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Evaluation and reduction of the end friction effect in true triaxial tests on hard rocks

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1. Introduction

Since Von Kármán[1] first published conventional triaxial test data on rocks in 1911, the primary installation method has consisted of using a cylindrical specimen sandwiched by two metal platens. The mismatch in the elastic parameters (Young's modulus and Poisson's ratio) between the metal platens and rock specimen in the elastic and yielding ranges produces an interface friction when axially loaded, which results in a non-uniform stress distribution at the end of the specimen; this situation is defined as the end friction effect. Lubrication is an effective method to decrease the friction between opposing solid faces by applying a solid or fluid anti-friction agent. To reduce the end friction effect in rock mechanics uniaxial or conventional triaxial compression tests, anti-friction agents, such as "stearin" or stearic acid,[2] a Teflon sheet,[3] Teflon and copper sheets,[4,5] and low-modulus insert materials,[6] have been widely used. The theoretical solution method has been employed to analyse the stress distribution within a circular cylinder, in which the friction coefficient and boundary condition were considered.[7–9] Labuz and Bridell[10] proposed a new friction constraint reduction method in uniaxial compression tests and published the coefficients of friction of the anti-friction agent and deformation effect on the specimen. To date, no established or standard methods similar to ISRM[11] and ASTM[12] have been reported regarding ways to eliminate the end friction effect in rock compression tests.

Recently, the influence of the end friction effect has been presented and discussed in a number of professional rock mechanics tests such as shear tests,[13] split Hopkinson pressure bar tests[14] and true triaxial tests.[15] True triaxial tests can replicate the general stress state ($\sigma_1 > \sigma_2 > \sigma_3$)[16–20] in rock crust; thus, research needs have driven the development of true triaxial testing apparatuses. However, the end friction effect is more complex than the stress state observed in conventional triaxial apparatuses because more friction interfaces arise during specimen loading in the multi-axis configuration.

Mogi[21] directly applied a Teflon sheet, and Haimson and Chang[17] applied a mixture of stearic acid and Vaseline (MSV) with a thin copper sheet in their true triaxial tests. Furthermore, some numerical tools were also used to verify and quantify the end friction effect in true triaxial tests.[22–24] The friction mechanism and contact modelling of the end friction effect in true triaxial testing is complex, so some parameters and modelling have been simplified, which could affect the extraction of the influence mechanism from the numerical work. The stress distribution in the specimen is expected to be homogeneous in the design of a true triaxial apparatus.[21]

2. End friction effect and lubrication in true triaxial testing

Bowden noted that friction properties are influenced by material, temperature, rate of movement, area of contacts and surface films.[25] The function of the anti-friction agent is to form an intermediate film to separate the solid surfaces. Labuz and Bridell[10] determined the friction coefficients for graphite, double-sheet Teflon, a stearic acid and Vaseline mixture and alloy steel platens to be approximately 0.07–0.08, 0.05 and 0.02, respectively. Recently, an ethylene glycol material

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with attached hydrogen ions with an ultra-low friction coefficient (μ=0.004), placed been between Si_3N_4 and SiO_2, was reported,[26] but it has not yet been applied in rock mechanics compression tests.

The cylindrical specimen is axially loaded by the matched top and bottom alloy steel platens, and the ideal deformation is proportionally shortened in the axial direction and proportionally expanded in the radial direction to maintain the original cylinder shape. However, due to the end friction effect, a barrel-shaped specimen is often obtained, especially for soft rocks and soils. Furthermore, the friction stress distribution is not uniform on the end plane because the relative motion in the centre approaches zero; conversely, a relatively large motion arises at the edge of the sample, possibly linked to a transition from static friction to kinetic friction. With respect to end friction, Ferrero and Migliazza reported maximum values at the edge and minimum values at the centre of the specimen.[27]

In true triaxial tests, however, a rectangular prismatic specimen with an approximate length-width-height ratio of 1:1:2 or 1:1:1 was rigidly loaded on four surfaces[6,17,18] or six surfaces.[19] The intermediate principal stress (σ_2) acts on two rectangle surfaces, which produces an additional end friction effect. Although there is no rigid contact on the front and back surfaces when the fluid pressure produces the minor principal stress σ_3, the deformation is affected by the end friction effect resulting from the rigid loading. Consequently, the end friction effect must also be evaluated for the interface subjected to σ_2.

The end friction in true triaxial tests can be characterized at room temperature with small compression strain rates (approximately 10^{-5}/s), a high normal stress (up to hundreds of MPa), and plane friction consisting of a combination of static and dynamic friction. Because little comparative research has been conducted to investigate the end friction effect in true triaxial tests, some researchers have applied an anti-friction agent directly to the interface during testing, but the influence of the end effect on the deformation was not reported in detail. This study presents an evaluation of the end friction effect in true triaxial rock tests in view of this lack of research, with the goal of developing a proper approach for reducing end friction in true triaxial testing.

3. Experimental apparatus and method

A newly developed true triaxial apparatus combining rigid and flexible loading was used to evaluate the end friction effect experimentally [20]. A multi-point strain measurement method is proposed to evaluate the elastic strain distribution induced by the end friction effect. Strain rosette gauges are glued on the free face of the specimen to measure the deformation. Two elements are attached at one point such that the compression and expansion strain can be measured. A data logger (UCAM-60A, Kyowa Electronic Instruments, Chofu, Tokyo) was used to measure the strain signal.

All steel and granite rectangular prismatic specimens were machined to be 50×50×100 mm^3, and a grinding machine was used to polish the specimen surface. The dimensional tolerance and perpendicular tolerance are given as ± 0.01 mm and 0.02 mm, respectively, for each side. The Young's modulus (E) and Poisson's ratio (μ) for the alloy steel platen, steel specimen and granite specimen were determined in uniaxial compression to be approximately 230 GPa and 0.28, 208 GPa and 0.30, and 65 GPa and 0.25, respectively. A series of experiments were performed to investigate the end friction effect in the rue triaxial apparatus.

4. Results and discussion

4.1. Measurement of the friction coefficient

The friction coefficients of granite, Teflon, a composite of Teflon and MoS_2 (Dow Corning Molykote BR2 plus), and MSV against the alloy steel platen were measured in a true triaxial apparatus that was modified to function in a double direct-shear mode. The mixture of stearic acid and Vaseline (MSV) was prepared at a weight ratio of 1:1 by melting at 70 °C. Stearic acid is a fatty acid and thus acts as a solid lubricant, and Vaseline is added for ease of application; details were presented by Labuz and Bridell.[10] The same alloy steel platen and a shear rate of 0.005 mm/s were used in all tests.

There are two friction interfaces to balance the shear force in the tests, so the calculation of the friction coefficient is represented by

$$\mu = F/2N \tag{1}$$

where μ is the friction coefficient, F is the shear force, and N is the normal force.

The static friction coefficients that correspond to the onset of the bulk sliding of the specimen were measured under various normal loading forces of 25–200 kN. The static friction coefficients of the granite, Teflon, composite of Teflon and MoS_2, and MSV are plotted in Fig. 1. Each point in the figure represents the average value of three measurements, and the error bars indicate the standard deviation. Because of the very effective surface smoothing of the granite specimens, the friction coefficient between the granite and alloy steel platen was low and ranged from 0.146 to 0.157. The friction coefficients of the Teflon, the composite of Teflon and MoS_2, and the MSV tend to depend slightly on the normal loading force: the friction coefficient decreases with increases in the normal loading force. Linker and Dieterich reported the effects of variable normal stress on rock friction without using an anti-friction technique.[28] The mean friction coefficients for all the points of the Teflon, composite of Teflon and MoS_2, and MSV are 0.043, 0.021 and 0.018, respectively. The MSV exhibits a lower friction coefficient than the other interfaces due to its formation of a hydrodynamic film between the two sliding surfaces. The results of the composite of Teflon and MoS_2 shows a slightly raised friction coefficient under low normal forces; however, with increasing normal stress, the friction coefficient becomes smaller than that of the MSV. To obtain a uniform effect, the use of the composite of Teflon and MoS_2 is not suggested, and MSV instead is suggested for use in true triaxial compression testing.

4.2. End friction effect under loading in the short-axis direction

The end friction effect under loading in the short-axis direction is related to the direction of the intermediate principal stress loading in true triaxial tests, which features an additional end friction interface relative to the conventional triaxial tests. The MSV with a 0.02-mm-thick copper sheet was placed between the alloy steel platen and the specimen, on which the copper sheet was set. The strain at central point 2 was selected as a reference datum. Typical end constraint deformation can be observed for both the steel and granite specimens at the edges of the specimens (point 4 and 5). The compression strain

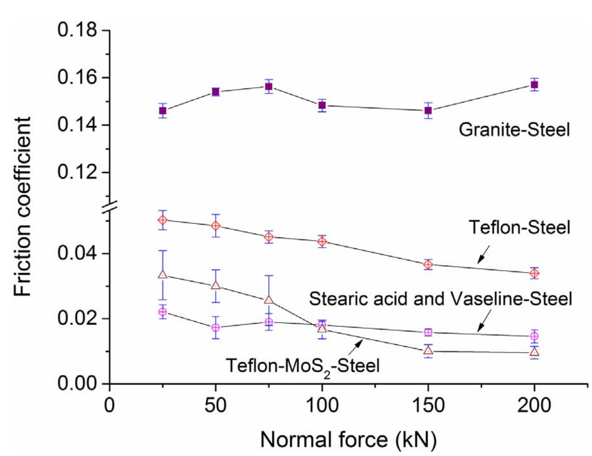

Fig. 1. Friction coefficient vs. normal loading force.