

# Interpretation of direct shear tests on rock joints

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**ABSTRACT:** The origins of shear strength are reviewed in the context of direct shear testing of rock discontinuities. A method of analysing data to correct for dilation over different increments of horizontal displacement throughout a test is demonstrated and various forms of presenting data are discussed. It is argued that the corrected strength envelope for the test as a whole can be used to derive appropriate lower bound strength parameters for design. Additional strength may be allowable to account for roughness at the field scale, but as an alternative approach, it is recommended that the dilation-corrected strength be used directly for design with a lower factor of safety on shear strength than would normally be adopted.

## 1 INTRODUCTION

The shear strength of natural rock discontinuities is often difficult to predict largely because of their roughness. In addition, different minerals have different frictional properties; furthermore infill or weathering can influence all other parameters including the effective roughness. The problems are compounded by the apparent effects of scale and normal stress level.

One option is to carry out direct shear tests on small samples even though it is generally recognised that these may be unrepresentative of the discontinuities in the field, particularly with respect to roughness. The recommended methods for testing published by ISRM (Brown, 1978) and by CANMET (Gyenge & Herget, 1977) emphasise the importance of careful monitoring of displacement data as well as loads, but give little guidance on interpretation of results.

Reported direct shear test data tend to show the same general trends of increasing shear strength with increasing roughness, especially at low normal stress levels, but often little consistency in the results achieved. Even for tests on artificial planar surfaces, consistent results are not always obtained and require skill for interpretation. For example, Nicholson (1994) reported a variation in friction angle of 12.5 degrees for saw-cut samples of the same sandstone tested by four different laboratories. He commented that even greater

variability would be expected for naturally rough discontinuities.

It is apparent that currently many geotechnical engineers consider direct shear tests on rock discontinuities to be of limited use for providing reliable design parameters. A procedure for analysing and interpreting test results which accounts for sample-variable roughness so that the data can be used with confidence is described in this paper.

## 2 ORIGINS OF SHEAR STRENGTH

### 2.1 Shear strength models

The most generally accepted models for rock shear strength appropriate to civil engineering or mining conditions are those of Ladanyi & Archambault (1970) and Barton and co-workers (as reviewed by Barton & Bandis, 1990 and Bandis, 1993). Both theories take the shear strength of a planar surface as a lower bound then add components of strength due to dilation or to damage of asperities. In Bartons model the lower bound planar surface strength is defined as the residual shear strength,  $\phi_r$ , or basic friction angle,  $\phi_b$ . The authors suggest that this value can be determined from tests on flat, saw-cut and sand blasted surfaces through the parent rock. From literature survey, typical values for  $\phi_r$  are given as  $30^\circ \pm 5^\circ$  ( $30^\circ \pm 1.5^\circ$  according

to Barton & Bandis, 1990). The strength contribution from roughness is estimated with reference to a series of joint roughness profiles (JRC) modified according to rock wall strength and stress level. Over twenty years, the criterion has been revised several times, most importantly to incorporate effects of scale on JRC and rock wall strength (JCS) and also to make it clear that it may be appropriate to allow for additional field roughness once JRC has been corrected for scale. Many recent papers on rock shear have concentrated on testing the JRC concept or on ways of better defining JRC (see for example Hsiung et al. 1993; Kulatilake et al., 1994; Odling, 1994). Very little attention has been given to the 'basic' friction component.

In the method of analysis of shear test data for natural joints, presented below, the effects of external work due to dilation are corrected for. It should be emphasised that the dilation-corrected frictional resistance thus determined is not the equivalent of  $\phi_r$  in Bartons empirical criterion as suggested by Bandis (1993).

One of the potential problems with the empirical approach is that engineers may assume that the "basic" or "residual" friction determined from a saw cut, sand-blasted surface or following considerable shear displacement of a natural joint is a unique parameter for a particular rock or rock joint. More importantly, they may also wrongly assume that that value is the lowest possible strength for the rock type.

It is well established that the shear strength of planar surfaces through the same rock can be quite variable depending upon surface finish (Coulson, 1971). Friction angles much lower than those for typical saw-cut and sand blasted surfaces can be measured from artificially polished surfaces (Byerlee, 1967) or following long displacements and the removal of debris (Hencher, 1976). Similarly, measured shear strengths for natural joints can be much lower than for a saw cut surface through the same rock. Data reported by Richards (1975) indicating friction angles as low as  $12^\circ$  for weathered sandstones were noted by Barton & Choubey (1977) who suggested that a correction factor could be applied to  $\phi_r$  when dealing with weathered rocks. This is done by using the ratio of the Schmidt hammer rebound value for a weathered surface to that of a fresh surface. In practice, weathered rock joints can exhibit higher shear strengths than their less weathered counterparts (Hencher & Richards,

1989). Furthermore this correction does not allow for fresh surfaces which have a high natural polish or surfaces which have a low friction coating both of which may have peak shear strengths far lower than  $\phi_r$  as previously defined.

A conceptual problem with the empirical approach is that Byerlee (1985) notes that, whilst the shear strength of rock joints at low stresses is extremely variable (due to variable roughness), at higher stresses, where the effect of roughness is assumed to be essentially lost, shear strength is frictional and that for the majority of rocks the friction coefficient is 0.85 ( $40.4^\circ$ ) for normal stresses below 200 Mpa. Bartons equation predicts that shear strength should approach  $\phi_r$  (about 10 degrees less) as the normal stress level approaches the compressive strength of the wall rock.

## 2.2 Physical origins of shear strength

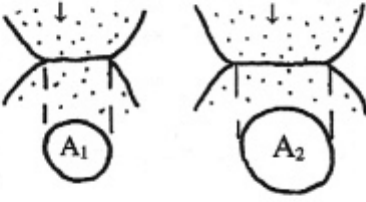
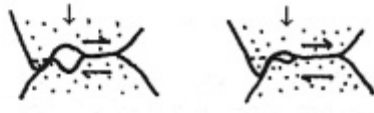

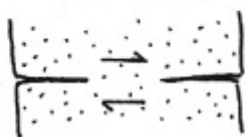
Fundamental work on the physical origins of rock friction includes that of Byerlee (1967), Engelder & Scholz (1976), Ohnaka (1975) and many others. A very useful, recent review from a fundamental viewpoint is presented by Scholz (1990).

The components of shear strength are represented schematically in Table 1 and discussed briefly below:

1. The lower bound strength for any discontinuity through rock is probably derived from chemical and physical bonds which are continually formed and broken during shear over the true area of contact as originally proposed by Terzhagi (1925) and established experimentally for metals by Bowden & Tabor (1964). It has not yet been confirmed that the adhesional theory of friction is entirely appropriate to rocks (Boitnott et al., 1992) but for many rocks it is clear that the lower-bound frictional strength is likely to be of the order of ten degrees. Certainly values this low can be approached for artificially or naturally polished rock surfaces.

2. Additional frictional strength at a textural scale is derived from the interaction of minor asperities which are deformed and damaged locally during shear without causing dilation of the whole discontinuity (by definition). In the case of a typical test on saw-cut surfaces for which a friction angle of 30 degrees is measured, it is estimated that perhaps 2/3 of shear resistance is due to surface textural damage and deformation processes. Surfaces which have even rougher

Table 1 Factors contributing to the shear strength of rock discontinuities (after Hencher, 1987)

<p>1. ADHESION (lower bound friction) increasing normal load <math>\rightarrow</math></p> <p><math>N_1</math>                      <math>N_2</math></p> 	<p>- Bonding over true area of contact (<math>A_1</math>, <math>A_2</math>)</p> <ul style="list-style-type: none"> <li>• proportional to normal load</li> <li>• does not cause dilation (by definition)</li> <li>• no reduction with displacement</li> <li>• same for different textural surfaces and roughness</li> </ul>
<p>2. INTERLOCKING AND PLOUGHING (additional friction) increasing normal load <math>\rightarrow</math></p> <p><math>N_1</math>                      <math>N_2</math></p> 	<p>- Surface texture component</p> <ul style="list-style-type: none"> <li>• proportional to normal load</li> <li>• does not cause dilation</li> <li>• generally decreases with displacement due to damage and the production of debris</li> <li>• increases with rougher surface texture</li> </ul>
<p>3. OVERRIDING</p> 	<p>- Work done due to dilation or compression</p> <ul style="list-style-type: none"> <li>• uphill sliding leads to an increase in measured strength and vice versa</li> <li>• purely geometrical effect</li> <li>• decreases with increasing normal load and decreasing wall rock strength</li> </ul>
<p>4. COHESION</p> 	<p>- Shearing of rock bridges and locked asperities</p> <ul style="list-style-type: none"> <li>• not proportional to normal load</li> <li>• independent of dilation</li> <li>• lost after peak strength</li> </ul>

surface textures than produced by a diamond saw, yet still have planar morphologies, will give even higher strengths without dilating.

3. Where a discontinuity is rough at a coarser scale, additional strength is derived from work done by overriding large asperities (dilation) and this can be accounted for by careful measurement and analysis as discussed later. Work is also done in deforming or damaging those same large asperities which cause dilation and this contribution is a matter of some debate (Barton,

1990; Kutter & Otto, 1990; Hencher et al., 1993; Papaliangas et al., 1994). From experience of testing natural discontinuities, this contribution to shear strength is essentially frictional (proportional to normal load) and inseparable from component 2 above. Nevertheless the detailed interaction of large asperities in any situation will be complex and depend upon geometry (and thus scale) and asperity strength relative to stress level much in the ways envisaged by Ladanyi & Archambault (1970) and Barton & Choubey (1977).

4. True cohesion results from the shearing of intact rock bridges or healed sections of discontinuities but will not be considered here; discussion will instead concentrate on continuous fractures. Locking of steep asperities can also give rise to a true cohesive strength involving shearing of the asperities, the work involved not being represented as an equivalent dilation angle (as is the case for asperity deformation and damage during the overriding of asperities, factor 3.).

No account will be given of the special problems associated with infilled joints.

In practice, there are two stages in determining shear strength for design. Firstly, the friction available at a textural scale needs to be determined (factors 1 & 2 above). This depends upon the finish and mineralogy of the natural surfaces and may be higher or lower than for saw-cut surfaces through the parent rock. Secondly, some account can be taken of the strength contributed by roughness interaction and impersistence (factors 3 & 4 above) at the field scale.

### 3 DIRECT SHEAR TESTING

The importance of roughness to shear strength at the relatively low stresses of most civil engineering situations is clear. Samples from the same rock type or even from the same discontinuity but with different roughness will exhibit different shear strength behaviour. Furthermore the effective roughness of a single sample will be directional so that different strengths will be measured for the same sample depending upon the way the sample is set up (Huang & Doong, 1990). For this reason a single parameter or set of parameters cannot be expected adequately to represent the roughness of a specific sample.

Following Pattons (1966) appraisal of shear strength at relatively low stress levels as comprising a "basic" friction angle together with a dilation angle, many researchers have found that, if corrections are made for dilation at peak strength, (generally by simply taking away a measured dilation angle from the peak friction angle) then a less scattered shear strength envelope is produced. Such an approach has been employed by various authors including Ross-Brown & Walton (1976) and is recommended by CANMET (Gyenge & Herget, 1977). The method of analysis discussed below employs the same principle but corrections are made in an incremental fashion for volumetric

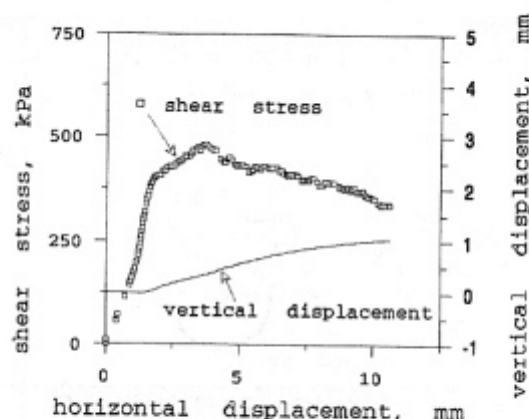


Figure 1 Measured data from a direct shear test on a natural discontinuity

work done throughout the test. After correction, the underlying frictional resistance of effectively planar surfaces of natural texture and mineralogy is revealed.

### 4. DATA PRESENTATION AND ANALYSIS

Hencher and Richards (1989) discuss procedures for shear testing at the laboratory scale. The importance of careful description and documentation to the interpretation of results is emphasised. Shear stress, horizontal displacement and vertical displacement should be measured at the same times throughout the test. These raw data can be plotted as suggested by ISRM (Brown, 1978) and shown in fig.1.

Incremental dilation angles leading to each shear stress measurement can be calculated from the relationship:

$$i = \tan^{-1} \delta v / \delta h$$

1

where:

$i$  is the angle of dilation or compression, and  $\delta v$  is the increment of vertical displacement through the line of normal loading over a selected increment of horizontal displacement,  $\delta h$ . The increment of horizontal displacement over which to measure dilation must be selected with due regard to the necessary detail of analysis and the potential errors. If dilation is measured over relatively large increments of displacement, then reading errors are reduced, but a less detailed picture of shear behaviour is obtained. This can lead to significant



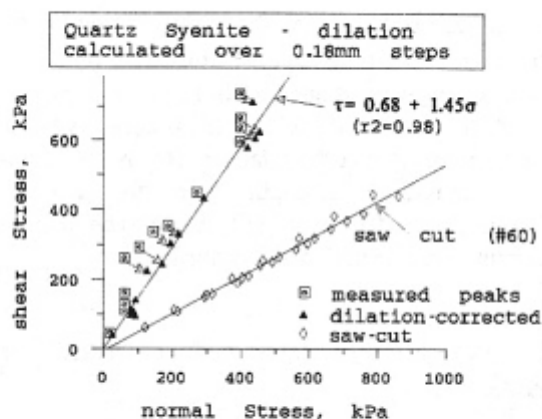


Figure 2 Peak and corrected peak strengths for quartz syenite. Saw-cut strengths for comparison.

differences in interpretation, particularly in the case of discontinuities undergoing strong volumetric changes, and should be investigated during analysis. In practice, experience shows that, for a system measuring to an accuracy of about  $\pm 0.005$  mm, analysis over horizontal displacement increments of about 0.2 mm generally gives reasonably smooth dilation curves whilst retaining most of the detail. The work directly attributable to dilation or contraction can then be corrected for by resolving the stresses with respect to the actual plane of sliding by using the following equations:

during dilation:

$$\tau_c = (\tau \cos i - \sigma \sin i) \cos i \quad 2$$

$$\sigma_c = (\sigma \cos i + \tau \sin i) \cos i \quad 3$$

during contraction:

$$\tau_c = (\tau \cos i + \sigma \sin i) \cos i \quad 4$$

$$\sigma_c = (\sigma \cos i - \tau \sin i) \cos i \quad 5$$

where:

$\tau$  = shear stress as measured horizontally,  
 $\sigma$  = normal stress as measured vertically,  
 $\tau_c$  = shear stress along the actual plane of sliding,  
 $\sigma_c$  = normal stress across the actual plane of sliding.

The corrected data can be presented in a number of ways. Corrections made solely at peak strength are shown in figs. 2 and 3. Data from a series of tests on a well matched, rough tensile fracture through very strong quartz syenite are presented in fig.2. Over the applied stress range, the very high, non-dilatational strength envelope ( $\phi_p \approx 55^\circ$ ) is

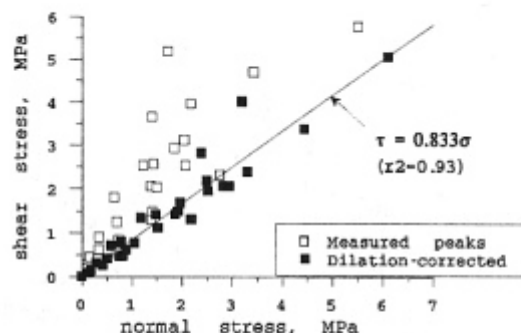


Figure 3 Published, measured peak strength data for various rocks, corrected for dilation.

clearly essentially frictional. For comparison, data from saw cut surfaces are included in this figure with  $\phi = 28^\circ$ . In 1982 a large rock slide took place through the same rock on a discontinuity dipping at only 21 degrees in dry conditions. This could only be understood following a series of direct shear tests which revealed that friction angles as low as 19 degrees were typical of some of the natural discontinuities involved in the failure at the stress levels involved. This case illustrates the importance of careful testing to engineering practice.

Peak strength data for a variety of rocks including granites, sandstone and siltstone presented by Barton & Bakhtar (1987) and Kutter (1974) are plotted in fig.3. Corrections have been made for dilation angles, either as reported directly, or measured from published graphs. It can be seen that the corrected data define a friction angle of about  $40^\circ$  quite clearly. The same, dilation-corrected, friction angle is commonly measured at low stress levels (say  $< 3$  MPa) for many natural discontinuities through silicate rocks, which do not have particularly tightly matching surfaces and which are not especially smooth or coated with low friction minerals. It is also of interest that this is the same angle reported by Byerlee (1978) as typical of a variety of rock discontinuities (data not corrected) at high stresses up to 200 MPa as noted earlier.

Although there is always considerable interest in peak strength behaviour it is often more useful to present data as illustrated in fig.4. Here shear stress data are plotted against normal stresses for the test as a whole, both as measured (corrected for gross contact area change) and corrected for dilation or compression. A corrected strength envelope is generally well defined by the majority of data even though individual datum points may

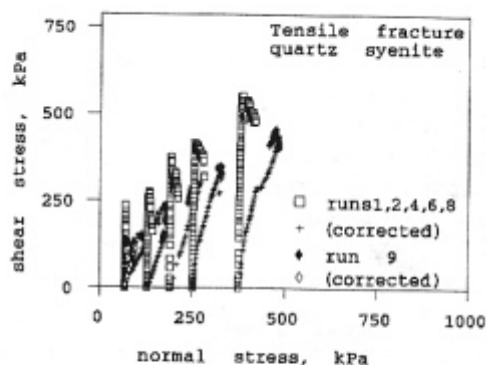


Figure 4 Stress path plots for a multistage test on quartz syenite.

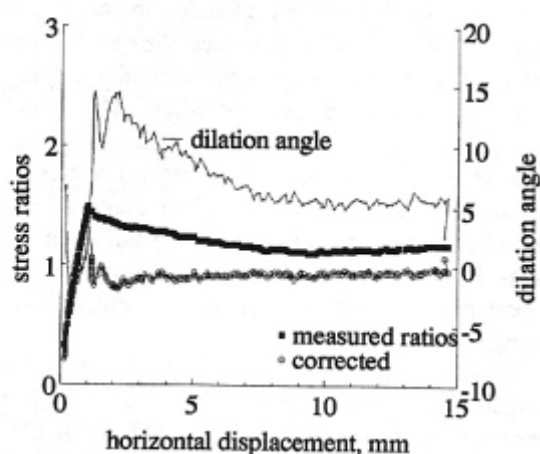


Figure 5 Shear stress:normal stress ratios and dilation angles throughout single test stage

lie either above or below the bulk of data points.

A third useful plot, which demonstrates detailed behaviour, is illustrated in fig. 5 which shows the ratios of shear to normal stresses (measured and corrected) plotted against horizontal displacement for a single stage of a multistage test on a closely matched discontinuity. Dilation angles calculated over horizontal displacements of 0.18 mm are also plotted against displacement. It can be seen that the dilation correction produces a fairly constant ratio over the latter part of the test but that the underlying friction still has a pronounced peak even in the absence of dilation. This is due to the interlocking of very strong minor asperities at early stages of shear in this case. The peak frictional resistance occurs at an early stage just as the discontinuity begins to dilate. As the joint dilates, so the peak caused by interlocking on a textural scale is lost. Note that peak strength

(measured) occurs when the dilation angle is only about 5° and that, by the time the maximum dilation angle of about 15° is reached, measured strength is already reducing. This is contrary to the common belief that the dilatancy rate is greatest at peak measured strength (see for example Goodman, 1989) and would not be seen without careful instrumentation and analysis.

## 5 INTERPRETATION AND USE IN PRACTICE.

Corrected shear test data reveal the underlying frictional resistance determined with the effect of sample-dependent volumetric changes removed. The strength is therefore for an effectively planar yet naturally textured surface. The influences of mineralogy are fully represented.

The shear strength thus determined might be taken as a lower-bound strength for design purposes, although additional strength may be allowable for the influence of roughness. A field dilation angle can be added following the methods described by Fecker & Rengers (1971) where the roughness is characterised by using plates of different size to measure deviations from the mean plane. This automatically allows for the effects of scale; the problem is then a matter of judging over what scale dilation might be allowed as discussed by Richards & Cowland (1982). It should always be remembered that the effective dilation angle will be that through which the centre of gravity of the sliding mass moves and not the angle of inclination of individual asperities at the surface of the discontinuity, even when allowance is made for their likely deformation and failure. Research reported by Bandis et al. (1981) and confirmed by Papaliangas et al. (1994) indicates a rapid reduction in measured dilation with length of discontinuity. A possible approach for design therefore, is to accept the dilation-corrected strength envelope as a lower bound, to ignore the potential effects of dilation, and then to reduce the required factor of safety on shear strength to perhaps 1.1 or 1.2 rather than the values of 1.3 or 1.4 which are often used.

## 6 CONCLUSIONS

Direct shear tests on natural discontinuities often yield a wide range of shear strengths based on

measured data. This is generally due to sample-dependent and direction-dependent roughness. During testing, continually resolving stresses relative to the actual plane of sliding, allows data to be plotted to reveal the underlying shear strength of an effectively planar yet natural surface. This friction angle is generally quite well defined for a set of discontinuities of similar surface texture and mineral coating and may be much lower or much higher than the strength determined for a saw-cut surface through the parent rock.

It is suggested that, for design, the corrected strength can be used directly as a lower bound and that in this case only a low factor of safety need be adopted for shear strength.

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