicted in Figure 15.

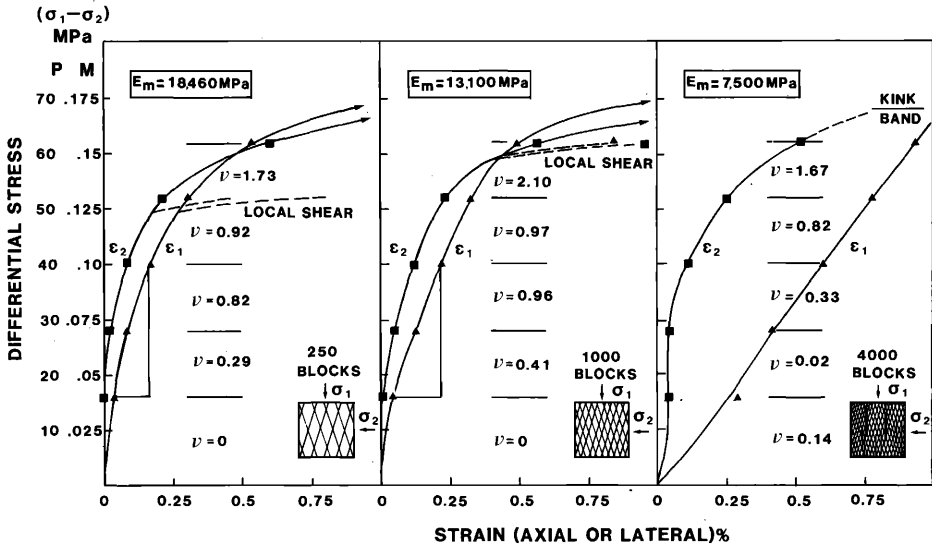


Figure 13. Contrasting deformation behavior exhibited by assemblies of different sized blocks.

Tests on smaller jointed blocks, for example on jointed drill core from the same rock mass, will automatically incur a size effect. The magnitude of this size effect may be significant if the particular joint set is non-planar. An example of measured size effects on shear stress-displacement behavior is given in Figure 16. A most significant point to note is that the assumed "residual" strength remaining at the end of the small-sample test is significantly higher than the peak strength of the full-size sample.

Tests on the natural-size blocks of a rockmass will obviously need to be performed in large numbers, before a statistically viable sample of test data is achieved. The combination of inexpensive tilt tests and Schmidt hammer tests is therefore attractive for obtaining the necessary shear strength data.

When deformability is also of concern, more expensive in situ block tests may need to be performed. Test volumes should then include a significant number of each of the joint sets thought to control

the deformability of the rock mass. Suitable choice of instrumentation to span intact rock, single joints and multiple joints will then provide invaluable data on the magnitude of potential size effects.

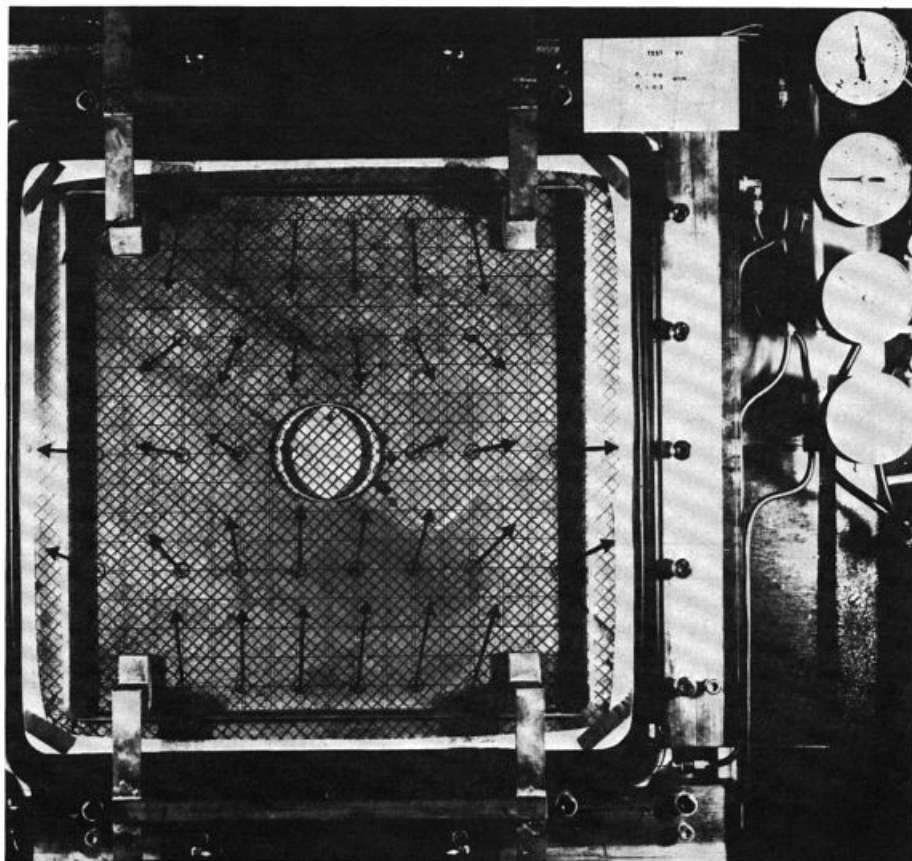


Figure 14. An example of the large values of Poisson's ratio (or transverse deformation) associated with shear and dilation of a jointed assembly of blocks. The displacement vectors were derived by photogrammetric analysis, and are relevant to the deformation occurring when the stress difference was increased from prototype (full-scale) values of 52 to 72 MPa.

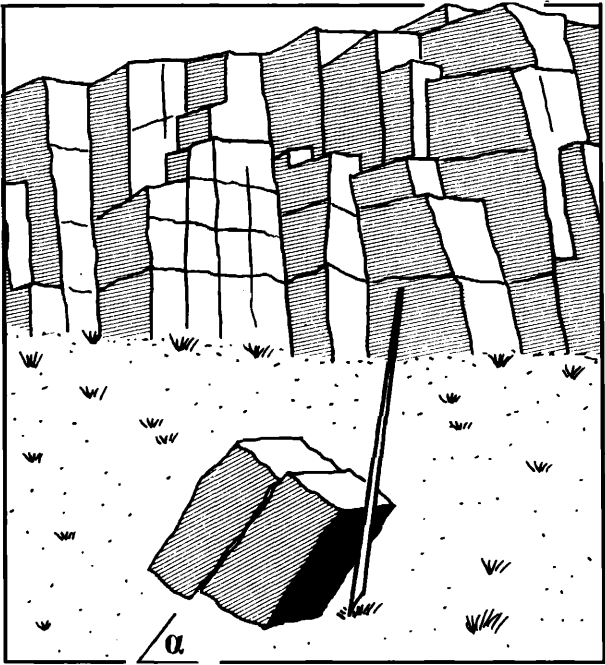


Figure 15. A simple method for obtaining a scale-free value of JRC when the natural rock blocks are not too large or difficult to extract.

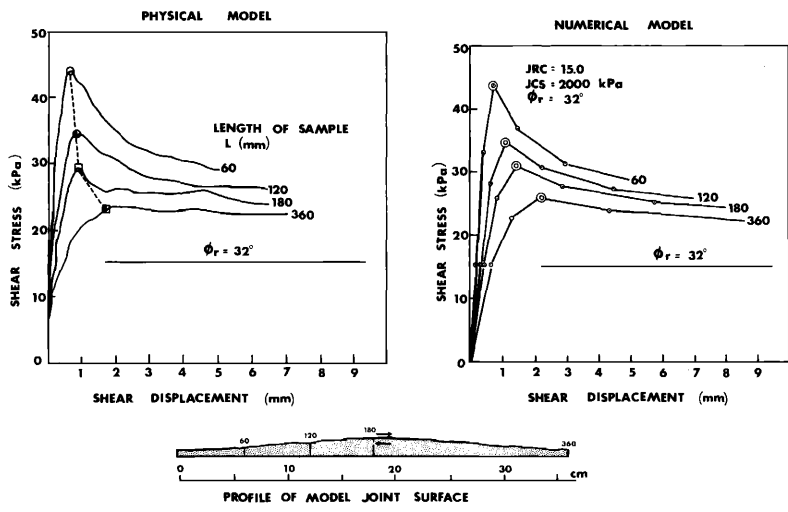


Figure 16. Measured size effects caused by testing jointed samples smaller than the full-size block. The physical model tests are reported by Bandis et al. (1981).

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