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Some considerations on the static and dynamic shear testing on rock discontinuities

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ABSTRACT: Although dynamic shearing properties of rock discontinuities are of great importance in many rock engineering applications, it is very rare to see dynamic shear tests on rock discontinuities. The author describes static, cyclic, one-way and two-ways dynamic shearing experiments on various natural rock discontinuities and saw-cut planes and discusses the shear strength characteristics obtained from the different testing techniques and interrelations. The experiments clearly showed that the dynamic shear behavior of discontinuities are very complex and anisotropic. Nevertheless, this study provides some fundamental understanding on the static and dynamic behavior of rock discontinuities and their correlation with each other.

1 INTRODUCTION

Dynamic shearing properties of rock discontinuities are of great importance in many rock engineering applications (Aydan et al. 2011). Nevertheless, dynamic shear tests on rock discontinuities are very rare. In this study, the author describes static, cyclic, one-way and two-ways dynamic shearing experiments on various natural rock discontinuities and saw-cut planes. Natural rock discontinuities involve schistosity planes in quartzite, green-schist, cooling planes in andesite, saw-cut planes of Ryukyu limestone, Motobu limestone, andesite and basalt from Mt. Fuji, dolomite from Kita-Daitojima, granodiorite from Ishigaki and Inada granite and Oya-tuff.

The experiments clearly showed that the dynamic shear behavior of discontinuities are very complex and anisotropic (Aydan et al. 1996). Furthermore, the degradation of roughness of the discontinuity planes results in further complexity in regard with modeling shear behavior under dynamic conditions. Nevertheless, the dynamic response at the first full cycle provides a basis for the overall dynamic shear behavior of discontinuities. and interfaces. Unpolished saw-cut planes of rocks should never be used for evaluating their shear responses under dynamic conditions in the first step (Aydan 2016). The dynamic shear behavior of actual discontinuities should be carried out as the next step.

The experimental results are compared with those from static and one-way dynamic shearing experiments and their implications in practice are discussed. Although more experiments are necessary for the selection of appropriate dynamic loading pattern with the consideration possible loading conditions in-situ, this study provides some fundamental understanding on the static and dynamic behavior of rock discontinuities and their correlation with each other.

2 STATIC SHEAR TESTING TECHNIQUES

2.1 *Tilting tests*

Tilting tests are known as a laboratory technique for measuring the friction angle in physics and illustrating the concept of friction (Aydan, 2016; Aydan et al. 1995, 2017). This technique is one of the most popular technique due to its simplicity and it is one of the most suitable technique to perform and to obtain the frictional characteristics of rock discontinuities and interfaces in-situ. This technique can be used to determine the apparent friction angle of discontinuities (rough or planar) under low stress levels. It definitely gives the maximum apparent friction angle, which would be one of the most important parameters to determine the shear strength criteria of rock discontinuities as well as various contacts.

2.1.1 *Theory of tilting tests*

Let us assume that a block is put upon a base block with an inclination α as illustrated in Fig. 1. The

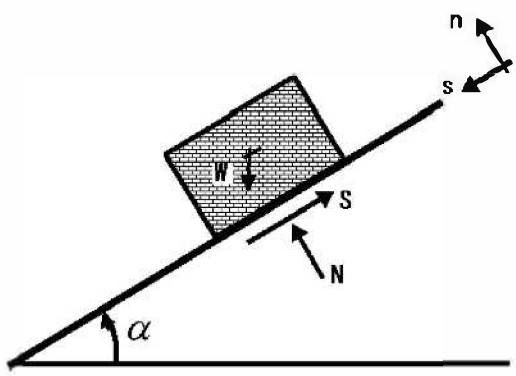

Figure 1. Mechanical model for tilting experiments.

dynamic force equilibrium equations for the block can be easily written as follows:

For s-direction

$$W\sin\alpha - S = m\frac{d^2s}{dt^2} \tag{1}$$

For n-direction

$$W\cos\alpha - N = m\frac{d^2n}{dt^2} \tag{2}$$

Let us further assume that the following frictional laws holds at the initiation and during the motion of the block (Aydan et al. 2017) as illustrated in Fig. 2: At initiation of sliding

$$\frac{S}{N} = \tan\phi_s \tag{3}$$

During motion

$$\frac{S}{N} = \tan\phi_d \tag{4}$$

At the initiation of sliding, the inertia terms are zero so that the following relation is obtained:

$$\tan\alpha = \tan\phi_s \tag{5}$$

The above relation implies that the angle of inclination (rotation) at the initiation of sliding should correspond to the static friction angle of the discontinuity. If the normal inertia term is negligible during the motion and the frictional resistance is reduced to dynamic friction instantenously, one can easily obtain the following relations for the motion of the block

$$\frac{d^2s}{dt^2} = A \tag{6}$$

where $A = g(\sin\alpha - \cos\alpha\tan\phi_d)$.

The integration of differential equation (6) will yield the following

$$s = A\frac{t^2}{2} + C_1t + C_2 \tag{7}$$

Since the followings hold at the initiation of sliding

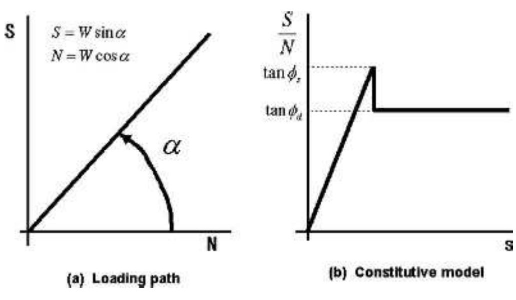

Figure 2. Loading path in tilting experiments and constitutive relation.

$$s = 0 \text{ and } v = 0 \text{ at } t = T_s \tag{8}$$

Eq. (7) takes the following form

$$s = \frac{A}{2}(t - T_s)^2 \tag{9}$$

Coefficient A can be obtained either from a given displacement s_n at a given time t_n with the condition, that is, $t_n > T_s$

$$A = 2\frac{s_n}{(t_n - T_s)^2} \tag{10}$$

or from the application of the least square technique to measured displacement response as follows

$$A = 2\frac{\sum_{i=1}^{n} s_i(t_i - T_s)^2}{\sum_{i=1}^{n}(t_i - T_s)^4} \tag{11}$$

Once constant A is determined, the dynamic friction angle is obtained from the following relation

$$\phi_d = \tan^{-1}\left(\tan\alpha - \frac{1}{\cos\alpha}\frac{A}{g}\right) \tag{12}$$

2.1.2 *Tilting test device and setup*

An experimental device consists of a tilting device operated manually. During experiments, the displacement of the block and rotation of the base is measured through laser displacement transducers produced by KEYENCE while the acceleration responses parallel and perpendicular to the shear movement are measured by a three component accelerometer (TOKYO SOKKI) attached to the upper block and WE7000 (YOKOGAWA) data acquisation system. The measured displacement and accelerations are recorded onto lap-top computers. The weight of the accelerometer is about 0.96N. Fig. 3 shows the experimental set-up.

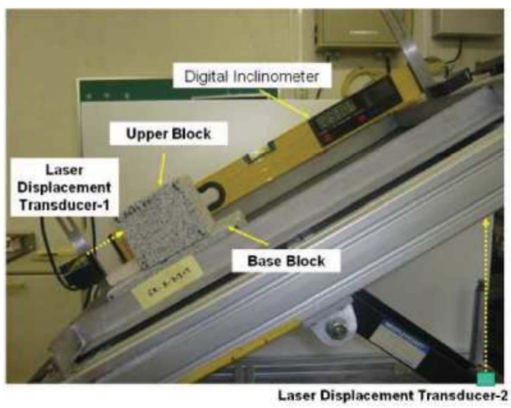

Figure 3. A conceptual illustration of experimental set-up.

2.1.3 *Tilting tests*

Some tilting experiments are describe herein and saw-cut discontinuity planes of Ryukyu limestone samples are chosen as an example. Fig. 4 shows responses measured during a tilting experiment on a saw-cut plane of Ryukyu-limestone. The static and dynamic friction coefficients of the interface were calculated from measured displacement response explained in previous section and they were estimated as 28.8-29.6° and 24.3-29.2° respectively.

2.2 *Stick-slip tests*

2.2.1 *Theory of stick-slip test*

In this model, the basal plate is assumed to be moving with a constant velocity v_m and overriding block is assumed to be elastically supported by the surrounding medium as illustrated in Fig. 5 (Ohta & Aydan 2010; Bowden & Leben, 1939; Jaeger & Cook, 1979). The basic concept of modeling assumes that the relative motion between the basal plate and overriding block is divergent. The governing equation of the motion of the overriding block may be written as follow:

During the stick phase, the following holds

$$\dot{x} = v_s, \qquad F_s = k \cdot x \tag{13}$$

where v_s is belt velocity and k is the stiffness of the system. The initation of slip is given as (Fig. 5)

$$F_y = \mu_s N \tag{14}$$

where μ_s is static friction coefficient, and N is normal force. For block shown in Fig. 5, it is equal to block weight W and it is related to the mass m and

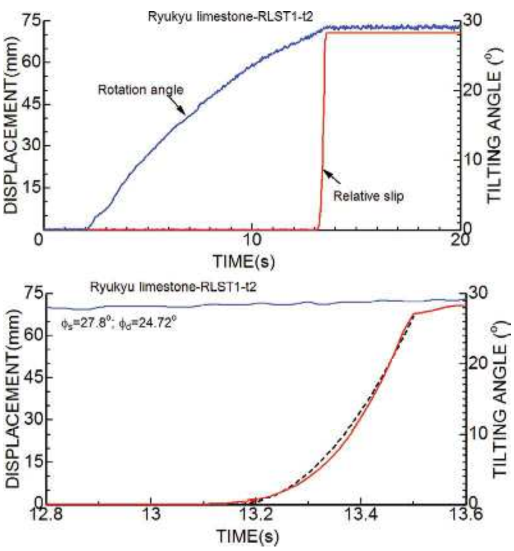

Figure 4. Responses of saw-cut discontinuity planes of Ryukyu limestone samples during a tilting test.

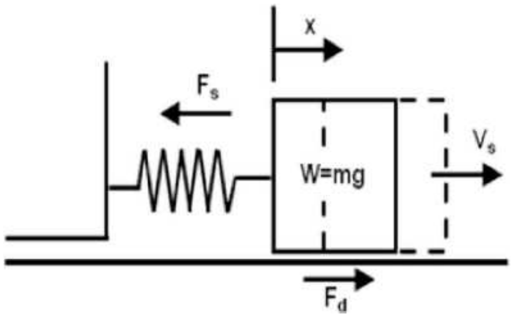

Figure 5.Mechanical modeling of stick-slip phenomenon.

gravitational acceleration g through mg. During slip phase, the force equilibrium yields:

$$-kx + \mu_k W = m\frac{d^2x}{dt^2} \tag{15}$$

where μ_k is dynamic friction angle. The solution of above equation can be obtained as.

$$x = A_1 \cos\Omega t + A_2 \sin\Omega t + \mu_k \frac{W}{k} \tag{16}$$

If initial conditions $t = t_s$, $x = x_s$ and $\dot{x} = v_s$) are introduced in Eq. (16), the integration constants are obtained as follow.

$$x = \frac{W}{k}(\mu_s - \mu_k)\cos\Omega(t - t_s) + \frac{v_s}{\Omega}\sin\Omega(t - t_s) + \mu_k \frac{W}{k}$$

$$\dot{x} = -\frac{W}{k}(\mu_s - \mu_k)\Omega\sin\Omega(t - t_s) + v_s\cos\Omega(t - t_s)$$

$$\ddot{x} = -\frac{W}{k}(\mu_s - \mu_k)\Omega^2\cos\Omega(t - t_s) - v_s\Omega\sin\Omega(t - t_s)$$

(17)

where $\Omega = \sqrt{k/m}$ and $x_s = \mu_s \frac{W}{k}$.

At $t = t_t$, velocity becomes equal to belt velocity, which is given as $\dot{x} = v_s$. This yield the slip period as:

$$t_t = \frac{2}{\Omega}\left(\pi - \tan^{-1}\left(\frac{(\mu_s - \mu_k)W\Omega}{k \cdot v_s}\right)\right) + t_s \tag{18}$$

where $x_s = v_s \cdot t_s$. The rise time, which is slip period is given by (Fig. 6)

$$t_r = t_t - t_s \tag{19}$$

Rise time can be specifically obtained from Eqs. 19 and 18 as

$$t_r = \frac{2}{\Omega}\left(\pi - \tan^{-1}\left(\frac{(\mu_s - \mu_k)W\Omega}{k \cdot v_s}\right)\right) \tag{20}$$

If belt velocity is negligible, that is, $v_s \approx 0$, the rise time reduce (t_p) to the following form

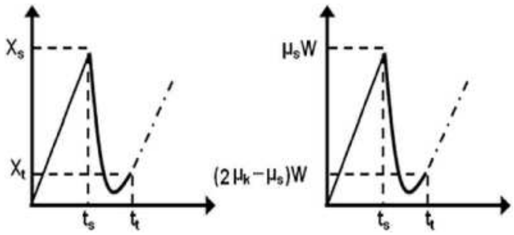

Figure 6. Frictional forces during a stick-slip cycle.

$$t_r = \pi\sqrt{\frac{m}{k}} \tag{21}$$

The amount of slip is obtained as

$$x_r = |x_t - x_s| = 2\frac{W}{k}(\mu_s - \mu_k) \tag{22}$$

The force drop during slip is given by

$$F_d = 2(\mu_s - \mu_k)W \tag{23}$$

It should be noted that the formulation given above does not consider the damping associated with slip velocity. If the damping resistance is linear, the governing equation (15) will take the following form

$$-kx - \eta\dot{x} + \mu_k W = m\frac{d^2x}{dt^2} \tag{24}$$

2.2.2 *Device of stick-slip tests*

Figure 7 shows a view of the experimental device. The experimental device consists of an endless conveyor belt and a fixed frame. The inclination of the conveyor belt can be varied so that tangential and normal forces can be easily imposed on the sample as desired. To study the actual frictional resistance of interfaces of rock blocks, the lower block is stuck to a rubber belt while the upper block is attached to the fixed frame through a spring as illustrated in Figure 5. We conducted the experiment using the rock samples of granite with planes having different surface morphologies. The base blocks were 200-400mm long, 100-150mm wide and 40-100mm thick. The upper block was 100-200mm long, 100mm wide and 150-00 mm high.

When the upper block moves together on the base block with at a constant velocity (stick phase), the spring is stretched at a constant velocity. The shear force increases to some critical value and then a sudden slip occurs with an associated spring force drop. Because the instability sliding of the upper block occurs periodically, the upper block slips violently over the base block. Normal loads can also be easily increased in experiments.

2.2.3 *Stick-slip tests*

A series of stick-slip experiments are carried out on the saw-cut discontinuities of Ryukyu Limestone. The peak (static) friction angle can be evaluated from the T/N response while the residual (kinetic) friction angle is obtained from the theoretical relation (Aydan et al. 2018). Fig. 8 show the stick-slip responses of discontinuity planes shown. The residual (kinetic) friction angle of saw-cut discontinuity plane of Ryukyu limestone obtained from stick-slip experiments are very close to those obtained from tilting experiments. Nevertheless, the kinetic or residual friction angle is generally lower than those obtained from the tilting experiments.

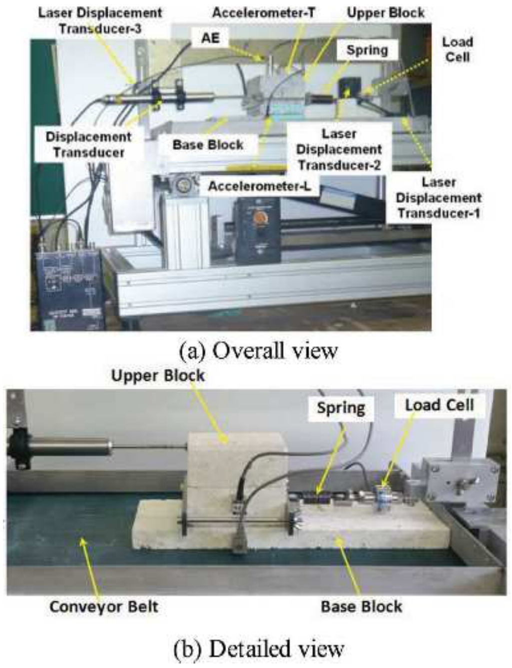

Figure 7. Stick-slip experimental setup.

2.3 *Direct shear tests*

Direct shear testing device is commonly used. The loading step may be monotonic under a constant normal loading or multi-stage normal loading. A multi-stage (multi-step) direct shear test on a saw-cut surface of sandy Ryukyu limestone sample, which consist of two blocks with dimensions of 150x75x37.55mm, was varied out (Figs. 9 and 10).

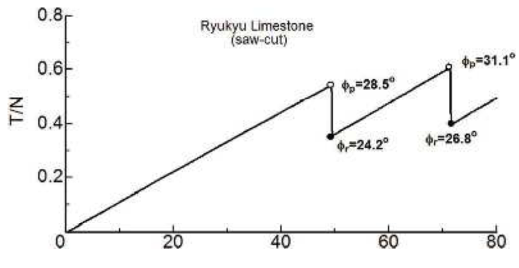

Figure 8. Stick-slip response of saw-cut plane of Ryukyu limestone.

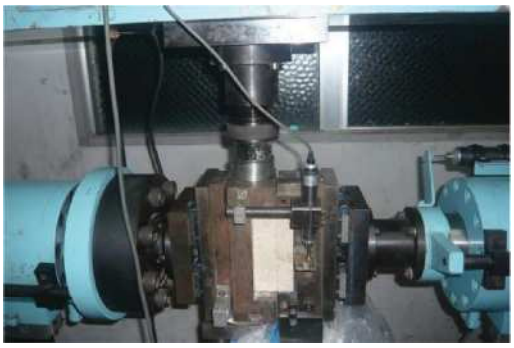

Figure 9. A view of direct shear test on a saw-cut discontinuity plane.

Figure 10. A view of a saw-cut discontinuity plane after a direct shear test.

The initial normal load was about 17 kN and increases to 30, 40, 50, 60 and 70 kN during the experiment. Fig. 11 shows the shear displacement and shear load responses during the experiment. As noted from the figure, the relative slip occurs between blocks at a constant rate after each increase of normal and shear loads. This experiment is likely to yield shear strength of the interface two blocks under different normal stress levels. Fig. 11 shows the peak and residual levels of shear stress for each level of normal stress increment. Tilting tests were carried out on the same interface and the apparent friction angles ranged between 35.4 and 39.6 degrees. Tilting test results and direct shear tests are plotted in Fig. 12 together with shear strength envelopes using the shear strength failure criterion of Aydan (Aydan 2008; Aydan et al. 1996).

Therefore, the data for determining the parameters of the shear strength criteria for rock discontinuities should utilize both tilting test and direct shear experiment.

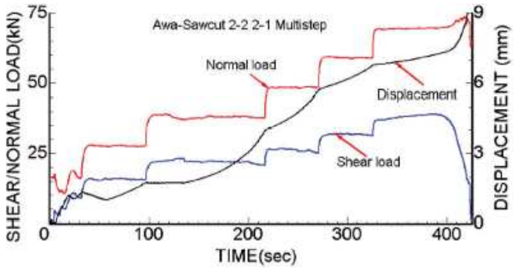

Figure 11. Shear stress-shear load response of the interface of sandy limestone blocks during the multi-stage(step) direct shear experiment.

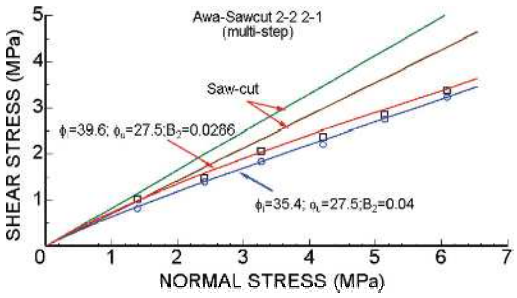

Figure 12. Comparison of shear strength envelope for the interface of sandy limestone blocks with experimental results from the multi-stage(step) direct shear experiment and tilting tests.

As noted from the figure, the friction angles obtained from tilting tests are very close to the initial part of the shear strength envelopes. However, the friction angle becomes smaller as the normal stress level increases. In other words, the friction angle obtained from tilting tests on saw-cut surfaces can not be equivalent to the basic friction angle of planar discontinuities and interfaces of rocks. The basic friction angle of the planar interface of sandy limestone blocks is obtained as 27.5 degrees for the range of given normal stress levels.

3 DYNAMIC SHEAR TESTING TECHNIQUES

3.1 *Direct cyclic shear tests*

Cyclic shearing tests rock discontinuities and interfaces are performed under cyclic loads with a given period results in relation to machinery vibration and/or earthquakes. Fig. 9 is a shear testing machine capable of cyclic loading (Aydan et al., 1994, 2016).

3.2 *Dynamic one-way shear tests*

Dynamic one-way shear testing is one of the techniques to investigate the dynamic shear testing of discontinuities (Aydan et al. 1994; Aydan 2018).

Particularly, this procedure is important to evaluate the dynamic behaviour of discontinuities including the linear response. The device is the shear testing machine upgraded by Aydan et al. (2016) with a one way-shear testing capability as shown in Fig. 13.

3.3 *Dynamic two-ways shear tests*

A series of two-ways direct shear tests were carried out saw-cut discontinuity planes of Ryukyu limestone. Fig. 14 shows the normalized shear resistance (T/N) response of the saw-cut planes and acceleration during the two-ways shearing with ±15 mm forced displacement amplitude. As noted the acceleration response is quite different than that anticipated and it has a very irregular response with an amplitude less than 0.42g.

Fig. 15 shows the relative displacement-T/N relation. In the same figure, the trajectory of the first cycle is distinguished. It is quite interesting to note that the shear resistance of the discontinuity plane gradually changes after each cycle of shearing. At the end of the experiment, a thin powder is recognized on the discontinuity plane.

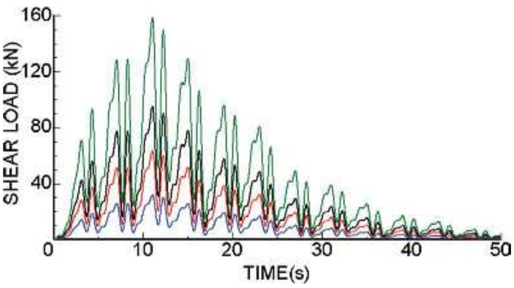

Figure 13. Adopted direct shear loading patterns in the dynamic shear testing machine (OA-DSTM).

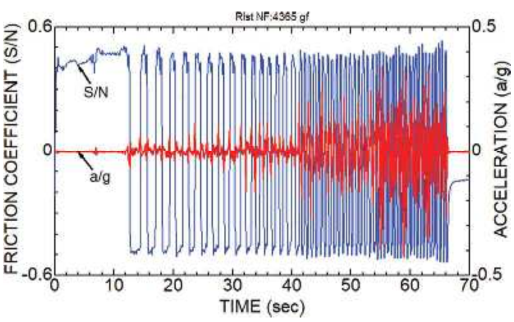

Figure 14. The response of the normalized S/N and acceleration response of a saw-cut plane during two shearing experiment.

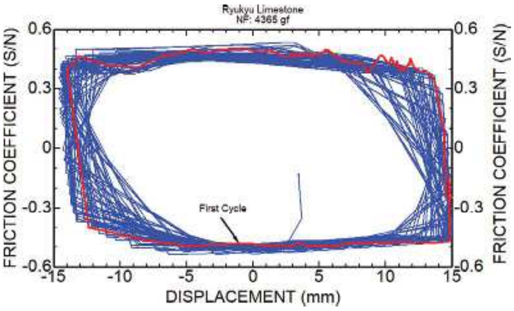

Figure 15. Shear response of a saw-cut discontinuity plane of Ryukyu limestone shown in Figure 14 in the space of relative displacement and T/N.

4 DISCUSSIONS AND CONCLUSIONS

The author performed many shear testing on natural rock discontinuities involve schistosity planes in quartzite, green-schist, cooling planes in andesite, saw-cut planes of Ryukyu limestone, Motobu limestone, andesite and basalt from Mt. Fuji, dolomite from Kita-Daitojima, grano-diorite from Ishigaki and Inada granite and Oya-tuff. The static and dynamic (kinetic) friction angles on these discontinuities are plotted in Fig. 16 in order to compare static and dynamic shear testing results as an example. Most of experimental indicate that the dynamic (kinetic) friction angle of natural and saw-cut discontinuities is about 0.87 times that of the static friction angle.

This theoretical and experimental study on various natural rock discontinuities and saw-cut planes utilizing different experimental techniques

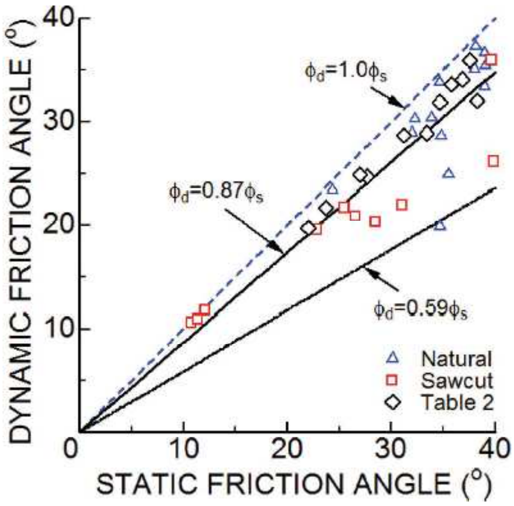

Figure 16. Comparison of static and kinetic friction angles obtained from tilting experiments on various rock discontinuities.

clearly showed that their static and dynamic shear properties would be different. Experimental results indicated that peak (static) friction angle for both discontinuity planes obtained from tilting tests and stick-slip experiments are very close to each other. Furthermore, the residual or dynamic friction angle for rough discontinuity planes and saw-cut discontinuity planes obtained from stick-slip experiments are very close to those obtained from the tilting experiments. Nevertheless, the dynamic or residual friction angle is generally lower than those obtained from the tilting experiments.

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