AN EXPERIMENTAL STUDY ON FRICTIONAL PROPERTIES OF FAULTS

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The frictional properties of faults, which govern the magnitude of earthquakes and resulting strong motions, are very important and there is almost no experimental studies on actual fault planes. The authors have initiated an experimental program to study the frictional properties of fault planes using samples gathered from the normal faults observed in Western Turkey with overthrows more than 30-40 m in brecciated limestone formation. Frictional experiments were carried out using three different techniques, namely, tilting tests, stick-slip tests and dynamic two-ways shearing tests. The authors report the outcomes of preliminary results on the actual fault planes and compare with each other. They also discuss their implications in earthquake rupture simulations.

Key Words : *Fault, friction angle, tilting test, stick-slip tests, two dynamic shear test .*

1. INTRODUCTION

The frictional properties of faults govern the magnitude of earthquakes and resulting strong motions (e.g. Aydan et al. 2011). However, there is almost no experimental studies on actual fault planes and it is urgently required to implement such studies. As earthquake faults are very deep, the sampling is quite difficult. Luckily, there are some active normal faults outcropping in western Turkey and it is possible to samples having fault surfaces. Figure 1 shows some views of normal faults in western Turkey. The authors have initiated a collaborative research program on the characterization of normal faults in western Turkey and their shear characteristics using different techniques. This study is a first step of this collaborative study.

In this study, the authors present the experimental studies on normal fault surfaces sampled from the Efes (Ephesus) Fault in western Turkey. The experiments involve tilting tests, stick-slip tests and two-way dynamic shear tests. The outcomes of these experiments are presented and discussed with its implications in earthquake science.

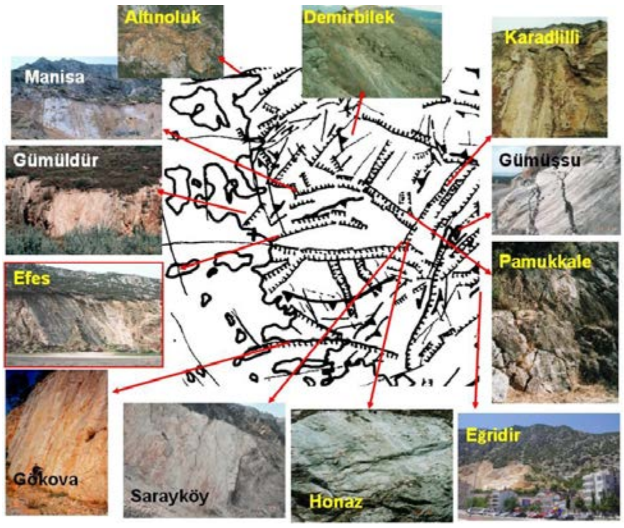

Figure 1. Location of faults in western Turkey (fault map from Aydan 1997).

2. FAULTS IN WESTERN TURKEY

Western Turkey is a well-known region in the world undergoing extension in north-south direction due to subduction of African Plate beneath Anatolian Platelet restrained by the Euro-Asian plate in the north (Aydan 1997). As a result of this tectonic regime, there are many normal faults with slight sinistral or dextral slip component (Figure

1). Some of well known normal faults are Gökova, Efes, Gümüldür, Davutlar, Sarayönü, Honaz, Soma, Balçova, Dinar, Gümüксu, Karadilli, Pamukkale. Most of these normal faults have relative slip more than 40-50 m with well observed striations. Efes, Manisa and Davutlar faults are located in brecciated limestone formation. This limestone has a well-defined faults surface implying that brecciated limestone is re-crystallized to form such a surface. The rock fragments may be up to 10-20 cm in diameter (Figure 2).

(a) Efes Fault (b) Striations

Figure 2. A view of Efes Fault and a close-up view of its surface

3. SAMPLING OF FAULT PLANE SAMPLES

When one visits fault sites, there are many fallen detached rock samples with well defined fault surfaces. In other words, the sampling does not cause any major damage to the existing fault-surfaces at each site, which are the indicators of ongoing and past geological activities of the regions. In this study, samples collected from Efes Fault are utilized and Figure 3 show some of fault plane samples. Collected rock samples are taken to the rock mechanics laboratories of University of the Ryukyus, Pamukkale University or Tokai University for preparation of rocks samples for tilting, stick-slip and two-ways dynamic shear testing.

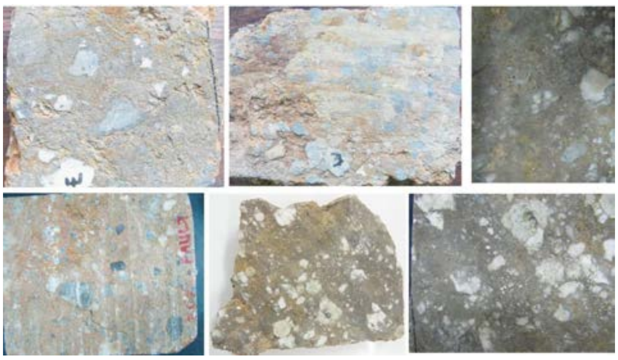

Figure 3. Views of surface of samples from Efes Fault utilized in this study

4. TILTING TESTS

Rock Mechanics laboratory of the University of the Ryukyus has a well-equipped tilting testing device. Figure 4 shows an illustration of tilting test concept. The details of this device is described elsewhere (Aydan et al. 2017, 2018). A three component accelerometer and laser displacement transducers are used to measure rotation angle and relative slip of the upper block. The accelerometer allows us to assess the time of failure as well as vibrations caused by slippage, which may also provide some vibration data for large-scale slip phenomenon in nature. Figure 5 shows an example of records during a tilting experiment. The slip induced a fluctuation of acceleration in the direction of slippage. The high acceleration is due to shock caused by the top block when it hit the barrier to terminate its motion. The rotation angle is directly obtained from the acceleration component in the direction of sliding surface.

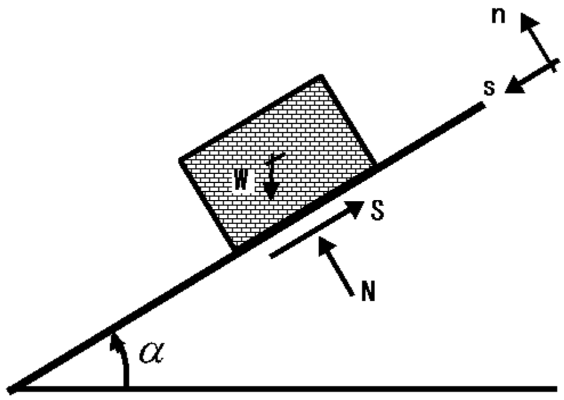

Figure 4. An illustration of tilting test concept.

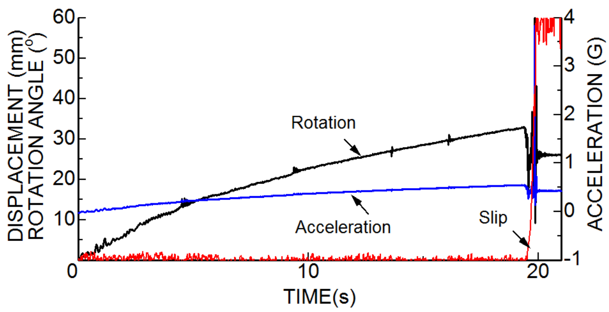

Figure 5. Responses of parameters during a tilting experiment.

The static and dynamic friction angles are obtained from the following relations (e.g. Aydan et al. 2017, 2018)

Static friction angle

$$\phi_s = \tan^{-1}(\tan\alpha) \qquad (1)$$

where α is the inclination of fault plane at the time of slippage.

Dynamic friction angle

$$\phi_d = \tan^{-1}\left(\tan\alpha - \frac{1}{\cos\alpha}\frac{A}{g}\right) \qquad (2)$$

where g is gravitational acceleration. A is specifically given by

$$A = g(\sin\alpha - \cos\alpha\tan\phi_d) \qquad (3)$$

However, coefficient A is determined from the application of the least square technique to measured displacement response as follows

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

Figure 6 shows an application of the above procedure to determine static and dynamic friction angles of fault surface shown in Figure 3. This procedure is applied to the slip response between 26.073 and 26.5 seconds. The same procedure has been applied to all experiments and determined parameters are given in Table 1.

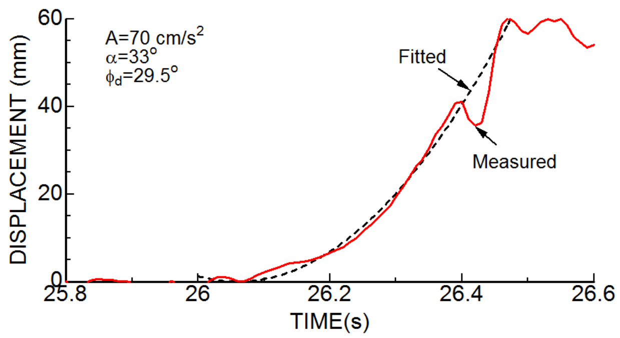

Figure 6. Determination of dynamic friction angle of a fault plane from the measured responses.

Table 1. Determined static and friction angle of discontinuities from tilting tests.

Test No.	Static (°)	A (cm/s^2)	Dynamic (°)
Efesfault_bfp1_tfp1_t1	33.2	75	29.4
Efesfault_bfp1_tfp1_t2	33.5	70	29.5
Efesfault_bfp1_tfp1_t3	36.7	85	32.3
Efesfault_bfp1_tfp2par_t1	27.0	95	21.8
Efesfault_bfp1_tfp2par_t2	30.6	80	26.4
Efesfault_bfp1_tfp2par_t3	31.1	40	29.1
Efesfault_bfp1_tfp2per_t1	35.0	95	30.2
Efesfault_bfp1_tfp2per_t2	35.2	60	32.2
Efesfault_bfp1_tfp2per_t3	32.5	80	28.4

5. STICK-SLIP TESTS

Stick-slip tests were carried out on the same samples after cleaning the surface of fault plane samples according to the suggested method of ISRM on tilting experiments (Alejano et al. 2018). As suggested by Aydan et al. (2018), the first 1-3 cycles of stick-slip responses may be used to determine the static and dynamic friction angle of fault plane samples. Experiments were carried out under three different normal loads, namely dead-weight (DW), DW+730 gf and DW+1730 gf. Figure 7 illustrates the fundamental concept of a stick-slip test. Figure 8 shows the responses in initial stages of the stick-slip experiment under three different normal loads.

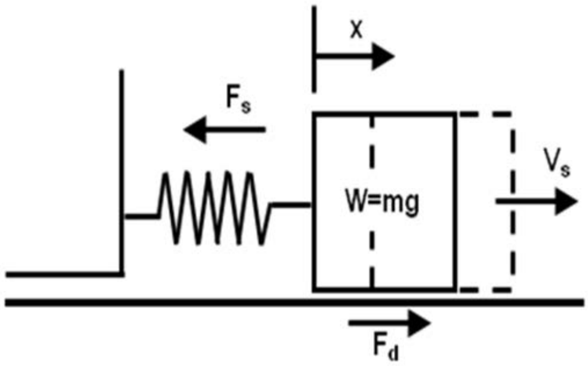

Figure 7. An illustration of a stick-slip test.

Static and dynamic friction angles from a typical slip phase can be determines as illustrated in Figure 9. Force drop (F_d) at a given slip phase under a given normal load (N) can be shown to be (e.g. Aydan 2017, Aydan et al. 2018; Bowden and Leben 1939; Jaeger and Cook 1979).

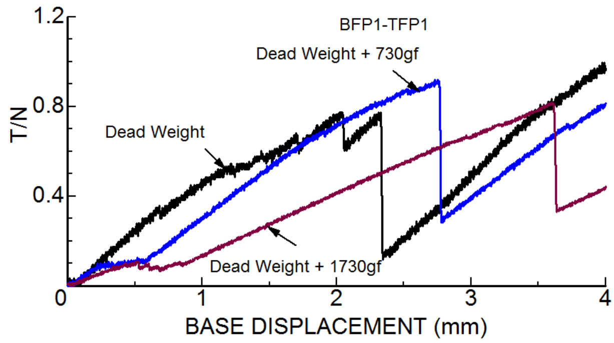

Figure 8. Responses in initial stages of the stick-slip experiment under three different normal loads

$$\frac{F_d}{N} = 2(\mu_s - \mu_k) \qquad (5)$$

Re-arranging Eq. (5) yields the relation for dynamic friction angle as

$$\phi_k = \tan^{-1}\left(\mu_s - \frac{1}{2}\frac{F_d}{N}\right) \quad (6)$$

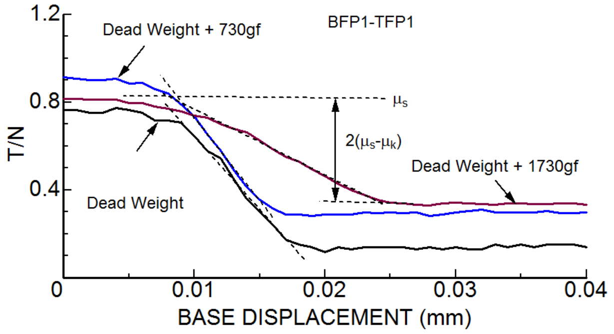

Figure 9. Responses during a typical slip phase under three different normal loads.

The procedure has been applied to all stick-slip experiments and determined parameters are given in Table 2. Although the results obtained from stick-slip test are somewhat scattered, the overall trend of static and dynamic friction angles are quite similar to those of the tilting experiments.

Table 2. Determined static and friction angle of discontinuities from stick-slip tests

Test No.	N (gf)	Static (°)	Dynamic (°)
Efesfault_bfp1_tfp1_t1	850	37.6, 37.6	34.4,24.3
Efesfault_bfp1_tfp1_t2	1580	42.0,42.0,35.0	30.7,35.4,27.9
Efesfault_bfp1_tfp1_t3	2580	39.4,28.4	30.1,26.8
Efesfault_bfp1_tfp2par_t1	687	26.1,26.1,36.5	20.1,21.6,20.0
Efesfault_bfp1_tfp2par_t2	1417	26.1,42.6,28.5	14.9,24.7,26.3
Efesfault_bfp1_tfp2par_t3	2417	30.5,34.6,28.4	23.3,25.6,27.3
Efesfault_bfp1_tfp2per_t1	687	31.8,46.1,45.3	24.3,36.1,28.6
Efesfault_bfp1_tfp2per_t2	1417	34.2,31.0,29.7	25.4,19.8,18.9
Efesfault_bfp1_tfp2per_t3	2417	30.5,29.7,22.3	25.9,19.3,15.6

6. TWO-WAYS DYNAMIC SHEAR TESTING

Two-way dynamic shearing tests were carried out using an experimental set-up developed by Aydan et al. (2015) and updated recently (Figure 10). Figure 11 shows an example of experiment tested under three different normal loads. Depending upon the frequency of cycles, the friction angle are slightly different from each other. However, the friction angle is reduced as the frequency of cycles increases. Except the initial and final cycles, the friction angle ranges between 34 and 38 degrees. The static and dynamic friction angles obtained from the experiments are given in Table 3 by excluding the friction angles at the initial and final cycles.

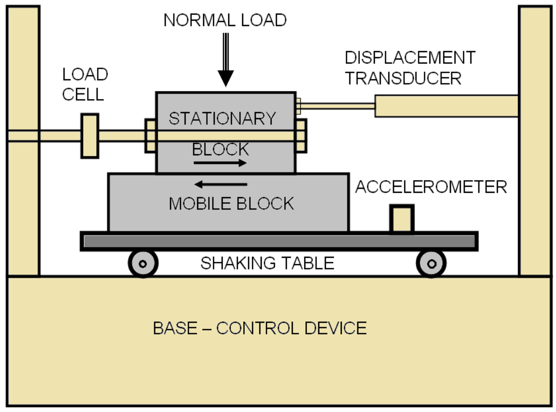

Figure 10. An illustration of two-way dynamic shear test device.

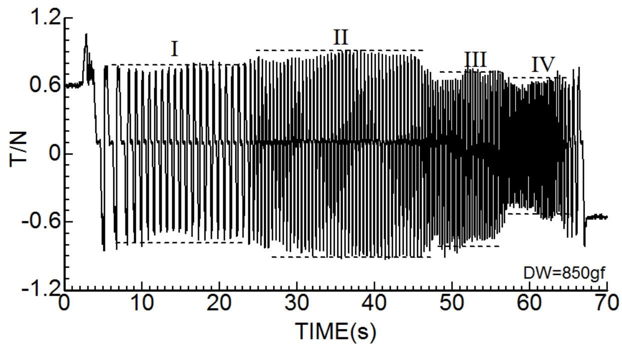

Figure 11. Variation of shear resistance during a two-way dynamic shearing experiment under a normal load of 850 gf.

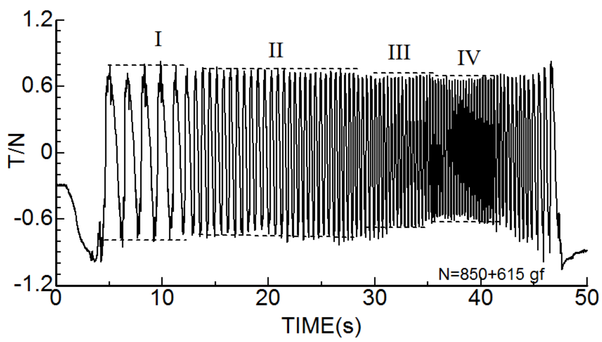

Figure 12. Variation of shear resistance during a two-way dynamic shearing experiment under a normal load of 1465 gf.

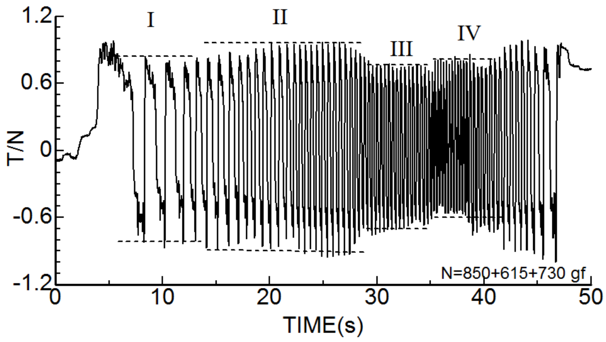

Figure 13. Variation of shear resistance during a two-way dynamic shearing experiment under a normal load of 2195 gf.

Table 3. Determined static and friction angle of discontinuities from two-way dynamic shearing experiments

Test No.	N(gf)	Static (°)	Dynamic (°)
Efesfault_bfp1_tfp1_t1	687	38.7,42.8, 36.5	34.2,39.3 , 33.8
Efesfault_bfp1_tfp1_t2	1465	38.7,37.6, 34.6	35.8,34.6 , 28.8
Efesfault_bfp1_tfp1_t3	2195	40.0,44.1, 38.0	37.6,40.0 , 26.6
Efesfault_bfp1_tfp2par_t1	687	29.4,28.4, 24.2	25.6,21.3 , 17.7
Efesfault_bfp1_tfp2par_t2	1465	27.9,24.9, 21.8	25.2,23.5 , 15.6
Efesfault_bfp1_tfp2par_t3	2195	28.8,28.4, 24,9	26.6,21.3 , 13.6
Efesfault_bfp1_tfp2per_t1	687	35.6,33.0, 23.6	22.8,21.8 , 17.8
Efesfault_bfp1_tfp2per_t2	1465	35.5,32.1, 33.0	29.1,19.9 , 23.4
Efesfault_bfp1_tfp2per_t3	2195	28.8,28.4, 21.8	24.7,23.7 , 18.3

7. COMPARISONS AND DISCUSSIONS

The static (peak) and residual (kinetic) friction angles obtained from tilting tests and stick-slip experiments are compared herein. As stated previously, peak (static) friction angle for discontinuity planes obtained from tilting tests and stick-slip experiments are very close to each other as seen in Figure 14. The residual or kinetic friction angle of discontinuity planes obtained from stick-slip experiments are very close to those obtained from the tilting experiments as seen in Figure 14. Nevertheless, the kinetic or residual friction angle is generally lower than those obtained from the tilting experiments and the relation between kinetic friction angle obtained from stick-slip experiments is about 0.9 times those obtained from tilting experiments as seen in Figure 15.

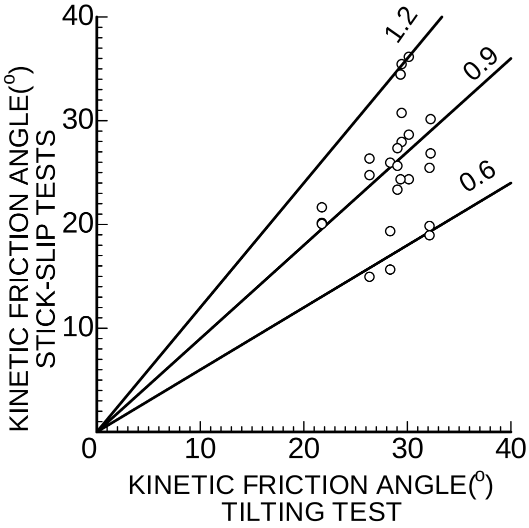

Figure 14. Comparison of kinetic friction angles obtained from titling and stick-slip experiments.

The authors performed some tilting tests on natural and saw-cut surfaces previously (Aydan et al. 2017). Most of experimental indicate that the kinetic friction angle of natural discontinuities is about 0.87 times that of the static friction angle. The previously reported results are quite similar to those obtained in this study. It is expected that these results would be quite useful for simulating the post-failure motions of failed bodies in rock slope engineering, underground openings and projectile intrusions during impacts.

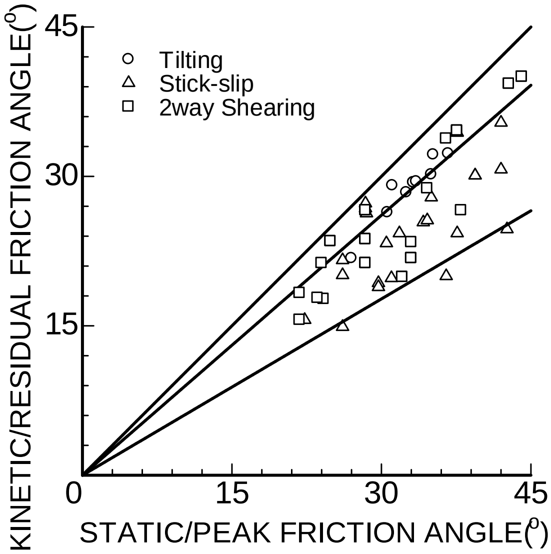

Figure 15. Comparison of static and kinetic friction angles obtained from tilting experiments on various rock discontinuities.

8. CONCLUSIONS

In this study, the authors described an experimental study on static and kinetic friction angles of actual fault planes from the normal faults in western Turkey. In addition the theoretical background of tilting and stick-slip experiments are briefly presented. Experimental results indicated that peak (static) friction angle for both discontinuity planes obtained from tilting tests, stick-slip experiments and two-way dynamic shear tests are very close to each other. Nevertheless, the kinetic or residual friction angle is generally greater than those obtained from the tilting experiments. The relation between kinetic friction angle obtained from stick-slip experiments is about 0.9 times those obtained from tilting experiments.

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