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Stick-slip behavior of rock discontinuities by difference in rock types

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ABSTRACT: The stick-slip phenomenon is used to explain as a mechanism of earthquake recurrence. A number of stick-slip experiments have been performed to clarify the mechanism of recurring slip instabilities and slip weakening. Although the amplitude of sliding of most experiments is quite smaller than actual earthquakes, and the observed acceleration is larger. The authors have developed a new experimental setup, in which blocks move on a conveyor belt and is restrained by the spring, and conducted stick-slip experiments. This experimental setup is able to simulate conditions in actual earthquakes better than previous stick-slip experimental devices. In this study, we conducted stick-slip experiment which focused on difference of the rock types and confirmed the the applicability of this experimental setup and the validity of the result. Moreover, the theoretical results of stick-slip phenomenon indicate the need for taking account of slip weakening and roughness of the contact surface and geometrical shape.

1 INTRODUCTION

The stick-slip is a phenomenon that interfaces is repeated sticking (accumulation of stress) and slip (release of stress). In the field of rock engineering, it is very important to explain the periodic occurrence of earthquakes as well as creep behavior of unstable zones of slope movement and large underground cavities. Brace & Byerlee (1966) conducted some laboratory experiments using rocks to explain the mechanism of occurrence of earthquakes, and proposed that the stick-slip phenomenon is associated with this mechanism.

However, there are many reports on conditions whether stick-slip phenomenon is prone to occur, and there are few reports on effect of experimental parameters such as confining pressure, rate of loading and test machine specifications on experimental results such as acceleration, slippage and stress drop. Moreover, most were using the compression testing equipment in the above studies, amount of slippage was very small with 1μm-1 mm and the peak accelerations during slipping were very large with 10^2–10^5 m/s^2 (Ohnaka 2003). These results are quite different from case of medium/large earthquakes, slip amount of 10 cm-1 m, peak acceleration of 1–10 m/s^2. On the other hand, the experiment using the rotary shear testing equipment is able to simulate a condition close to actual earthquakes. Though these studies are performed for the purpose of elucidation of the friction mechanism that dynamic friction coefficient becomes smaller if sliding speed becomes faster, and these were not intended for stick-slip phenomenon (Chang et al. 2012).

The authors have developed a new experimental setup, in which blocks move on a conveyor belt and is restrained by the spring, and conducted stick-slip experiments. This experimental setup is able to simulate conditions in actual earthquakes better than previous stick-slip experimental devices. During experiments, the velocity of base block, stiffness of springs and normal load acting on block interface were varied to study their effect on the periodicity and stick-slip response. The results of this experiment are quite similar to the relations of the earthquake parameters obtained from earthquake observations, and they are consistent with those of previous stick-slip experiments (Ohta & Aydan 2010; Iwata et al. 2016). However, as these experiments are limited in quantity and some man-made surfaces of granite, they had some issues such as not being able to evaluate influence by the type of rocks and difference of the test specimen.

In this study, stick-slip experiments using blocks of Kumamoto quartzite and Turkey quartzite block are performed, and the consistency of the experimental results and the effect of the difference of rock types are investigated. Thus, the results were consistent with the results of previous experiments and the same result as the correlation between empirical seismic parameters. It was also found that the difference of the rock types (i.e. the roughness of the contact surface and geometrical shape) affected the stick-slip phenomenon.

2 OUTLINE OF THE EXPERIMENT

2.1 *Materials*

The rock types of the block used in this experiment are Kumamoto quartzite and Turkey quartzite rocks, which comes from the famous Menderes metamorphic massif. The stick-slip experiment is carried out with the upper block placed on the base block. The base block is 200 mm long, 100 mm wide and 40 mm thick. The upper block is 100 mm long, 100 mm wide and 100 mm high.

Figure 1 shows the contact surface between the upper and base blocks of the Kumamoto quartzite and Turkey quartzite rocks. We also show the block of granite used in the previous experiment (Iwata et al. 2016). The contact surface of the Kumamoto quartzite and Turkey quartzite rocks is a natural schistosity surface, and granite is a man-made surface.

2.2 *Tilting test*

In order to confirm the strength characteristics of the contact surface prior to the stick-slip test, the static and dynamic friction angle of the contact surface was determined through the tilting test. The static and dynamic friction angle was calculated from the displacement response and block weight of the block measured by the laser transducer using the tilting testing device shown in Figure 2. The inclination angle when the block begins to slide by increasing the inclination of the tilting tester is equivalent to the static friction angle. In addition, the dynamic friction angle was calculated from the coefficient obtained by the minimum square method for the relation between the response displacement and the time from the beginning of slipping.

2.3 *Stick-slip experiment*

Figure 3 shows a stick-slip experimental device. The experimental equipment consists of a rubber conveyor belt and a fixed frame, and the conveyor belt's moving speed can be changed freely.

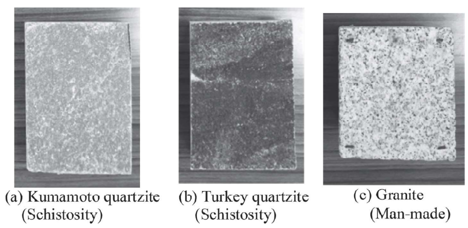

Figure 1. Contact surface of rock blocks.

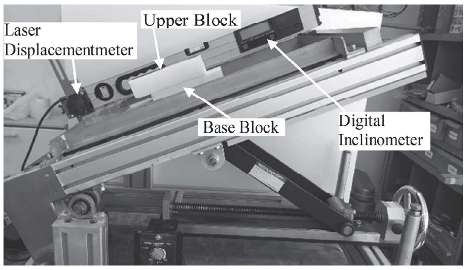

Figure 2. Tilting experimental setup.

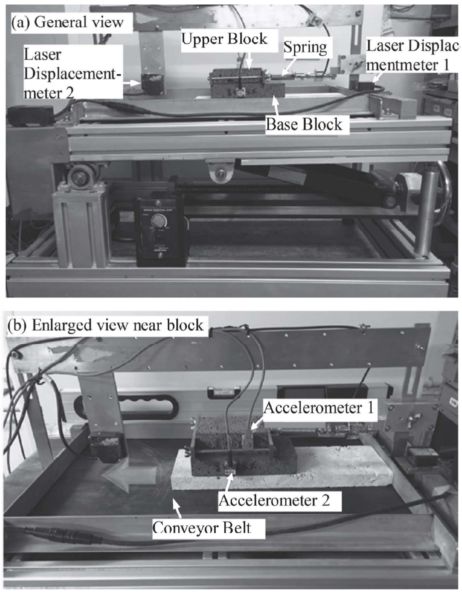

Figure 3. Stick-slip experimental setup.

The base block is on the conveyor belt, and the upper block is fixed to the fixed frame through the spring. When the conveyor belt is operated, the upper and base blocks are moved in the direction where the spring is stretched together, but when it exceeds a certain displacement, a slip is caused by the restoring force of the spring connected to the upper block. The repetition of this behavior is a stick slip phenomenon.

In the experiment, in order to measure the force acting on the upper block due to the stick-slip, the load cell was installed between the spring and the fixed frame, and the accelerometer was installed on the side of the upper block and the base block to measure the horizontal acceleration of the conveyor belt movement direction. The horizontal displacement of the upper and base blocks during the experiments are measured as the distance between the fixed frame by the non-contact type

Table 1. Parameters of stick-slip experiments.

Parameters	Conditions
Base block velocity (mm/s); v	0.7, 1.5, 1.9
Normal load (N);	N 7.1, 10.0, 14.9, 19.8/19.0

laser displacement meter attached to the frame. The measurement sampling interval was 10 ms, and the displacement, load and acceleration were recorded on the computer using a dynamic strain amplifier. The experimental conditions were based on the case given in Table 1, and the velocity of the base block and the normal load were changed. The spring used is an elastic spring with a stiffness of 1.0 N/mm.

3 EXPERIMENTAL RESULTS

3.1 *Tilting test*

Figure 4 shows an expanded view of the time of the rock block slipping for the displacement of the upper rock block in the tilting test. Table 2 summarizes the results of the tilting test. The static friction angle of the Kumamoto quartzite is 35.1°, the dynamic friction angle is 21.6°, the static friction angle of the Turkey quartzite is 26.9°, the dynamic friction angle is 24.8°, and the relation between the static and dynamic friction angle of both rock type were inferred.

3.2 *Stick-slip experiment*

Figure 5 shows the time histories of spring force, acceleration and displacement of the upper block in some experimental cases. Figures 5(a)–(c) is Kumamoto quartzite, Figure 5(d) shows the results of Turkey quartzite. In both cases, the spring force just before sliding (hereinafter referred to as the peak frictional force) and the spring force immediately after sliding, and the change of the spring force before and after the slip (hereinafter referred to as the force drop) is not stationary and differ significantly from the slip event. This is due to the influence of asperity. Comparing Figures 5(a) and (b), when the base block speed becomes faster, the recurrence time (the time from the end of the slip to the start of the next slip, stress accumulation time) becomes shorter, and the spring force and the amount of slippage (displacement difference before and after the slip occurrence of the upper block) tend to be small. Comparing Figures 5(a) and (c), when the normal load of the block becoms larger, the recurrence time becomes longer and the spring force becomes larger. Comparing Figures 5(a)-(c) of Kumamoto quartzite and Figure 5(d) of the Turkey quartzite, the recurrence

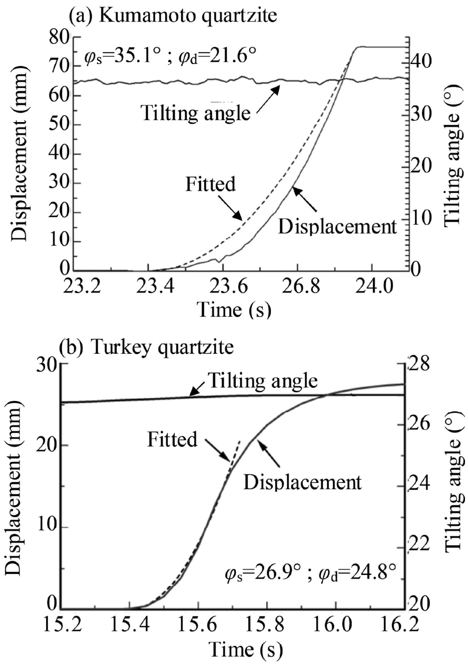

Figure 4. Displacement response in tilting test.

Table 2. Results of tilting tests.

Rock types	Contact surface	Friction angle	
		Static: φ_s	Dynamic: φ_d
Kumamoto quartzite	Schistosity	35.1°	21.6°
Turkey quartzite	Schistosity	26.9°	24.8°
Granite*	Man-made	32.3°	30.3°

*Result of previous experiment (Iwata et al. 2016).

time and slippage are very different. It is thought that the differences of the friction angle, roughness, and geometrical shape of the contact surface have strong influences.

4 DISCUSSION ON EXPERIMENTAL RESULTS

4.1 *Relation between friction coefficient and behavior of upper block*

Figure 6 shows the relation between static friction coefficient (the ratio of the spring force just before sliding and the normal load) and recurrence time. As a result, the static friction coefficient increases

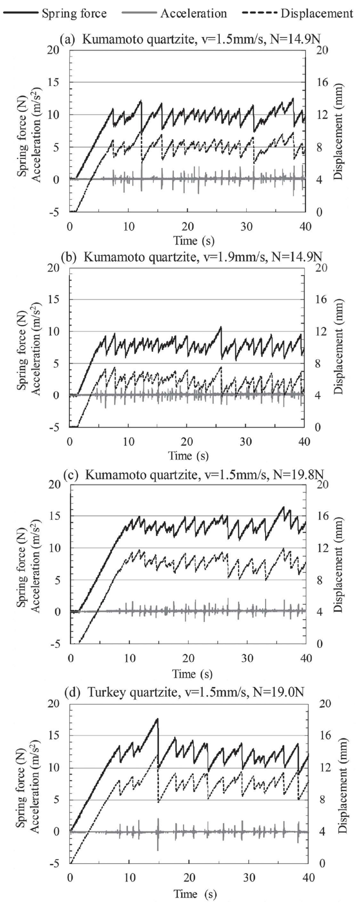

Figure 5. Time histories of stick-slip response.

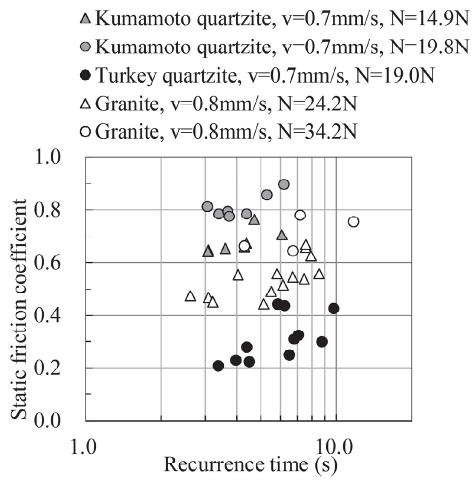

Figure 6. Relation between static friction coefficient and recurrence time.

as the recurrence time increases in the same rock types, and this result is consistent with the result shown by Dieterich (1979) and Aochi & Matsu'ura (2002). Compared with each rock type, the relation of magnitude of the static friction coefficients from stick-slip test and the static friction angle obtained by the tilting test is consistent with each other. In addition, in comparison of the same rock types, the static friction coefficient tends to increase as the normal load increases (Δ to o), this is thought to be due to the increased strength of the asperity contact area of the block with the increase by the normal load.

Figure 7 shows the relation between dynamic friction coefficient (the ratio of the spring force and the normal load when the slip acceleration is zero) and maximum velocity. The dynamic friction coefficient tends to increase as the normal load increases as well as the static friction coefficient (Δ to o). However, the correlation between the maximum velocity and the dynamic friction coefficient is not sharp in any cases and rock types. According to Reches & Lockner (2010), in rotary shear apparatus with high speed friction test, the dynamic friction coefficient decreases in the sliding velocity 10^{-2} m/s or less, and increase in the sliding velocity 10^{-1} m/s or higher. In the range of the sliding velocity 10^{-2}–10^{-1} m/s, the dynamic friction coefficient is in range of transition from decrease to increase, the dynamic friction coefficient remains almost unchanged. As the range of the maximum velocity obtained in this experiment is 10^{-2}–10^{-1} m/s and the dynamic friction coefficient remains almost constant, it is consistent with the above results.

4.2 *Relation between force drop and slippage*

Figure 8 shows the relation between recurrence time and force drop. The force drop increases as the recur-

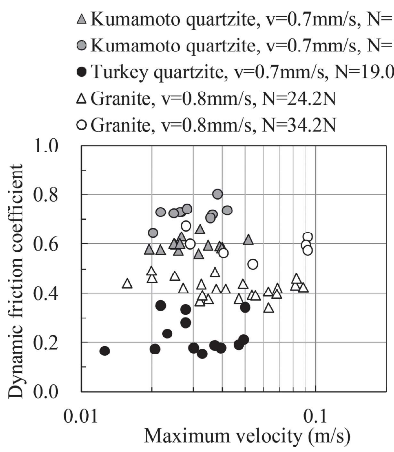

Figure 7. Relation between dynamic friction coefficient and maximum velocity.

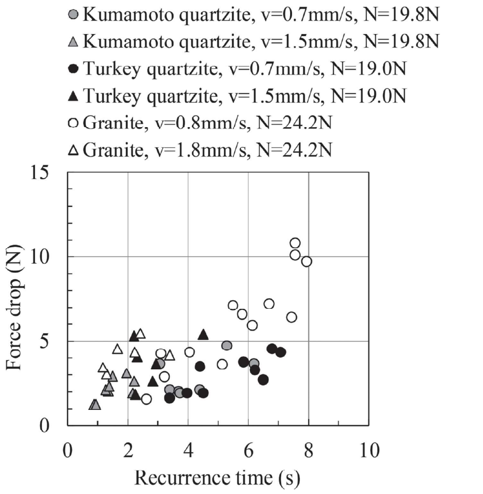

Figure 8. Relation between force drop and recurrence time.

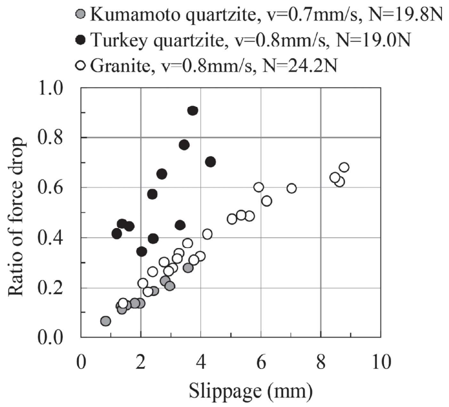

Figure 9. Relation between ratio of force drop and amount of slippage.

rence time increase in all case. Kanamori & Anderson (1975) and Molnar (1975) proposed that seismic moment increases with increase of recurrence time. Thus force drop is proportional to recurrence time as seismic moment is proportional to recurrence time. As for the difference of maximum velocity, the data group (Δ) is distributed in the lower left area in case the maximum velocity is fast because recurrence time is short, conversely the data group (o) is distributed in the upper right area in case, in which the maximum velocity is slow. In addition, as the force drop is determined by the difference between static friction coefficient and dynamic friction coefficient, the relation between the force drop of each rock type and the friction angle of the contact surface is not necessarily to be consistent.

As shown in Figure 6, since the static friction coefficient increases as the recurrence time increases, and the peak frictional force just before sliding also increases. As mentioned above, since the force drop increases as the recurrence time increases, the relation between the ratio of force drop (ratio of force drop and peak frictional force) and the slippage was also confirmed in Figure 9. The ratio of force drop is proportional to the amount of slippage in all conditions. Ohnaka (2003) proposed the relation between shear stress drop rate and frictional sliding as shown below;

$$\frac{\Delta\tau_b}{\tau_p} = \beta\left(\frac{D_c}{\lambda_c}\right)^M \tag{1}$$

where $\Delta\tau_b$ = shear stress drop; τ_p = peak shear strength; D_c = critical slip displacement (displacement amount required for stress drop); λ_c = Characteristic wavelength representing geometric roughness in friction surfaces; β and M are the non-dimensional parameters. When shear stress drop rate $\Delta\tau_b / \tau_p$ and critical slip displacement D_c in Equation (1) are substituted with force drop rate and amount of slippage in Figure 9, they are consistent with the relationship of Equation (1) and they have in a linear relationship. However, the inclination of the linearity is different for each rock type. This result is considered to be due to the roughness of the contact surface of each rock type and the influence of surface morphology, as critical slip displacement D_c is normalized by the characteristic wavelength in the Equation (1). However, these effects should be investigated in the future studies.

4.3 *Relations of slippage and velocity and acceleration*

Figures 10(a), (b) shows the relation between slippage, which is relative displacement during sliding, and maximum velocity/acceleration for stick-slip events of each rock type. As result, it is seen positive correlation between the slippage and the maximum velocity/acceleration of each rock type. Moreover, it is assumed that the maximum velocity and maximum acceleration have a positive correlation. These relations are consistent with the biaxial experimental results (Ohnaka 2003) as well as stick-slip experiments reported by Ohta & Aydan (2010). In this experiment, because we use an elastic spring, the force drop is proportional to the slippage. When slippage is substituted with force drop in Figure 10(a), the maximum velocity is proportional to the force drop. This relation is consistent with the result that is provided from past earthquake records (Kanamori & Anderson 1975).

As for the difference of the rock types, a correlation between the slippage and the maximum velocity is not clearly observed. In relation between slippage

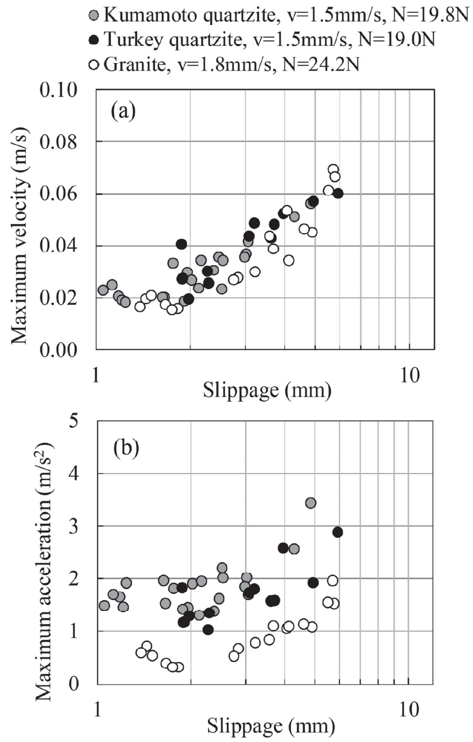

Figure 10. Relation of stick-slip response: (a) Maximum velocity versus slippage. (b) Maximum acceleration versus slippage.

and maximum acceleration, the maximum acceleration of the granite of the man-made surface is small, and the maximum acceleration of the Kumamoto quartzite is slightly increased in the natural schistosity surface. As these relationships are not consistent with the magnitude of the friction angle of contact surface of each rock type, the influence of the roughness and surface morphology of the contact surface should be also considered as described above.

5 CONCLUSIONS

In this study, the results of the stick-slip phenomenon which focused on the difference of the rock types were examined from the experimental results. and the following findings were obtained.The findings obtained from this study are summarized as follows:

1. The static friction coefficient becomes larger as the recurrence time becomes longer, and the magnitude of static friction coefficient of each rock type is consistent with the magnitude relationship of static friction angle obtained by tilting test.
2. The dynamic friction coefficient is not changed clearly in the range of the maximum velocity in this experiment.
3. The force drop becomes larger as the recurrence time becomes longer. However, the magnitude of the force drop of each rock type is not necessarily consistent with the friction angle of the contact surface.
4. The ratio of force drop is proportional to the amount of slippage. On the other hand, the inclination of the linear is different for each rock type.
5. The maximum velocity/acceleration is proportional to the amount of slippage. However, the magnitude of the maximum velocity/acceleration of each rock type is not necessarily consistent with the friction angle of the contact surface.

As described above, the results in this study were consistent with past stick-slip experiments, and the results were similar to the correlation of the obtained seismic parameters. It was also found that the difference of the rock types (i.e. the roughness of the contact surface and geometrical shape) affected the stick—slip phenomenon. In the future, we would like to evaluate the effect of the roughness of contact surface and geometrical shape.

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