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Rotation and stress changes on a plane joint during direct shear tests

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1. Introduction

The ISRM Suggested Method for laboratory determination of the shear strength of rock joints recommends the use of three to four transducers to measure normal displacement.[1] However, most previous studies consider only average normal displacements to evaluate the dilation of jointed specimens during direct shearing.[2–10] Mandal et al.[11] investigated the effect of rotation considering the direct shear test as a multiple inclusion system and they proved that rotation is basically induced by the traction exerted by the flowing matrix on the surface of the inclusion during deformation. Non-uniform deformations and stresses in the soil specimens during direct shear tests were revealed,[12–14] but evaluation of direct shear tests of rock or rock like materials with plane joints considers only the average shear stress to evaluate the shear strength of the contact surface.[15]

In this research, special attention is paid to the rotational behavior of the specimen and to the inhomogeneous stress distribution along the joint interface. The mechanism of rotation during a conventional direct shear box test is discussed and modifications of direct shear box tests are proposed to decrease the sample rotation and non-uniform stress development.

2. Laboratory testing

Direct shear tests on plane joints were performed using the GS-1000 shear box device.[16] The tests were conducted as multi-stage normal loading CNL-tests (30kN, 60kN, 90kN, 180kN and 360kN) with different shear velocities (100 mm/min, 10 mm/min, 3 mm/min, 1 mm/min, and 0.1 mm/min). Shear displacement was measured by a horizontal LVDT attached to the bottom part of the shear box. The normal displacement is measured by four high-accuracy vertical LVDTs (± 0.001 mm). These LVDT's are positioned at the four corners of the upper part of the shear box. Normal and shear loads were measured by load-cells integrated into the vertical and horizontal loading pistons.

The specimen size is $300\ \text{mm} \times 160\ \text{mm} \times 150\ \text{mm}$ (length/width/height). Each specimen contains a plane joint which separates the specimen into two equal halves 75 mm high. The inherent roughness of this shear plane is determined by the wooden formwork used for manufacturing and has less than 1 mm deviation from a perfect plane. The specimens were made of CEM I 32.5 R cement and Hohenpockaer glass and with a mass ratio of 1:3. Specimens are cured at room temperature (about 20 °C) for 28 days. At that time samples showed the following parameters: tensile strength 2.5 MPa, compression strength 19.1 MPa, Young's modulus 30 GPa, Poisson's ratio 0.2, cohesion 7.2 MPa, internal friction angle 30, dilation angle10° and density 2.50 g/cm^3. The specimen installation procedures followed the principles reported by in .[17] Input parameters used for the different stages of testing are summarized in Table 1.

An example for the relationship between shear force and shear

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Table 1
Set-up for CNL multi-stage tests.

Plane joint				
Sample	Stage	Input parameters		
		F [kN]	v [mm/min]	u_{s_max} [mm]
CNL01	1	30	3	20
	2	60	−3	20
	3	90	3	20
	4	90	−3	20
	5	60	3	20
	6	30	−3	20
CNL02	1	90	3	20
	2	180	−3	20
	3	360	3	20
	4	360	−3	20
	5	180	3	20
	6	90	−3	20
CNL03	1	60	100	25
	2	60	−10	25
	3	60	10	20
	4	60	−1	20
	5	60	1	20
	6	60	−0.1	20
CNL04	1	90	100	25
	2	90	−10	25
	3	90	10	20
	4	90	−1	20
	5	90	1	20
	6	90	−0.1	20
CNL05	1	180	100	25
	2	180	−10	25
	3	180	10	20
	4	180	−1	20
	5	180	1	20
	6	180	−0.1	20

displacement for shear velocity of 3.0 mm/min is presented in Fig. 1(a). Shear forces increase with increasing normal forces. During each direct shear stage shear force increases linearly with increasing shear displacement until the peak shear force is reached. After reaching the peak shear force, frictional sliding is observed at a residual shear stress level nearly identical to the peak value. Fig. 1(b) shows a bi-linear inclination (rotation) behavior of the sample during shearing.

Rotation of the upper part of the specimen was calculated using the formula:

$$\alpha = \arctan\left(\frac{|u_{n(a)}| + |u_{n(b)}|}{l_{Specimen}}\right) \quad (1)$$

where $u_{n(a)}$ is the normal displacement of left side, $u_{n(b)}$ is the normal displacement of right side, and $l_{Specimen}$ is the total length of specimen (=300 mm)

Positive and negative displacement rates, respectively, increase up to about 2.5 mm of shear displacement and become much smaller afterwards. Fig. 1(c) shows that sample rotation (inclination) decreases with increasing shear velocity. Under normal loadings of 30 kN, 90 kN, and 180 kN, with the decrease of shear velocities the peak angle of inclination has the similar increasing trend. At the same shear velocity, the peak angle of inclination increases with increasing normal load.

3. Numerical simulation

In order to examine the shear behavior of the smooth flat joint by numerical simulations, FLAC^{3D} [18] is used to simulate the direct

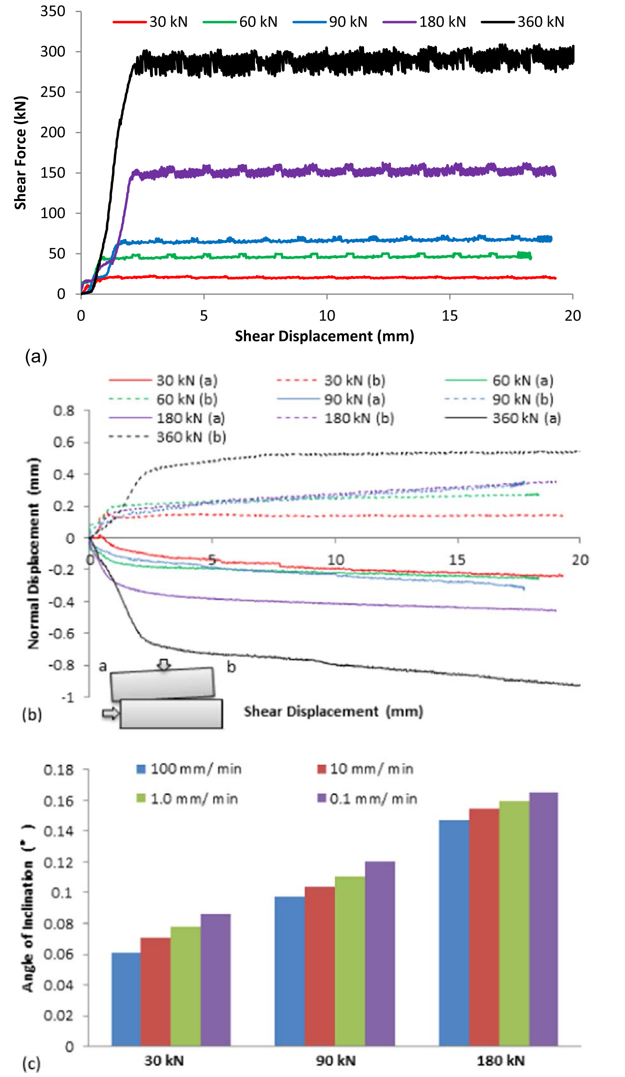

Fig. 1. Lab test results: (a) Shear displacement versus shear forces under different normal loading at shear velocity of 3 mm/min; (b) shear displacement versus normal displacement at shear velocity of 3.0 mm/min (a indicates left side, b indicates right side); (c) peak angle of inclination influenced by shear velocities under different normal loads.

shear tests. The whole model consists of several parts (Fig. 2): loading plate, lower shear box, upper shear box, lower and upper part of specimen and corresponding interfaces.

In the laboratory, the upper shear box is fixed and accommodates one half of the specimen and the lower shear box is in direct contact with the mechanism which provides the force necessary for shearing.[17] The joint is sheared by moving the lower shear box. Normal force is applied on the loading plate, and shear velocity is applied to the lower shear box. The model size of specimen is 300 mm × 160 mm × 150 mm (length/width/height), and the thickness of the shear box is 50 mm. The numerical model consists of 202568 grid points, 179184 zones, 16222 interface nodes and 27776 interface elements. A Mohr-Coulomb constitutive model is chosen for the specimen and the interfaces and an elastic constitutive model is chosen for the shear box. Mechanical parameters are shown in Table 2. Normal displacements at the four corners of the upper part of the specimen and the normal and shear stresses at the joint (sample interface) are recorded. These simulations are called Model O. The simulated displacement field (Fig. 3) reveals a counter-clockwise rotation of the sample.

As Fig. 4(a) shows a very inhomogeneous stress pattern with a