



## Standard Test Method for In Situ Determination of Direct Shear Strength of Rock Discontinuities<sup>1</sup>

This standard is issued under the fixed designation D 4554; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon ( $\epsilon$ ) indicates an editorial change since the last revision or reapproval.

### 1. Scope

1.1 This test method covers the measurement of peak and residual direct shear strength of in situ rock discontinuities as a function of stress normal to the sheared plane. This sheared plane is usually a significant discontinuity which may or may not be filled with gouge or soil-like material.

1.2 The measured shear properties are affected by scale factors. The severity of the effect of these factors must be assessed and applied to the specific problems on an individual basis.

1.3 The values stated in SI units are to be regarded as the standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

### 2. Terminology

2.1 *Definitions of Terms Specific to This Standard:*

2.1.1 *discontinuities*—this includes joints, schistosity, faults, bedding planes, cleavage, and zones of weakness, along with any filling material.

2.1.2 *peak shear strength*—the maximum shear stress in the complete curve of stress versus displacement obtained for a specified constant normal stress.

2.1.3 *residual shear strength*—the shear stress at which nominally no further rise or fall in shear strength is observed with increasing shear displacement and constant normal stress (Fig. 1). A true residual strength may only be reached after considerably greater shear displacement than can be achieved in testing. The test value should be regarded as approximate and should be assessed in relation to the complete shear stress - displacement curve.

2.1.4 *shear strength parameter,  $c$*  (see Fig. 2)—the projected intercept on the shear stress axis of the plot of shear stress versus normal stress (see Note).

2.1.5 *shear strength parameter,  $\phi$*  (see Fig. 2)—the angle of

the tangent to the failure curve at a normal stress that is relevant to design.

2.1.5.1 *Discussion*—Different values of  $c$  and  $\phi$  relate to different stages of a test (for example,  $c'$ ,  $c_r'$ ,  $\phi_a$ , and  $\phi_b$ , of Fig. 2).

### 3. Summary of Test Method

3.1 This test method is performed on rectangular-shaped blocks of rock that are isolated on all surfaces, except for the shear plane surface.

3.2 The blocks are not to be disturbed during preparation operations. The base of the block coincides with the plane to be sheared.

3.3 A normal load is applied perpendicular to the shear plane and then a side load is applied to induce shear along the plane and discontinuity (see Fig. 3).

### 4. Significance and Use

4.1 Because of scale effects, there is no simple method of predicting the in situ shear strength of a rock discontinuity from the results of laboratory tests on small specimens; in situ tests on large specimens are the most reliable means.

4.2 Results can be employed in stability analysis of rock engineering problems, for example, in studies of slopes, underground openings, and dam foundations. In applying the test results, the pore water pressure conditions and the possibility of progressive failure must be assessed for the design case, as they may differ from the test conditions.

4.3 Tests on intact rock (free from planes of weakness) are usually accomplished using laboratory triaxial testing. Intact rock can, however, be tested in situ in direct shear if the rock is weak and if the specimen block encapsulation is sufficiently strong.

### 5. Apparatus

5.1 *Equipment for Cutting and Encapsulating the Test Block*—This includes rock saws, drills, hammer and chisels, formwork of appropriate dimensions and rigidity, expanded polystyrene sheeting or weak filler, and materials for reinforced concrete encapsulation.

5.2 *Equipment for Applying the Normal Load* (see Fig. 3)—This includes flat jacks, hydraulic rams, or dead load of sufficient capacity to apply the required normal loads.

<sup>1</sup> This test method is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.12 on Rock Mechanics.

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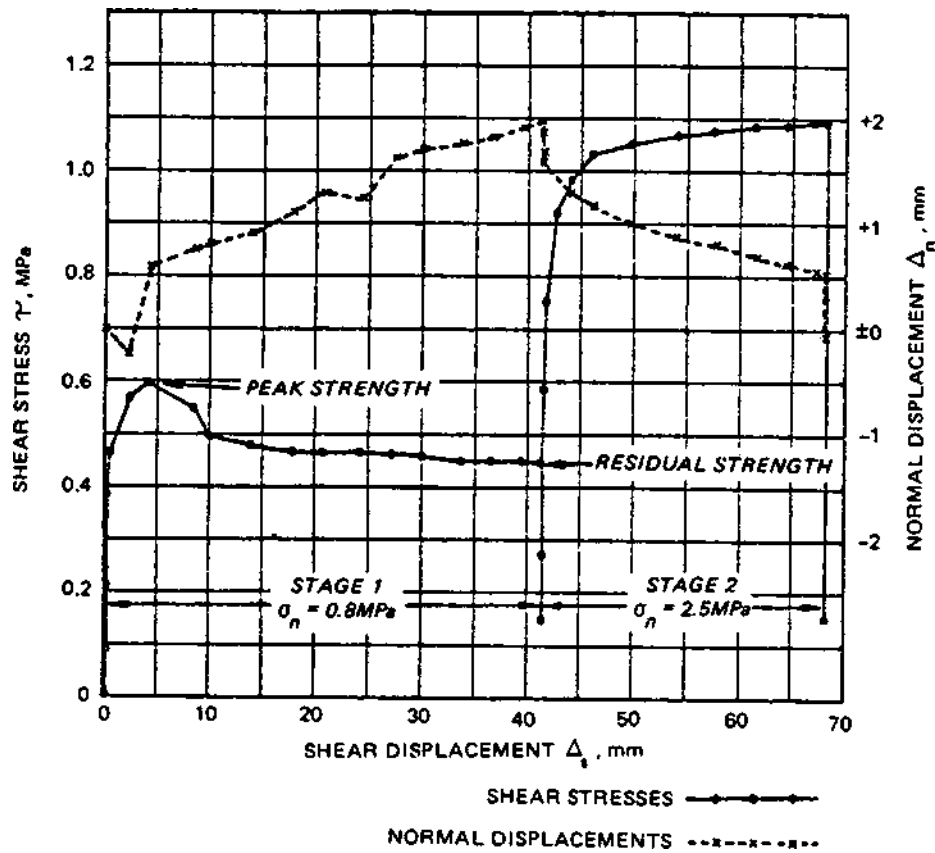


FIG. 1 Shear Stress - Displacement Graphs

NOTE 1—If a dead load is used for normal loading, precautions are required to ensure accurate centering and stability. If two or more hydraulic rams are used for loading, care is needed to ensure that their operating characteristics are identically matched and they are in exact parallel alignment.

5.2.1 Each ram should be provided with a spherical seat. The travel of rams, and particularly of flat jacks, should be sufficient to accommodate the full anticipated specimen displacement. The normal displacement may be estimated from the content and thickness of the filling and roughness of the shear surfaces. The upper limits would be the filling thickness.

5.2.2 *Hydraulic System*—A hydraulic system, if used, should be capable of maintaining a normal load to within 2 % of a selected value throughout the test.

5.2.3 *Reaction System*—A reaction system to transfer normal loads uniformly to the test block includes rollers or a similar low friction device to ensure that at any given normal load, the resistance to shear displacement is less than 1 % of the maximum shear force applied in the test. Rock anchors, wire ties, and turnbuckles are usually required to install and secure the equipment.

5.3 *Equipment for Applying the Shear Force* (see Fig. 3):

5.3.1 *One or More Hydraulic Rams*, of adequate total capacity with at least 150-mm travel.

5.3.2 *Hydraulic Pump*, to pressurize the shear force system.

5.3.3 *Reaction System*—A reaction system to transmit the shear force to the test block. The shear force should be distributed uniformly along one face of the specimen. The resultant line of applied shear forces should pass through the

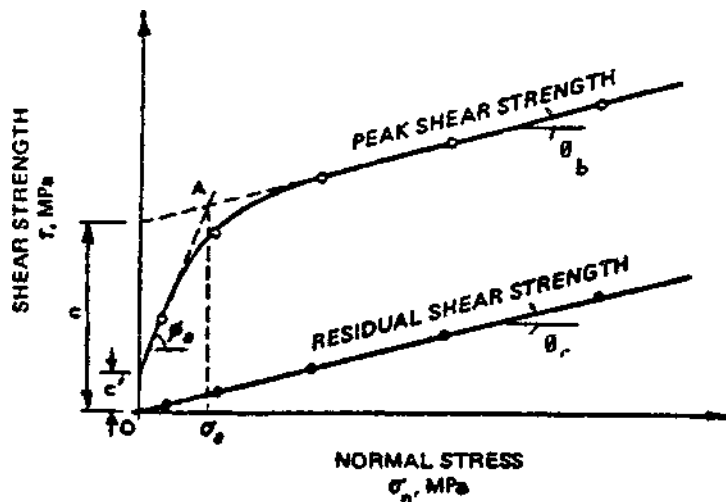
center of the base of the shear plane at an angle approximately  $15^\circ$  to the shear plane with an angular tolerance of  $\pm 5^\circ$ . The exact angle should be measured to  $\pm 1^\circ$ .

NOTE 2—Tests where both shear and normal forces are provided by a single set of jacks inclined at greater angles to the shear plane are not recommended, as it is then impractical to control shear and normal stresses independently.

5.4 *Equipment for Measuring the Applied Force*—This includes one system for measuring normal force and another for measuring applied shearing force with an accuracy better than  $\pm 2\%$  of the maximum forces reached in the test. Load cells (dynamometers) or flat jack pressure measurements may be used. Recent calibration data applicable to the range of testing should be appended to the test report. If possible, the gages should be calibrated both before and after testing.

5.5 *Equipment for Measuring Shear, Normal, and Lateral Displacement*—Displacement should be measured (for example, using micrometer dial gages) at eight locations on the specimen block or encapsulating material, as shown in Fig. 4 (Note 3). The shear displacement measuring system should have a travel of at least 100 mm and an accuracy better than 0.1 mm. The normal and lateral displacement measuring systems should have a travel of at least 20 mm and an accuracy better than 0.05 mm. The measuring reference system (beams, anchors, and clamps) should, when assembled, be sufficiently rigid to meet these requirements. Resetting of gages during the test should be avoided, if possible.

NOTE 3—The surface of encapsulating material is usually insufficiently



NOTE 1—In this case, intercept  $c_r$  on shear axis is zero.

- $\phi_r$  = residual friction angle,
- $\phi_a$  = apparent friction angle below stress  $\sigma_a$ ; point A is a break in the peak shear strength curve resulting from the shearing off of major irregularities on the shear surface. Between points O and A,  $\phi_a$  will vary somewhat; measure at stress level of interest. Note also that  $\phi_a = \phi_u + i$  where:
- $\phi_u$  = friction angle obtained for smooth surfaces of rock on rock, and
- $i$  = inclination angle of surface asperities.
- $\phi_b$  = apparent friction angle above stress level  $\sigma_a$  (Point A); note that  $\phi_a$  will usually be equal to or slightly greater than  $\phi_r$  and will vary somewhat with stress level; measure at the stress level of interest,  $r$ .
- $c'$  = cohesion intercept of peak shear strength curve; it may be zero.
- $c$  = apparent cohesion at a stress level corresponding to  $\phi_b$ , and
- $c_r$  = cohesion intercept of residual shear strength which is usually negligible.

FIG. 2 Shear Strength – Effective Normal Stress Graph

smooth and flat to provide adequate reference for displacement gages; glass plates may be cemented to the specimen block for this purpose. These plates should be of adequate size to accommodate movement of the specimen. Alternatively, a temperature calibrated tensioned wire and pulley system with gages remote from the specimen may be used. The system, as a whole, must be reliable and must conform with specified accuracy requirements. Particular care is needed in this respect when employing electric transducers or automatic recording equipment.

## 6. Procedure

### 6.1 Preparation of Test Specimen:

6.1.1 Outline a test block such that the base of the block coincides with the plane to be sheared. The direction of shearing should correspond, if possible, to the direction of anticipated shearing in the full-scale structure to be analyzed using the test results. To inhibit relaxation and swelling and to prevent premature sliding, it is necessary to apply a normal load to the upper face of the test specimen as soon as possible after excavation of the opening and prior to sawing the sides. The load, approximately equal to the overburden pressure, may, for example, be provided by screw props or a system of rock bolts and crossbeams. Maintain the load until the test equipment is in position. Saw the test block to the required dimensions (usually 700 by 700 by 350 mm) using methods that avoid disturbance or loosening of the block. Saw a channel approximately 200 mm deep by 80 mm wide around the base of the block to allow freedom of displacements during testing. The block and particularly the shear plane should, unless

otherwise specified, be retained as close as possible to its natural in situ conditions during preparation and testing.

NOTE 4—A test block size of 700 by 700 by 350 mm is suggested as standard for in situ testing. Smaller blocks are permissible, if, for example, the surface to be tested is relatively smooth; larger blocks may be needed when testing very irregular surfaces. For convenience, the size and shape of the test block may be adjusted so that the faces of the block coincide with joints or fissures. This adjustment minimizes block disturbance during preparation. Irregularities that would limit the thickness or emplacement of encapsulation material or reinforcement should be removed.

6.1.2 Apply a layer of weak material at least 20 mm thick (for example, foamed polystyrene) around the base of the test block, and then encapsulate the remainder of the block in concrete or similar material of sufficient strength and rigidity to prevent collapse or significant distortion during testing. Design the encapsulation formwork to ensure that the load bearing faces are flat (tolerance  $\pm 3$  mm) and at the correct inclination to the shear plane (tolerance  $\pm 2^\circ$ ).

6.1.3 Carefully position and align reaction pads, anchors, etc., if required to carry the thrust from normal and shear load systems to adjacent sound rock. Allow all concrete time to gain adequate strength prior to testing.

### 6.2 Consolidation of Test Specimen:

6.2.1 The consolidation stage of testing is necessary in order to allow pore water pressures, in the rock and especially in any filling material adjacent to the shear plane, to dissipate under full normal stress before shearing. Behavior of the specimen

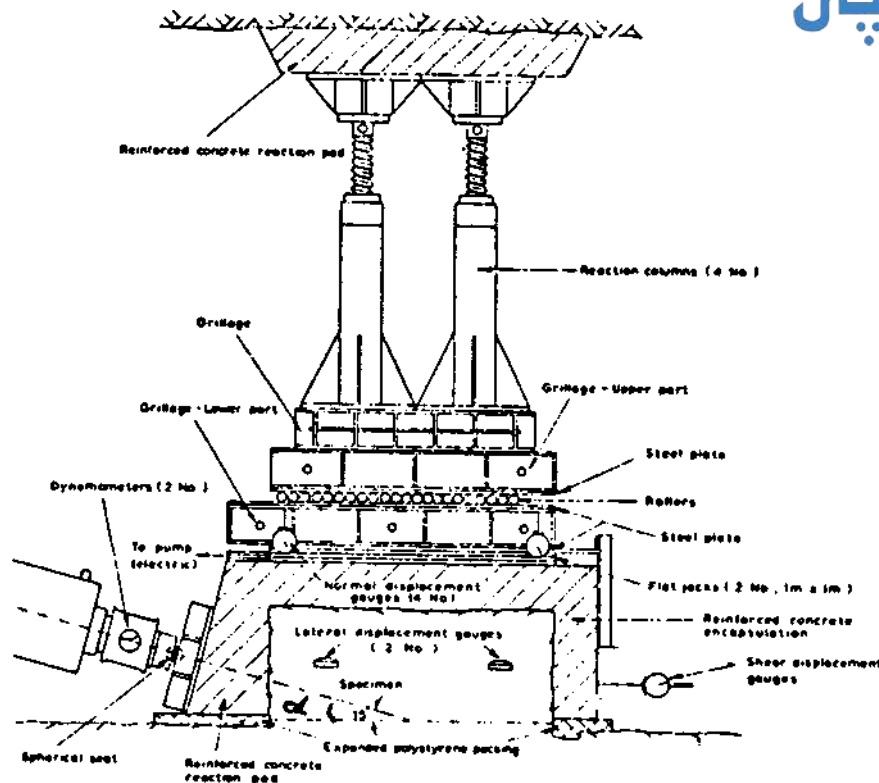


FIG. 3 Typical Arrangement of Equipment for In Situ Direct Shear Test

during consolidation may also impose a limit on permissible rate of shearing (see 6.3.3).

6.2.2 Check all displacement gages for rigidity, adequate travel, and freedom of movement, and record a preliminary set of load and displacement readings.

6.2.3 Raise normal load to the full value specified for the test, recording any consequent normal displacements (consolidation) of the test block as a function of time and applied loads (Fig. 5 and Fig. 6).

6.2.4 If consolidation occurs, it may be considered complete when the rate of change in normal displacement recorded at each of the four gages is less than 0.005 mm/min for at least 10 min. Shear loading may then be applied.

6.3 Shear Testing:

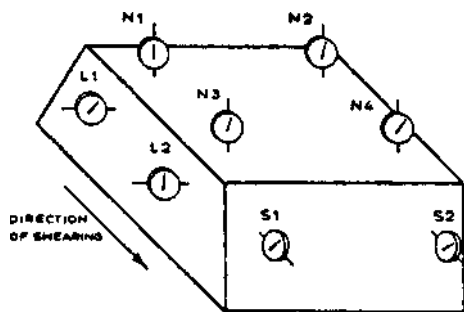
6.3.1 The purpose of shearing is to establish values for the peak and residual direct shear strengths of the test plane.

Corrections to the applied normal load may be required to hold the normal stress constant (see 7.5). A shear determination should preferably be comprised of at least five tests per block, tested at different but constant normal stress. If conditions warrant, test more than one block for each shear plane.

6.3.2 Apply the shear force either incrementally or continuously.

6.3.3 Take approximately 10 sets of readings before reaching peak strength (Fig. 1 and Fig. 3). The rate of shear displacement should be less than 0.1 mm/min in the 10-min period before taking a set of readings. This rate may be increased to not more than 0.5 mm/min between sets of readings, provided that the peak strength itself is adequately recorded. For a “drained” test, particularly when testing clayfilled discontinuities, the total time to reach peak strength should exceed  $6t_{100}$ , as determined from the consolidation curve (see 7.1 and Fig. 6). If necessary, the rate of shear should be reduced and the application of later shear force increments delayed to meet this requirement.

NOTE 5—The requirement that the total time to reach peak strength should exceed  $6t_{100}$  is derived from a conventional soil mechanics consolidation theory assuming a requirement of 90 % pore water pressure dissipation.<sup>2</sup> This requirement is most important when testing a clayfilled discontinuity. In other cases, it may be difficult to define  $t_{100}$  with any precision because a significant proportion of the observed “consolidation” may be due to rock creep and other mechanisms unrelated to pore pressure dissipation. Provided the rates of shear specified in the text are followed, the shear strength parameters may be regarded as having been measured under conditions of effective stress (“drained conditions”).



NOTE 1—Gages S1 and S2 are for shear displacement, L1 and L2 for lateral displacement, N1 through N4 for normal displacement.

FIG. 4 Arrangement of Displacement Gages

<sup>2</sup> Gibson, R. E., and Henkel, D. J., *Geotechnique* 4, 1954, pp. 10-11.

DIRECT SHEAR TEST DATA SHEET

1 Time elapsed (min)		2 Applied normal force $P_n$		3 Normal displacement $\Delta_n$				4 Applied shear force $P_s$		5 Shear displacement $\Delta_s$		6 Contact area A (corrected) $m^2$	7 $P_{ns}$ (kN)	8 $\sigma_n$ (MPa)	9 $P_{ss}$ (kN)	10 $\tau$ (MPa)
10		136	0.100 0.070 0.130 0.070				0	0 0			0.490	136		0		
25		233	0.130 0.065 0.140 0.080				137	0.05 0.05 0.05						142		
48		270	0.090 0.065 0.285 0.290				278	0.35 0.35 0.48						184		
84		308	-0.200 0.030 0.435 0.495				412	1.35 1.10 1.22						470		
87		343	-0.710 -0.305 0.600 0.720				549	2.55 2.30 2.42						568		
103		380	-2.165 -0.445 0.890 0.890				686	3.90 3.50 3.70						710		
131		417	-1.675 -0.615 0.710 0.970				824	5.15 4.60 4.60						853		
154		453	-1.965 -0.745 0.730 1.050				961	6.30 5.50 5.60						895		
172		490	-2.245 -0.880 0.730 1.105				1098	7.20 6.50 6.85						1137		
189		527	-2.480 -1.055 0.685 1.165				1235	8.20 7.40 7.80						1278		
206		564	-2.730 -1.205 0.640 1.165				1373	9.45 8.45 8.96						1421		
234		601	-3.075 -1.305 0.465 1.100				1510	11.00 10.00 10.50						1563		
253		637	-2.350 -1.430 0.380 0.810				1647	12.45 11.40 11.92						1705		
264		674	-3.675 -2.185 0.050 0.730				1784	14.00 13.00 13.40						1847		
276		711	-4.005 -2.595 -0.280 0.360				1922	15.55 14.40 14.98						1989		
289		748	-4.585 -3.125 -0.890 -0.030				2059	17.60 16.45 17.02						2132		
298	Rupture	784	-4.975 -3.375 -1.750 -0.280				2196	20.00 19.55 19.78						2274		

FIG. 5 Example Layout of Direct Shear Test Data Sheet

6.3.4 After reaching peak strength, take readings at increments of from 0.5 to 5 mm shear displacement, as required to adequately define the force-displacement curves (Fig. 1). The rate of shear displacement should be 0.02 to 0.2 mm/min in the 10-min period before a set of readings is taken, and may be increased to not more than 1 mm/min between sets of readings.

6.3.5 It may be possible to establish a residual strength value when the specimen is sheared at constant normal stress and at least four consecutive sets of readings are obtained

which show not more than 5 % variation in shear stress over a shear displacement of 1 cm.

NOTE 6—An independent check on the residual friction angle should be made by testing in the laboratory two prepared, flat surfaces of the representative rock. The prepared surfaces should be saw-cut and then ground flat with No. 80 silicon carbide grit or finer, depending upon the rock grain size.

6.3.6 Having established a residual strength, the normal stress may be increased or reduced and shearing continued to obtain additional residual strength values. Reconsolidate the specimen under each new normal stress (see 6.2.4) and continue shearing in accordance with 6.3.3-6.3.5.

NOTE 7—The normal load should, when possible, be applied in increasing rather than decreasing stages. Reversals of shear direction or resetting of the specimen block between normal load stages, sometimes used to allow a greater total shear displacement than would otherwise be possible, are not recommended because the shear surface is likely to be disturbed and subsequent results may be misleading. It is generally advisable, although more expensive, to use a different specimen block.

6.3.7 After the test, invert the block, photograph in color, and fully describe (see Section 7). Measurements of the area, roughness, dip, and dip direction of the sheared surface are required. Take samples of rock, infilling, and shear debris for index testing.

7. Calculation

7.1 Plot a consolidation curve (Fig. 6) during the consolidation stage of testing. Determine the time,  $t_{100}$ , for completion of "primary consolidation" by constructing tangents to the curve, as shown in Fig. 6. The time to reach peak strength from the start of shear loading should be greater than  $6t_{100}$  to allow pore pressure dissipation (see Note 5).

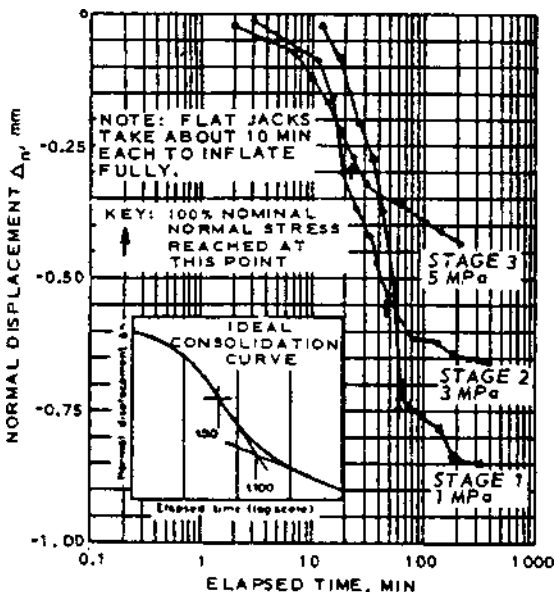


FIG. 6 Consolidation Curves for a Three-Stage Direct Shear Test, Showing the Construction Used to Estimate  $t_{100}$

7.2 Average displacement readings to obtain values of mean shear and normal displacements,  $\Delta_s$  and  $\Delta_n$ . Record lateral displacements only to evaluate specimen behavior during the test; although, if appreciable, lateral displacements should be taken into account when computing corrected contact area.

7.3 Shear and normal stresses are computed as follows:

$$\text{Shear stress, } \tau = \frac{P_s}{A} = \frac{P_{sa}(\cos\alpha)}{A} \quad (1)$$

$$\text{Normal stress, } \sigma_n = \frac{P_n}{A} = \frac{P_{na} + P_{sa}(\sin\alpha)}{A} \quad (2)$$

where:

- $P_s$  = total shear force, MPa,
- $P_n$  = total normal force, MPa,
- $P_{sa}$  = applied shear force, MPa
- $P_{na}$  = applied normal force, MPa,
- $\alpha$  = inclination of the applied shear force to the shear plane; if  $\alpha = 0$ ,  $\cos\alpha = 1$ , and  $\sin\alpha = 0$ , and
- $A$  = area of shear surface overlap (corrected to account for shear displacement), mm.

If  $\alpha$  is greater than zero, reduce the applied normal force after each increase in shear force by an amount  $P_{sa}(\sin\alpha)$  in order to maintain the normal stress approximately constant. The applied normal force may be further reduced during the test to compensate for area changes by an amount:

$$\frac{\Delta_s P_n}{700} \quad (3)$$

where:

- $\Delta_s$  = mean shear displacement, mm.

7.4 For each test specimen, plot graphs of shear stress (or shear force) and normal displacement versus shear displacement (Fig. 1). Annotate graphs to show the nominal normal stress and any changes in normal stress during shearing. Values of peak and residual shear strengths and the normal stresses and shear and normal displacements at which these occur are abstracted from these graphs.

7.5 From the combined results for all test specimens, plot graphs of peak and residual shear strengths versus normal stress. Shear strength parameters,  $\phi_a$ ,  $\phi_b$ ,  $\phi_r$ , and  $c$  are abstracted from these graphs, as shown in Fig. 2.

## 8. Report

8.1 Report the following information:

8.1.1 A diagram, photograph, and detailed description of test equipment and a description of methods used for specimen preparation and testing (note departures from the prescribed techniques),

8.1.2 For each specimen, a full geological description of the intact rock, sheared surface, filling, and debris, preferably accompanied by relevant index test data (for example, roughness profiles and Atterberg limits, water content, and grain-size distribution of filling materials),

8.1.3 Photographs of each sheared surface together with diagrams giving the location, dimensions, area, dip, and dip direction, and showing the directions of shearing and any peculiarities of the blocks, and

8.1.4 For each test block, a set of data tables, a consolidation graph, and graphs of shear stress and normal displacement versus shear displacement (Fig. 1, Fig. 5, and Fig. 6). Tabulate abstracted values of peak and residual shear strengths with the corresponding values of normal stress, together with derived values for the shear strength parameters (Fig. 2).

## 9. Precision and Bias

9.1 *Precision*—Due to the nature of rock materials tested by this test method, it is, at this time, either not feasible or too costly to produce multiple specimens that have uniform physical properties. Therefore, since specimens that would yield the same test results cannot be tested, Subcommittee D18.12 cannot determine the variation between tests since any variation observed is just as likely to be due to specimen variation as to operator or laboratory testing variation. Subcommittee D18.12 welcomes proposals to resolve this problem that would allow for development of a valid precision statement.

9.2 *Bias*—There is no accepted reference value for this test method; therefore, bias cannot be determined.

## 10. Keywords

10.1 discontinuities; in situ stress; loading tests; shear strength

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