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Technical Note

Investigating the effect of dilation on VNL and CNL types shear strength

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Abstract

Geometrical profile (roughness) of joint surfaces influences the behaviour of rock joints under shear loading. With regard to the dilation, there are two models of direct shear test that may simulate the original loading condition existing in the location from where the specimens have been sampled. The first model in which the normal load is constant (CNL) and the discontinuity is free to dilate in shearing, represents typical situations such as movement of a block on a surface slope as a result of its own weight. The second model in which the dilatancy is prohibited (VNL), simulates the condition of a block confined in a rock mass in an underground opening. A shear test conducted under restricted normal displacement (dilation) will generally yield considerably higher shear strength than one conducted under constant normal stress. In this research, both types of tests were conducted on smooth and rough surfaces of specimens made from rock like material. The results of the VNL and the CNL direct shear tests on regular teeth-shaped profile discontinuities indicates that at all levels of normal load, the linear Mohr-Coulomb criterion was not valid for rough surfaces that subscribed to the power law equations. Increasing normal load emphasized the difference between the results obtained from two methods, although for lower normal loads the results were nearly similar.

Keywords: Shear strength, Dilation, Variable normal load, Constant normal load.

1. Introduction

The behaviour of rock joints (including all discontinuities in rock mass) under shear loading depends upon not only the friction between surfaces and the joint material strength, but also the geometrical profile of the joints. Surface roughness is one of the most important parameters that affects directly the shear strength of the joint surface and also bring the concept of shear strength of discontinuities nearer to reality. When two rough surfaces of a discontinuity are moving relative to each other, due to undulations, the discontinuity will tend to thicken or "dilate" during shearing. The dilatancy is the difference between the normal displacements of the upper and lower block as a result of shear displacement. This dilation causes an increase in the applied normal load, the magnitude of which depends both on the stiffness of the normal loading system and on the magnitude of the dilation.

Because the dilation is virtually zero for planar surfaces, the total normal stress does not significantly differ from the initial normal stress. For non-planar discontinuities, however, the dilation undergoing shear contributes an important component to the shear strength. Skinas et al specified: "For a given joint type and boundary condition, the amount of dilation depends on normal stress acting across the joint surface and the stage of shear displacement" [1]. Also Goodman mentioned that the dilatancy and, to a considerable degree, the joint strength are controlled by the joint roughness [2]. Thus, the phenomenon of dilation is the most important component of discontinuity behavior with far reaching consequences.

Several researches have been conducted for investigating the effects of dilation on shearing strength of rock joints. Einstein et al reported the experimental and theoretical studies on mechanics of jointed rocks as well as the shear failure mechanisms of a simple tooth sample [3]. Barton [4] and Dight and Chiu [5] proposed the joint roughness coefficient (JRC) and the inclination angle respectively, as empirical relationships between the roughness and the shear strength of rock joints. A detailed presentation of the failure process of a rough surface has been also modelled by Xu et al [6]. Indraratna et al presented laboratory modeling of shear

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behavior of soft joints under constant normal stiffness condition [7]. Moreover, Haque and Indraratna [8] as well as Seidel and Haberfield [9] presented the experimental and numerical modeling of shear behavior of soft rock joints in laboratory under both Constant Normal Load (CNL) and Constant Normal Stiffness (CNS) conditions. More recently, Jafari et al evaluated the shear strength of rock joints under both static and cyclic loading conditions [10].

In current research, a comprehensive discussion on the phenomenon of dilation as a very important factor in shearing has been made. Due to the inability of triaxial tests in determining the factors such as dilation, the investigation of the mechanical behavior of rough discontinuities is conducted by means of direct shear test. The variable normal load (VNL) direct shear test is set up as a simulated type of triaxial test and its results are compared with the results of conventional direct shear test in which applied normal load remains constant (CNL) throughout the test. The relationship between the shear strength of a matched clean discontinuity tested in variable and constant normal load direct shear tests is established. Eventually, the results gained from these series of tests have been compared with the existing linear Mohr-Coulomb criterion and the exact failure envelopes are derived. In order to be able to have replicas of a regular teeth-shaped profile surface, artificial samples with using QuickRock (QR) synthetic material are used.

2. Experimental approach

To investigate the dilation effect, two models of CNL and VNL direct shear test could be considered to satisfy the original loading condition from which the specimens have been sampled. In the first model as CNL, the discontinuity is free to dilate in shearing which represents typical situations such as movement of a block on a surface slope as a result of its own weight. In the second model as VNL, the condition of a block confined in a rock mass in an underground opening is simulated in the prohibited dilatancy condition similar to triaxial environment. A shear test conducted under restricted normal displacement (dilation) will generally yield considerably higher shear strength than one conducted under constant normal stress. These types of tests were conducted on both smooth and rough surfaces of QR specimens. The specifications of developed test apparatus as well as the specimen preparation are subsequently explained.

2.1. Direct shear test apparatus

In order to investigate the shear behavior of rock interfaces and infilled joints, a new direct shear apparatus is manufactured which could test specimens under both CNL and VNL conditions (figure (1)). The device is capable of assessing the shear behavior of discontinuities existing in the cylindrical specimens up to 75 mm diameter and 150 mm length, subjected to high normal and shear loads. The manufactured direct shear apparatus consists of a pair of large shear boxes, the shear and normal loading devices, and displacement monitoring transducers. The device uses virtual software to accommodate the change in normal stress with dilation under a variable normal load (VNL) boundary condition. The variable load condition for this apparatus is reproduced using digital closed loop control in conjunction with electrical and hydraulic servos. Flat compression load cells monitor the normal loads, which are compared to the vertical joint displacements during the shearing process, and changed when necessary. The feedback sign is calculated from the normal stiffness value, as follows:

$$\Delta L = k \times \Delta d \quad (1)$$

$$L\,(t + \Delta t) = L\,(t) + \Delta L \quad (2)$$

where ΔL and Δd are the changes in the normal load and vertical displacement, respectively. It should be noticed that the device verification was done with comparison of series of shear tests between new and conventional apparatuses.

2.2. Specimens preparation

In order to investigate the dilatancy effect and compare the results obtained from CNL and VNL direct shear tests, a group of samples with identical properties was needed. It is difficult to find seemingly isotropic rocks and nearly impossible to secure rocks with natural weakness planes of identical strength characteristics. To overcome this difficulty, the laboratory specimens formed with a rapid-setting cementing material called “QuickRock”. This material could be simply moulded so that the shape, size and internal strength of the brittle rock-like jointed specimens remained constant. Hence, a series of specimens with smooth and rough surfaces were prepared so that their uniaxial compressive and tensile strengths are identical and equal 35 and 3.2 MPa, respectively while the asperities of the surface are regular with the angle of i (figure (2)).

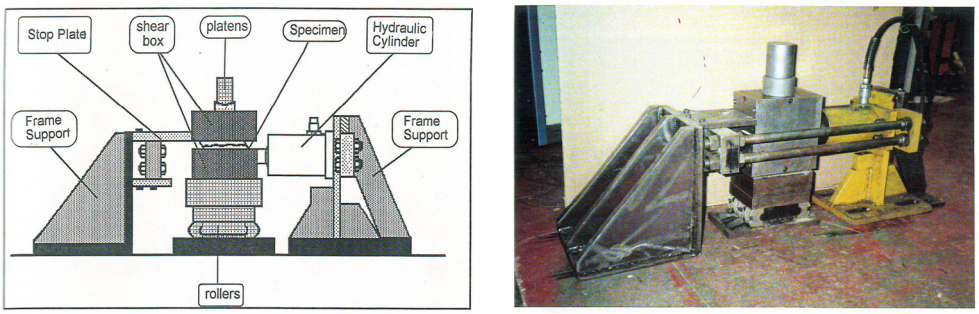

Fig. 1. Schematic cross-section view and photopraph of improved direct shear apparatus

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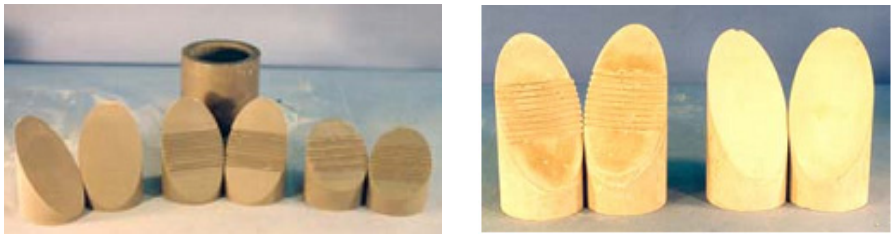

Fig. 2. a) The molds for casting the specimens, b) Prepared smooth and rough surfaces

3. Discussion of the results

The results of the CNL and VNL shear tests on both smooth and rough surfaces of QR specimens are discussed as follows:

3.1. Smooth surfaces

As mentioned earlier, the dilatancy taking place on planar surfaces was assumed to be zero. Therefore, the contact surface used for the calculation of the normal and shear stresses was a complete ellipse. The VNL and the CNL direct shear tests were conducted on smooth surfaces, but the corrections related to the surface changes and compression of intact parts were not taken into consideration. The conventional or CNL direct shear tests were conducted using a range of normal loads which were the same as maximum normal load in VNL direct shear tests. The reasons for performing the direct shear tests with variable and constant normal load was to compare the results of the VNL, which has been adopted in this study, with the conventional type of tests, particularly for peak shear strength.

The shear stress-deformation relationships of variable and constant direct shear tests are illustrated in figure (3). As is shown at low normal loads, the peak shear stresses of CNL tests were slightly lower than of VNL tests. However, the normal load increased the shear strength of CNL tests eventually resulted in higher peak shear stress than the VNL tests.

The shear stiffness of CNL tests, were slightly higher than the one for VNL tests and it may be attributed to the type of applied normal load on the specimens. While in the CNL tests the normal load is retained constant, from the initiation of the tests in VNL the normal load is increased where the shear displacement increases. Of some significance was the observation of regular stick-slip in the CNL tests. The stick-slip behavior was not observed in the VNL direct shear tests on smooth surfaces. Some investigators, for example Hoskins et al [11], have reported stick-slip for smooth surfaces. The presence of stick-slip phenomenon in the CNL direct shear tests confirmed their interpretations. The different type of sliding in the VNL and the CNL tests may be attributed to the difference in the nature of the applied normal load.

A further point may be identified in figure (3). As is shown, increasing normal load increased the amplitude of the stick-slip oscillations. The greater amplitudes of regular stick-slip belong to the medium normal load, after which the stick-slip was irregular. Transformation of stick-slip to stable sliding has taken place in most of the CNL tests with continuation of sliding. The results of both types of tests in conjunction with the normal stresses are listed in table (1). Figure (4) shows the Mohr envelopes corresponding to the results of the VNL and the CNL tests. As is shown, the envelope corresponding to the CNL tests reveals that there is an overestimation in the results of conventional direct shear tests on smooth surfaces conducted by previous investigators, although the difference is not too significant. The angle of failure for the VNL tests is 39° whereas in the CNL tests it is nearly 43°.

Table 1. VNL and CNL direct shear test results on smooth surfaces of QR specimens

Constant Normal Load		Variable Normal Load	
σ_n	τ_p(Exp.)	σ_n	τ_p(Exp.)
4.47	3.46	4.47	3.58
9.44	8.14	9.44	7.92
14.44	13.24	14.44	12.08
18.51	16.24	18.51	15.03

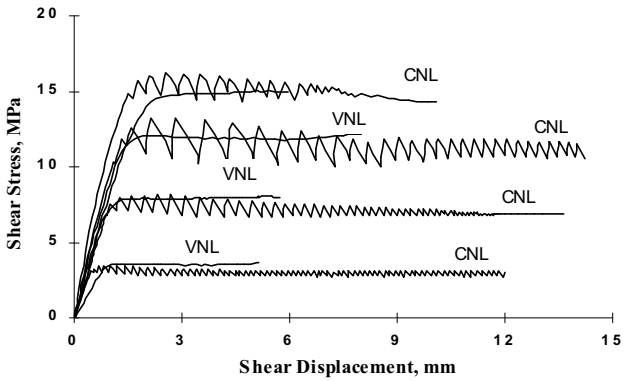

Fig. 3. shear stress vs. shear displacement of VNL & CNL on QR smooth surfaces

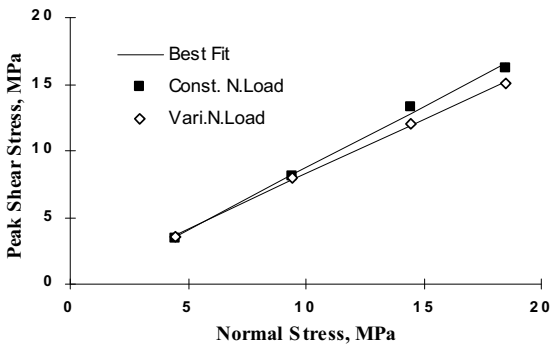

Fig. 4. VNL and CNL failure envelope for smooth surfaces of QR

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3.2. Rough surfaces

As for smooth surfaces, the VNL and the CNL type of direct shear tests were performed on the teeth-shaped profile discontinuity surfaces. For both type of tests, the dilation during shearing has been taken into account and the normal and shear stresses have been calculated with regard to the amount of dilation. There are various ways of representing the results of the dilation that have been frequently used by investigators. The most commonly used method is the plot of the vertical displacement against the horizontal displacement which illustrates the dilation behavior of the rough discontinuities.

The results of the VNL and the CNL direct shear tests on regular teeth shaped profile have been illustrated in figures (5) and (6).

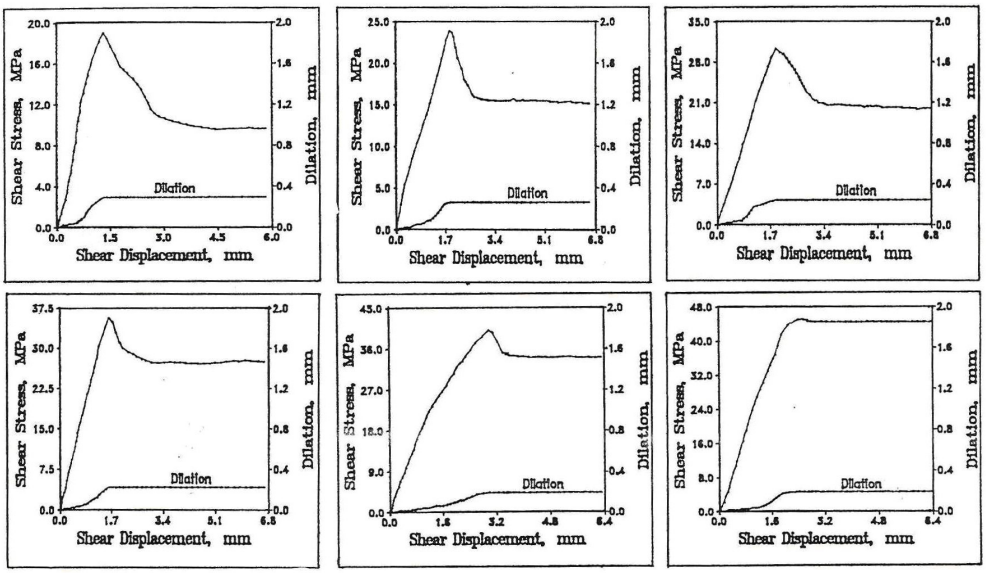

Fig. 5. Shear stress-shear displacement and dilation-shear displacement relationships for VNL test

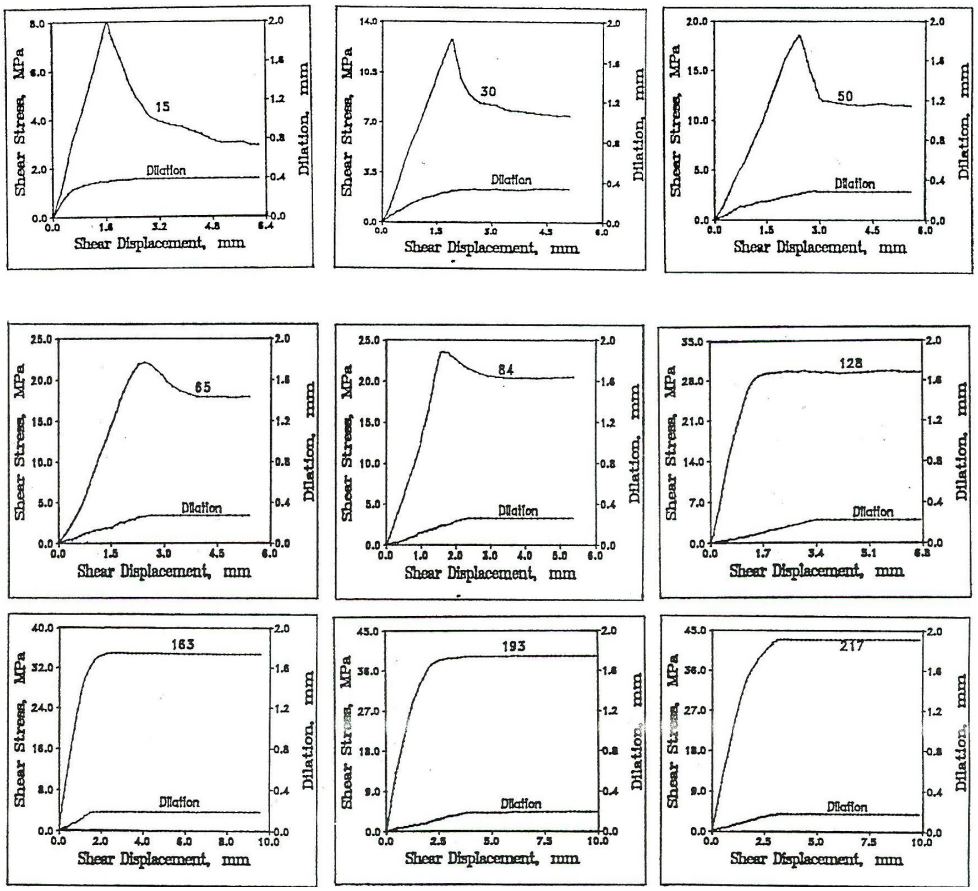

Fig. 6. Shear stress-shear displacement and dilation-shear displacement relationships for CNL test
(The numbers on the curves are applied constant normal load in kN)

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As the shear stress increases, a period of adjustment with slight dilatancy was followed by a rapid increase in the rate of dilation. The dilation rate was highest as the peak shear stress (the shear strength) was attained. Thereafter, the shear stress decreased continuously and the discontinuity dilated continuously until the residual displacement was attained a few millimeters beyond the peak. This model could be identified at all levels of normal load in the VNL and the CNL direct shear tests.

A significant difference in the dilation behavior was identified between the results of the VNL and the CNL tests. As is shown at all levels of normal load in the VNL tests the rate of dilation rapidly increased in the region just before attaining the peak shear stress, whereas for the CNL the increase of the dilation rate started from the very beginning of the tests. This behavior could be explained by taking into consideration that for the VNL tests the maximum applied load was not at the initiation of the tests, while in the CNL tests the maximum load was applied from the beginning of the tests.

Figures (7) and (8) show the VNL and the CNL tests. As one may see, the shear stiffness in both methods increased by increasing the normal load, although some exceptions can be identified in both figures. As is shown in the figures, at low normal load the brittle failure occurred by dilation and the asperities were sheared off from a surface above their base. As the normal load increased the asperities were sheared off from their base or at surfaces very near to their base and the strain softening immediately after the peak was not evident. This response was repeated in both VNL and CNL methods whereby an increase in the normal load resulted in a decrease of the magnitude of dilation. This has been illustrated in figures (9) and (10) and was also recognized from the inspection of the samples immediately after the failure of the asperities, indicating that the higher the normal load, the closer was the shear surface to the base of the regular asperities.

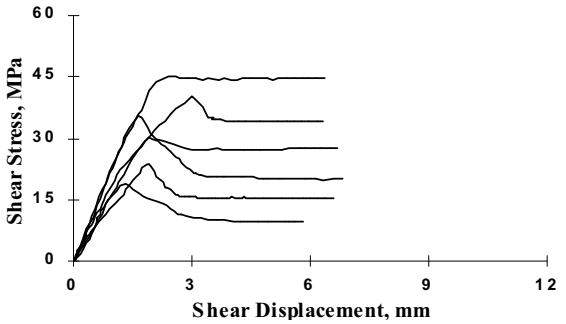

Fig. 7. Shear stress-shear displacement of QR teeth-shaped profile discontinuity surfaces in VNL test

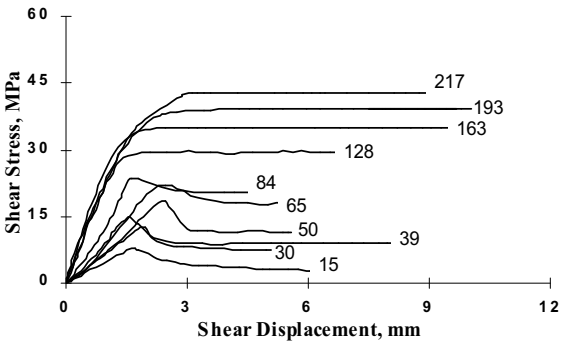

Fig. 8. Shear stress-shear displacement of QR teeth-shaped profile discontinuity surfaces in CNL test
(The numbers on the curves are applied constant normal load in kN)

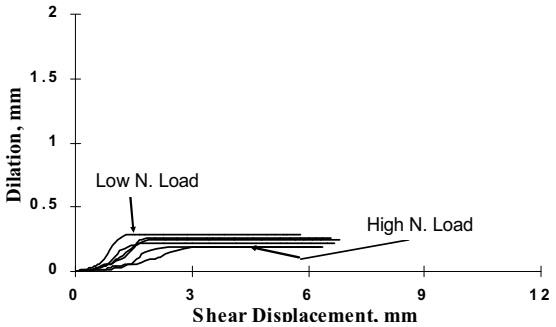

Fig. 9. Effect of increasing normal load on dilation-shear displacement relationship in VNL test

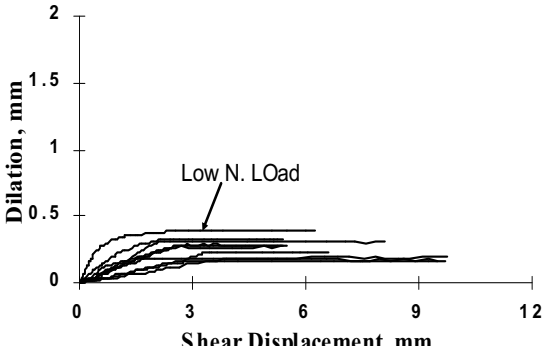

Fig. 10. Effect of increasing normal load on dilation-shear displacement relationship in CNL test

The results of the VNL and the CNL direct shear tests on regular teeth-shaped profile discontinuities have been listed in table (2) and illustrated in figure (11). The plot in the figure indicates that at all levels of normal load the linear Mohr-Coulomb criterion was not valid for rough surfaces that subscribed to the power law equations:

$$\tau_p = A(\sigma_n)^B \qquad (3)$$

where A and B are constants which shown in table (3).

As shown in figure (11), the plot corresponding to the VNL

Table 2. The results of the VNL and the CNL direct shear tests on rough surfaces of QR specimens

Const. Normal Load Test		Vari. Normal Load Test	
N.Stress (MPa)	Sh.Stress(MPa)	N.Stress(MPa)	Sh.Stress(MPa)
0.00	0.00	0.00	0.00
4.30	7.97	12.38	18.95
8.43	12.74	17.78	23.80
10.72	14.81	25.35	30.22
13.80	18.48	32.74	35.51
17.94	22.08	39.46	40.08
22.48	23.55	47.70	45.09
34.64	29.70		
43.65	34.95		
50.54	38.32		
58.10	42.94		

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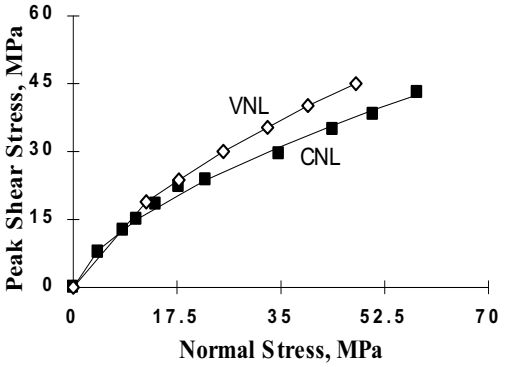

Fig. 11. Failure envelope of QR clean teeth-shaped profile discontinuity surfaces in VNL and CNL tests

Table 3. Constants A and B of equation (1)

	A	B
Variable Normal Load	3.73	0.646
Constant Normal Load	3.37	0.625

tests lies above the CNL test results. Increasing normal load emphasized the difference between the two results, although for lower normal loads the results were nearly similar.

At low normal load, brittle failure of the teeth for both types of the tests was dominant and dilation occurred similarly for both methods resulting in nearly similar behavior (figure 11). As mentioned before, the normal load applied on the discontinuity in a CNL test is the maximum applied load and is kept constant throughout the test, namely, from beginning to the end of the test. Therefore, at higher normal loads, dilation in the CNL tests were less than the VNL tests in similar shear displacement as a result of higher normal load at these points. The higher the dilation is the smaller shear surfaces are and as a consequence the higher will be the shear stresses in the VNL type of direct shear tests. Examination of the specimens after the tests revealed the same features of the failure surfaces for both type of direct shear tests, i.e. partial failure of the asperities at lower normal loads and fully sheared off asperities at higher normal loads.

4. Conclusion

The effect of dilation on the shear strength of specimens with a discontinuity was investigated in this research through direct shear methods. For this mean, a new method of direct shear test called VNL was performed as a simulated type of triaxial test in which, the normal load continually varies during the tests. To compare the results of this type of direct shear tests with the conventional one as CNL, several tests were conducted with constant normal load on various types of discontinuity surfaces i.e. smooth and rough. In order to prepare a group of samples with identical properties, the laboratory specimens formed with a rapid-setting cementing material called “Quickrock” was used. Finally the results of conventional and new direct shear test method were compared with the existing peak shear strength criteria to select the most applicable for engineering applications. The results on regular teeth-shaped profile discontinuities indicates that at all levels of normal load, the linear Mohr-Coulomb criterion was not valid for rough surfaces that subscribed to the power law equations. Increasing normal load emphasized the difference between the results obtained from two methods, although for lower normal loads the results were nearly similar.

References

[1] Skinas, C.A., Bandis, S.C.and Demiris C.A.: 1990, Experimental investigations and modelling of rock joints behaviour under constant stiffness, Int.Symp. on Rock Joints, pp:301-308.

[2] Goodman, R.E.: 1989, Introduction to rock mechanics, 2nd. Edition, London: John Wiley & Sons.

[3] Einstein, H.H., Bruhn, R.W. and Hirschfeld R.C.: 1970, Mechanics of jointed rock, experimental and theoretical studies, MIT Cambridge, Dept.Civil Eng. Report.

[4] Barton, N.: 1973, Review of a new shear strength criterion for rock joints, Engineering Geology,Vol.(7), pp:287-332.

[5] Dight, P.M., and Chiu H.K.: 1981, Prediction of shear behaviour of joints using profiles, Int.J.Rock Mech.Min.Sci., Vol.(18), pp:369-388.

[6] Xu, S., and De Frietas M.H.: 1990, Kinematic mechanisms of shear deformation and the validity of Barton's shear model, Int.Symp. on Rock Joints, pp:767-773.

[7] Indraratna, B., Haque, A. and Aziz, N.: 1999, Shear behavior of idealized in filled joints under constant normal stiffness, Geotechnique, Vol.(49), pp:331–355.

[8] Haque A., Indraratna B.: 2000, Experimental and Numerical Modeling of Shear Behavior of Rock Joints, GeoEng 2000, an International Conference on Geotechnical & Geological Engineering.

[9] Seidel, J.P. and Haberfield, C.M.: 2002, Laboratory Testing of Concrete-Rock Joint in Constant Normal Stiffness Direct Shear, Geotechnical Testing Journal, Vol.(25), pp: 391–404.

[10] Jafari M. K., Hosseini K. A., Pellet F.: 2003, Evaluation of shear strength of rock joints subjected to cyclic loading, Soil Dynamics and Earthquake Engineering, vol.23, pp.619-630.

[11] Hoskins, E.R., Jaeger, J.C.and Rosengren, K.J.: 1968, A medium scale direct friction experiment, Int.J.Rock Mech.Min.Sci., Vol.(5), pp:143.

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