2019 Rock Dynamics Summit– Aydan et al. (eds)
© 2019 Taylor & Francis Group, London, ISBN 978-0-367-34783-3

Experimental study of scale effect in rock discontinuities on stick-slip behavior

R. Kiyota & N. Iwata
Chuden Engineering Consultants, Hiroshima, Japan

Ömer Aydan & N. Tokashiki
University of the Ryukyus, Okinawa, Japan

ABSTRACT: The stick-slip phenomenon is used to explain 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 an experimental setup, in which blocks move on a conveyor belt and is restrained by the spring, and conducted stick-slip experiments. However, the amplitude of slippage and acceleration observed in these experiments were quite smaller than actual earthquakes. Therefore, a large-scale experimental device was improved to be able to experiment with a larger rock blocks, and the experiment which changed the size and the type of the rock blocks was conducted. In this study, the results of large-scale experimental device were compared with the results of previous experiments, and the scale effect of rock discontinuities on the stick-slip phenomenon was investigated.

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, and seismic moment and displacement accompanying the stress drop at the fault plane, 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, most were using the compression testing equipment in the past studies, amount of slippage was very small with 1μm-1mm 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 10cm-1m, peak acceleration of 1-10 m/s^2.

The authors have developed an experimental setup (50cm long), in which blocks move on a conveyor belt and is restrained by the spring, and conducted stick-slip experiments (Ohta & Aydan 2010, Iwata et al. 2016). 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. On the other hand, since the area of discontinuous surface is quite different in the actual earthquake fault and the specimen in the laboratory experiment, for the estimation and evaluation of ground motion and displacement in earthquake faults, it is necessary to consider the scale effect of them. However, there are studies on the scale effect of the shear strength and deformation characteristics of rock discontinuities (Yoshinaka et al. 2006), but there are few studies on the scale effect of the stick-slip behavior. Therefore, in order to confirm the scale effect of the contact surface, a larger scale experimental device was improved to be able to experiment with a larger rock blocks, and the experiment which changed the size of four types of rock blocks was conducted. In this paper, the results obtained from this experiment will be described, which examines the influence of the scale effect of the rock discontinuities on the stick-slip behavior and its factors.

2 OUTLINE OF THE EXPERIMENT

2.1 *Materials*

The rock types of the block used in this experiment are gabbro, granite, andesite and diorite rocks. The stick-slip experiment is carried out on the base block made of each rock type with the upper block of each rock type made so that the contact area is 100 cm ^{2}, 200 cm ^{2} and 300 cm ^{2}. Where, the contact area indicates the area of bottom of the upper block, it refers to the apparent contact area.

Figure 1 shows the contact surface of each rock type used in this experiment. The contact surface between upper and base block of gabbro and granite are man-made surfaces, and andesite and diorite are natural schistosity surfaces.

Table 1 shows the classification of the characteristics of the contact surfaces of the block of each rock type used in this experiment, by the roughness of discontinuous of the hard rock surface shown in JGS 3811-2011 (JGS 2013).

2.2 *Stick-slip experiment*

Figure 2 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. 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.

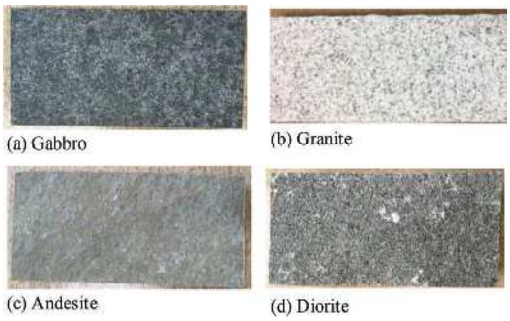

Figure 1. Contact surface of rock blocks.

Table 1. Classification of the characteristics of the contact surfaces by the roughness of hard rock discontinuous surface shown in JGS 3811-2011 (JGS 2013). Parentheses indicate the results of classifying the contact surfaces of rock blocks used in this experiment.

Small scale (10cm) / Large scale (1~2m)	Rough : r	Slightly rough : m	Smooth: s
Stepwise : s	r_{sr}	r_{sm}	r_{ss}
Wavy : w	r_{wr} (Diorite)	r_{wm} (Andesite)	r_{ws}
Planar : p	r_{pr}	r_{pm} (Granite)	r_{ps} (Gabbro)

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 upper 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 contact type displacementmeter attached to the frame. The measurement sampling interval was 5ms, 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 2, and the velocity of the conveyor belt and the normal load were changed. Where, the normal stress shown in Table 2 refers to the apparent normal stress, which is obtained by dividing the normal load (the weight of the upper block and the loaded weights) by the apparent contact area. The normal stresses are adjusted by the the loaded weight. The spring used is an elastic spring with a stiffness of 1.0 N/mm.

3 EXPERIMENTAL RESULTS

Figure 3 shows the time histories of spring force in each rock type and each block size. Figure 4 shows the cumulative slip amount of the upper block (base block displacement minus upper block displacement). The cumulative slip amount is zero when the upper and base blocks are moving on sticking, and is added when slippage occurs. Therefore, it is repeated that the spring force decreases with the

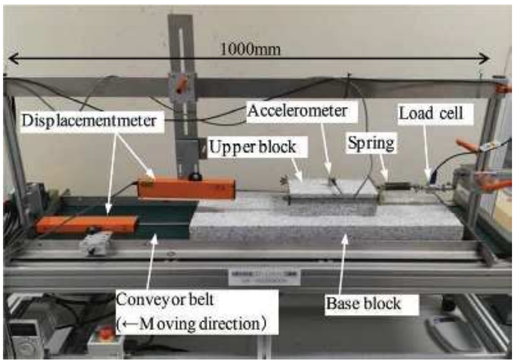

Figure 2. Stick-slip experimental setup.

Table 2. Stick-slip experimental conditions.

Rock types	Contact area (cm^2)	Normal stress σ_n (kPa)	Velocity of conveyor velt (mm/s)
Gabbro	100, 200	1.5, 2.0	0.5, 1.0, 1.5, 3.0
Granite	100, 200, 300	1.5	(for all rock types)
Andesite	100, 200, 300	1.5, 2.0	
Diorite	100, 200, 300	2.0	

increase of the cumulative slippage when the spring force reaches the peak load after only the spring force is increased in a state where the cumulative slippage is constant.

As shown in Figures 3, 4, the magnitude of the spring force and the slippage are different depending on the upper block size, i.e. contact area. In addition, the stick-slip behavior varies depending on the rock type, the recurrence time (the time from the end of the slip to the start of the next slip, stress accumulation time) becomes longer as the contact surface becomes rougher, and the change of the spring force before and after the slip (hereinafter referred to as the force drop) and the slippage tend to be large. Thus, it is considered that the state of asperity, such as the roughness of the contact surface shown in Table 1, influences the stick-slip behavior. Figures 3, 4 show the case where the moving speed of the conveyor belt is 1.0 mm/s, in this paper, the results of this case will be discussed.

4 DISCUSSION ON EXPERIMENTAL RESULTS

4.1 *Relation between friction coefficient and contact area*

In order to confirm the effect of the difference of contact area on stick-slip behavior, the friction coefficient (the ratio of the spring force and the normal load) is compared. Figure 5 shows the friction coefficient at the time of the peak load (spring force just before slipping), i.e. the static friction coefficient, for each contact area. As shown in Figures 5(a), (b), in the case of gabbro and granite where the contact surfaces are smooth or the entire surface is planar, the magnitude of the static friction coefficient is almost unchanged depending on the contact area. On the other hand, as shown in Figures 5(c), (d), in the case of andesite and diorite where the contact surfaces are rough or entire surface is wavy, the static friction coefficient sharply decreases in the range of $100cm^2$ to $200cm^2$ where the contact area is small, in the

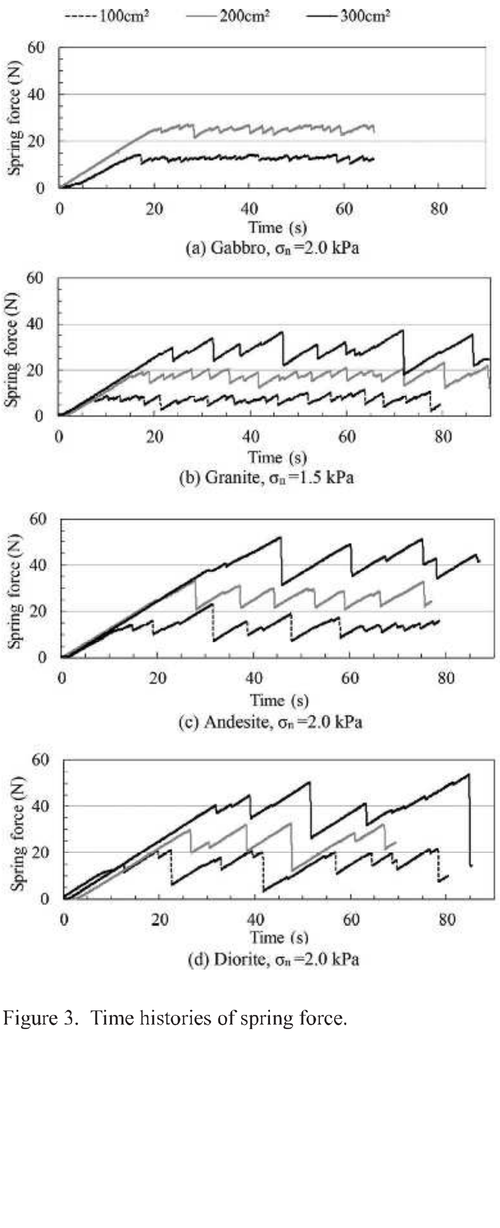

Figure 3. Time histories of spring force.

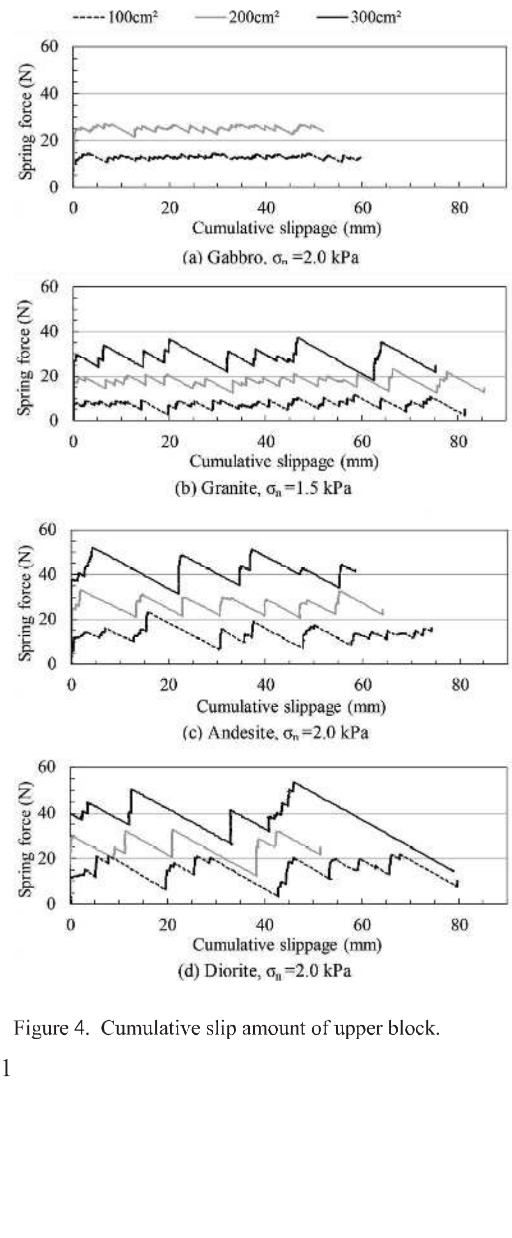

Figure 4. Cumulative slip amount of upper block.

range of 200cm^2 to 300cm^2, the change in static friction coefficient is small. Yoshinaka et al.(2006) confirmed that the shear resistance angle of the smooth surface of the saw-cut granite corresponds to the static friction angle and is no affected by the shear area, and that the peak shear strength of the fracture surface of granite which is man-made has a significant decrease due to the increase of the shear area in the small range of the shear area which is generally less than 1,000cm^2. The results of experiment in this study are almost consistent with the characteristics of the scale effect on the shear strength.

Figure 6 shows a conceptual diagram of the contact part of the discontinuous surface (Scholz, C. H. 2010). In the actual discontinuous surface, the contact area is only the area of the true contact area A_r of several asperities in the apparent contact area A, and

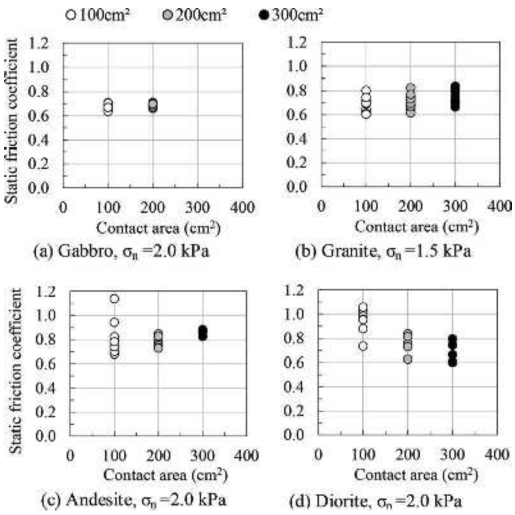

Figure 5. Relation between static friction coefficient and contact area.

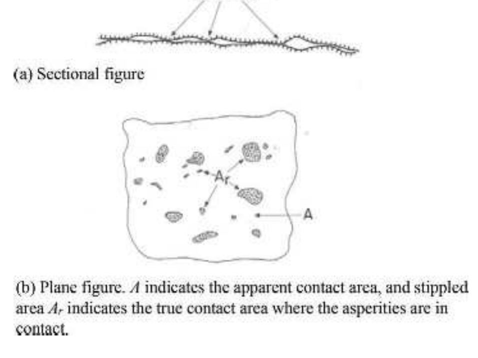

Figure 6. Conceptual diagram of the contact part of the discontinuous surface (Scholz, C. H. 2010).

the frictional force of the discontinuous surface is the sum of the shear strength of the true contact area A_r.

Figure 7 shows the contact part of the upper and base blocks of the gabbro and diorite. In the case of gabbro shown in Figure 7(a), both the upper and base blocks have a smooth surface and the entire surface is planar. Because variations in the shape of the contact surface is small, even if the apparent contact area A increases, the ratio of the true contact area A_r almost unchanged. Therefore, even if the apparent contact area A_r increases, the friction coefficient does not change. In the case of gabbro shown in Figures 7(b), (c), both the upper and base blocks have a rough surface and the entire surface is wavy with a long wavelength. In the case of contact area 100cm^2 shown in Figure 7(b), variations in the shape of the contact surface is large, and it becomes engaged condition when sticking, so that the ratio of the true contact area A_r becomes larger than the smooth surface. Therefore, the frictional force, i.e. the friction coefficient tends to be large. In the case of contact area 300cm^2 shown in Figure 7(c), due to the influence of the surface roughness and the wavelength of the entire surface shape, the upper and base block surfaces become hardly to contact. Thus, when the variations in the large and small wavelength of the contact surface shape is large, the ratio of a true contact area A_r tends to small when the apparent contact area A increases, and the friction coefficient decreases. However, when the apparent contact area A becomes further large and the shape wavelength of the entire surface contains a certain number of wavelengths within the apparent contact surface, even if the apparent contact area A increases, it is presumed that the ratio of the true contact area A_r hardly changes.

4.2 *Relations of slippage and velocity and acceleration*

Figures 8, 9 show the relation between slippage, which is relative displacement during sliding, and maximum velocity/acceleration for stick-slip events of each rock

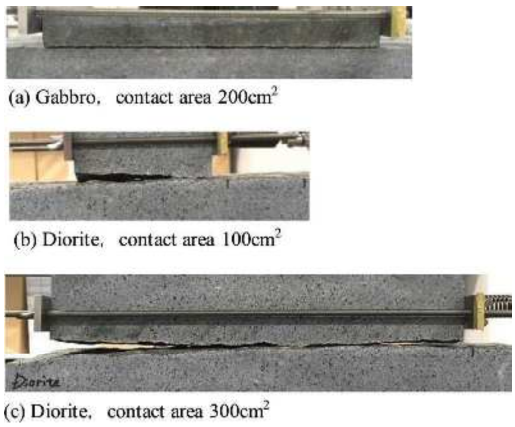

Figure 7. Contact condition of upper and base block.

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 by 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 as shown in Figure 4. When slippage is substituted with force drop in Figure 8, 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 contact area, a correlation between the slippage and the maximum velocity is not clearly observed. In the relation between slippage and maxi mum acceleration shown in Figure 9, as the contact surface becomes coarser, the variation of the relationship and the difference of the maximum acceleration due to the magnitude of the contact area become larger. The frictional force at the time of slipping can be described by the relationship between the friction coefficient of the contact surface and the normal load, and it can also be described from the relationship between the block weight and the acceleration from the motion equation. From the above, it is inferred that the maximum acceleration at the time of slipping is related to the characteristic due to the variation of the friction coefficient and the difference in the contact area shown in Figure 5.

4.3 *Relation between force drop and slippage*

Since the seismic moment is proportional to the amount of force drop on the fault surface (Kanamori & Anderson 1975, Molnar 1975), the characteristics of the force drop obtained in this experiment is confirmed. Figure 10 shows the relation between the ratio of force drop (ratio of force drop and frictional force) and the slippage for stick-slip events. The ratio of force drop is proportional to the amount of slippage in all conditions. It is also confirmed by the relation between the shear stress drop rate and the slip displacement amount in the frictional slip indicated by Ohnaka (2003) and from the past experimental results by Kiyota et al. (2018). In the case of Figure 10(a), (c), (d) with the same normal stress, the inclination of the linearity is almost the same for the same contact area. In addition, since the

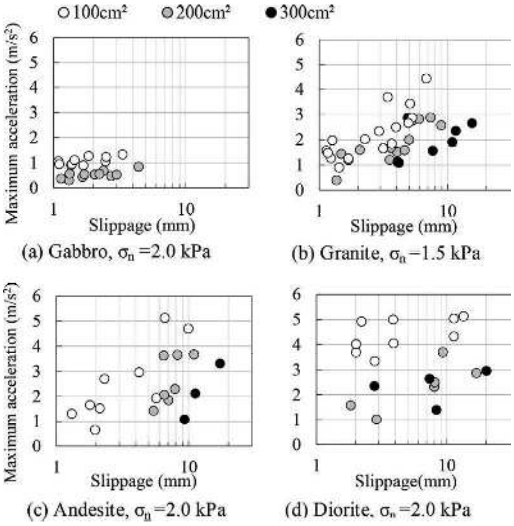

Figure 9. Relation between maximum acceleration and slippage for stick-slip events.

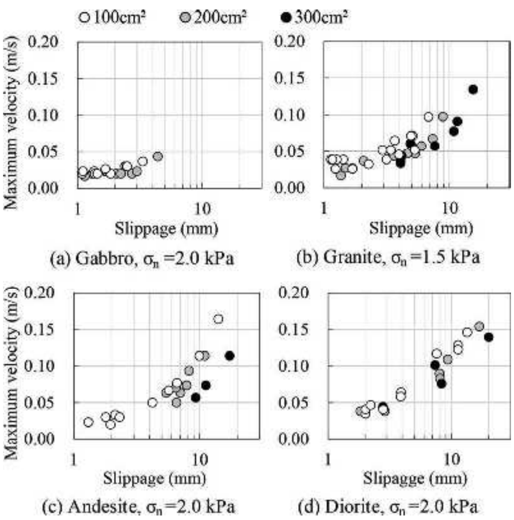

Figure 8. Relation between maximum velocity and slippage for stick-slip events.

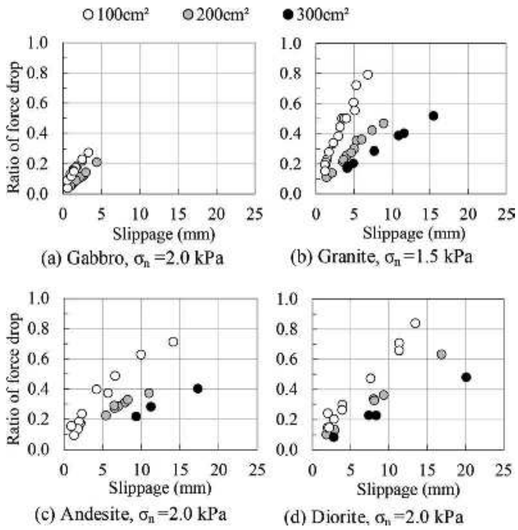

Figure 10. Relation between ratio of force drop and amount of slippage.

magnitude of the inclination of the linearity for each contact area within the same rock type is roughly the inverse ratio of the contact area in any rock type, the relationship between the ratio of force drop per unit area and the slip amount is uniform. Therefore, the relation between the ratio of force drop and the slippage is hardly influenced by the scale effect, and it is thought that it depends on the magnitude of the normal stress and the stiffness of the elastic spring.

5 CONCLUSIONS

In this study, in order to confirm the scale effect in the stick-slip behavior of rock discontinuities, a stick-slip experiment using rock blocks of different contact areas was conducted for four rock types. The findings obtained from this study are summarized as follows:

1. In the case where the contact surface is smooth or the entire surface is planar, the influence of the scale effect is small. On the other hand, In the case where the contact surface is rough or the entire surface is wavy, the friction coefficient significantly decreases with increase of the contact area in the range where contact area is small, and as the contact area becomes larger, the variation in the friction coefficient becomes smaller.
2. The maximum velocity and the maximum acceleration of the block at the time of sliding have a positive correlation with the amount of slippage. However, the influence of the scale effect on the maximum velocity is small regardless of the roughness of the contact surface. As for the maximum acceleration, as the contact surface is rough or the entire surface becomes wavy, the scale effect is more significant as well as the friction coefficient.
3. Although the amount of slippage and the force drop are in linear relation, the scale effect is small regardless of the roughness of the contact surface, and the inclination of the linear is determined by the normal stress and the stiffness of the spring.

As described above, in order to estimate the characteristics of the stick-slip phenomenon on the discontinuous rock surface, when the shape of the discontinuous rock surface is uniformly smooth and the variation is small, it is thought that it can be inferred by the experiment with the contact area of several $100cm^2$ as in this experiment. On the other hand, in the case where shape is complicated and there are many variations, it is desirable to evaluate the experimental results to some extent increase the contact area. However, since this study is a qualitative evaluation, we would like to evaluate the geometric shape and pattern of the contact surfaces quantitatively, and experiment and evaluate them with consideration. In the future, these findings are used for parameter setting of displacement and stress drop of fault plane in fault rupture simulations.

REFERENCES

Brace, W. F. & Byerlee, J. D. 1966. Stick-slip as a mechanism for earthquakes. *Science*, 153: 990–992.

Iwata, N., Takahashi, Y., Adachi, K., Aydan, Ö. & Tokashiki, N. 2016. Stick-slip behavior of rock discontinuities and its implications in the estimation of strong motions during earthquakes. *Proc. of the ISRM 9th Asian Rock Mechanics Symposium (ARMS9), Bali.*

JGS (The Japanese Geotechnical Society). 2013. Method for engineering clasification of rock mass, JGS3811–2011. *Japanese Standards and Explanations of Geotechnical and Geoenvironmental Investigation Methods*: 60–76.

Kanamori, H. & Anderson D.L. 1975. Theoretical basis of some empirical relations in seismology. *Bull. Seism. Soc. Am.*, 65(5): 1073–1095.

Kiyota, R., Iwata, N., Takahashi, Y., Adachi, K. & Aydan, Ö. 2018. Stick-slip behavior of rock discontinuities by difference in rock types. *Proc. of the 3rd International Confrence on Rock Dynamics and Applications (RocDyn-3), Trondheim*: 563–568.

Molnar, P. 1975. Earthquake recurrence intervals and plate tectonics. *Bull. Seism. Soc. Am.*, 69(1): 115–133.

Ohta, Y. & Aydan, Ö. 2010. The dynamic responses of geomaterials during fracturing and slippage. *Rock Mechanics and Rock Engineering*, Vol.43, No.6: 727–740.

Ohnaka, M. 2003. A constitutive scaling law and a unified comprehension for frictional slip failure, shear fracture of intact rock, and earthquake rupture. *J. Geophys. Res.*, 108(B2): 6-1-21.

Scholz, C. H. 2010. *The mechanics of earthquakes and faulting. 2nd edition*, Kokon shoin: 51–97.

Yoshinka, R., Yoshida, J., Sasaki, T. & Sasaki, K. 2006. Evaluation of mechanical design parameters of rock discontinuities considering scale effect. *Journal of Japan Society of Civil Engineers, Ser. C*, Vol.62, No.2: 457–470 (in Japanese).