

Rupture sequence with single and double events in a laboratory experiment

Shingo Yoshida and Aitaro Kato

Earthquake Research Institute, University of Tokyo, Tokyo, Japan (shingo@eri.u-tokyo.ac.jp)

Abstract

Stick slip experiments were performed in a direct shear apparatus using large Inada granite blocks. The dimensions of the pre-existing fault surface were 100 cm (length) \times 10cm (width). By applying heterogeneous normal stress using three actuators of which forces could be independently controlled, two asperities with different strengths were formed on a fault plane. Under a certain normal stress distribution, single asperity failure and double asperity failure occurred alternately. The single asperity failure refers to a stick slip event in which a weaker asperity ruptures alone, without triggering the rupture of a stronger asperity. The double asperity failure is an event in which a rupture of a weak asperity triggers the rupture of a strong asperity, resulting in a failure of the whole fault. For triggering of a rupture, it is necessary that stress at the strong asperity is accumulated to a certain level just prior to the failure of the weak asperity.

Introduction

The size of large earthquakes that occur in subduction zones is strongly affected by asperity distribution. It is known that the dimensions of the ruptured area sometimes vary during successive earthquake cycles in the same subduction zone. If asperity continues to exist in the same location with the same dimension over several earthquake cycles, the dimension of the ruptured area should be determined mainly by the number of asperities that rupture during the earthquake. Recently, such an idea has been supported by several studies on the rupture processes of large earthquakes. Nagai and Kikuchi [1999] studied the rupture process of the 1968 Tokachi-oki earthquake (M7.9) and the 1994 Sanriku-haruka-oki earthquake (M7.5) by waveform inversion and found that the asperity that ruptured during the Sanriku-haruka-oki was identical to one of the asperities that broke during the 1968 Tokachi-oki earthquake.

The observation implies that when asperities are distributed on a fault plane, sometimes one asperity ruptures during an earthquake, and during other earthquakes two or more asperities rupture. This raises the question of what physical conditions determine whether the rupture is confined to one asperity or propagates over two or more asperities. Is it impossible to predict the final size of the rupture before the rupture starts? It is difficult to address this phenomenon by means of laboratory experiments, because the pre-existing fault surface is not sufficiently large in ordinary biaxial tests, and consequently, slip almost always occurs on a whole fault ; i.e., it is not confined to a particular area. Little data is available for confined slip events in large scale tests [e.g., Dieterich, 1981]. Mogi and Mochizuki [1990] developed a large biaxial apparatus, in which slip occurs along pre-existing large faults in a double-direct shear configuration under heterogeneous normal stress distribution controlled by three independent actuators. A confined slip event is expected to occur in this apparatus. Using this apparatus, we conducted laboratory experiments to study the interaction of adjacent asperities under heterogeneous normal stress distribution. We also discuss whether there is a correlation between a magnitude of precursory slip and a final earthquake size.

Experimental Procedure

Mogi and Mochizuki [1990] developed a large biaxial apparatus in which slip occurs along two pre-existing large faults, each 100 cm in length by 10 cm in width, in a double-direct shear configuration (Figure 1). One of the advantages of this apparatus is its large size, and another advantage is that it allows us to control three independent actuators for applying a normal force to the fault planes. Therefore, we can produce heterogeneous normal stress distribution on the fault planes. Using this biaxial apparatus, we conducted a series of stick-slip tests at a constant displacement rate of $0.6 \mu\text{m/s}$ under various normal stress distributions with Inada granite in order to study the interaction of asperities.

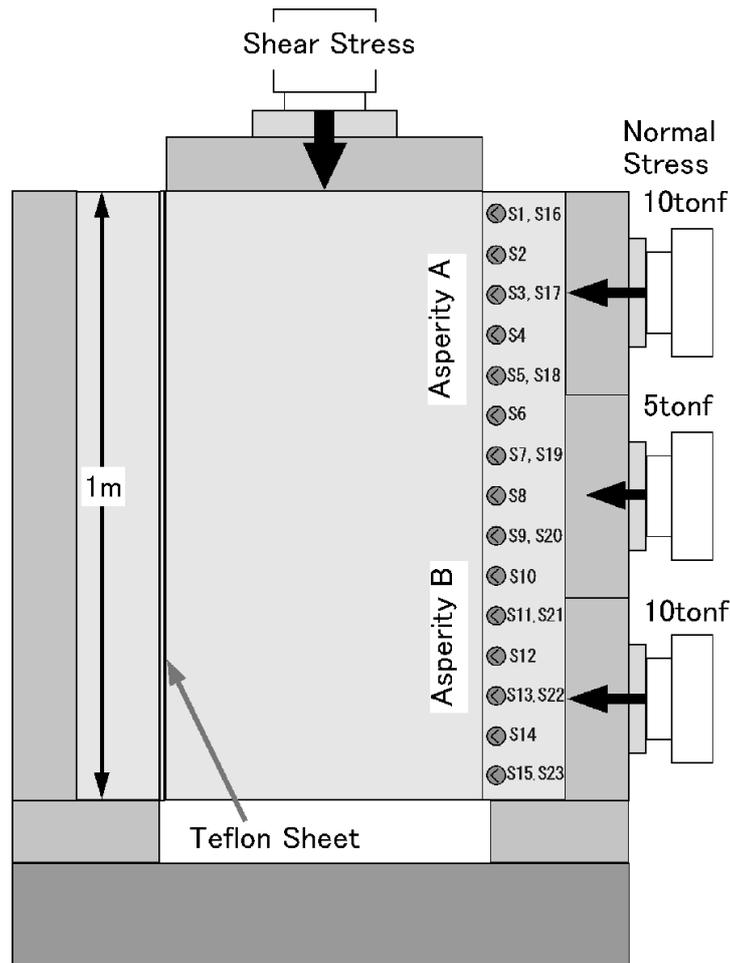


Figure 1: Diagram of apparatus and sample assembly (map view). The sliding surface is 100 cm in length by 10 cm in width. 15 strain gauges (S1-S15) are mounted on the top face along the fault, and 8 strain gauges (S16-S23) are mounted on the bottom face.

Even if the loading forces applied by the three actuators are set to be equal, the normal stress has a heterogeneous distribution as a result of geometric roughness with a long wavelength of the fault surface. By adjusting the normal force distribution, we can control the intensity of the heterogeneity.

As we focus on the interaction between asperities distributed on one fault, a Teflon sheet with a low frictional strength is inserted along the untargeted fault to prevent this fault from influencing the target fault. In this system, the three granite blocks were set horizontally. Shear strain gauges were mounted on the top and bottom faces of the outer block along the target sliding surface in order to observe the local strain as a function of time and position. We mounted 15 strain gauges

on the upper surface at 65 mm intervals, and 8 gauges on the bottom surface at 130 mm intervals, as shown in Fig.1.

Experimental Results

Single event and double event

When we set the normal forces to be 10, 5, and 10 tonf, two asperities (asperity A and asperity B) are formed, separated by a weakly coupled area (Fig.2). Because the fault surface is not completely flat, the two asperities have different frictional strengths.

The time histories of the local shear strains at a sampling frequency of 10 Hz are shown in Fig. 2. We found that a single asperity failure and a double asperity failure alternatively occurred. For example, at $t=1472$ s, indicated by the arrow labeled "Single Event" in Fig.2, a dynamic stress drop occurs at asperity B, while the stress suddenly increases at asperity A. This means that the slip occurs at asperity B, and the dynamic rupture propagation is stopped by asperity A, which plays the role of a barrier. We will hereafter refer to this event as "single asperity failure" or "single event". For comparison, at $t = 1508$ s, indicated by the arrow labeled "Double Event", a dynamic stress drop occurs over a whole fault. This event will be referred to as "double asperity failure" or "double event", in which both asperity A and asperity B break. From the strain change recorded at a sampling frequency of 1 kHz (not shown), we found that the stress drop at asperity B occurred slightly earlier than that at asperity A, implying that the rupture of asperity B triggered the rupture of asperity A during the double event.

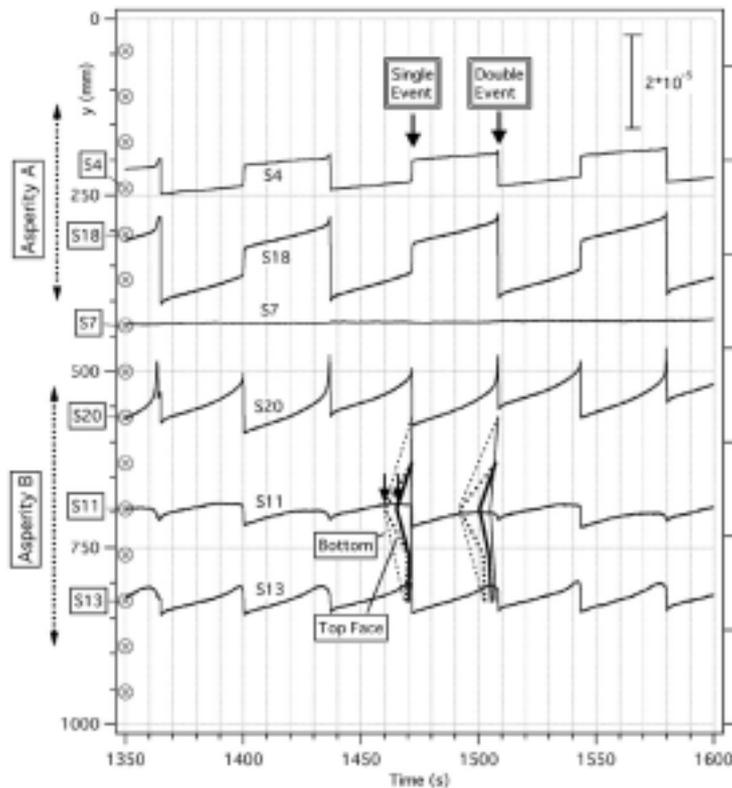


Figure 2: Local shear strain changes. Double events (in which asperity A and B rupture) and single events (in which asperity B ruptures without triggering the rupture of asperity A) occur alternatively. The broken line indicates the time at which the strain change deviates from elastic change, and the solid line indicates the time of peak shear strain, for the top surface (thick lines) and for the bottom surface (thin lines).

The single and double events cyclically occurred. The asperity distribution depends on geometric roughness with a long wavelength of the fault surface. Because the size of the asperity is much longer than the slip displacement during an event (on the order of 10^{-5} m), the position of the two asperities did not vary over several cycles.

Regarding the physical conditions that determine whether a single or double event occurs (i.e., the final rupture size), the most important factor is the accumulated stress level at asperity A at the time of rupture of asperity B. If the stress is accumulated to a certain level at strong asperity A, rupture of weak asperity B can trigger a rupture of strong asperity, resulting in a double event. In contrast, if the accumulated stress level at asperity A is not relatively high, asperity A can sustain the sudden increase of stress produced by rupture of asperity B, and therefore a single event occurs.

We carried out another test, in which we decreased the normal force applied to asperity A to be 8 tonf in order to reduce the strength of asperity A. Under this condition, double events occurred without single event occurrence. A rupture of asperity A was always triggered by a rupture of asperity B. For uni-mode cycle in which a only double event occurs, the strength difference between the two asperities is smaller. Because the strength of asperity A is low, asperity A cannot become a barrier to stop the rupture propagation from asperity B.

Nucleation process

In Fig. 2, the broken line indicates the time at which the strain change deviates from elastic change, and the solid line indicates the time of peak shear strain. They express the rupture nucleation zone, which grows at the weak asperity. Pre-slip occurs during the rupture nucleation process [e.g., Ohnaka and Kuwahara, 1990]. Figure 3 shows the quasi-static shear strain decrease during the nucleation process for the single event and for the double event. If we can assume that the larger pre-slip produces the larger strain decrease, Fig. 3 suggests that the seismic moment released before the double event is slightly larger than that for the single event. The pre-slip at weak asperity may be affected by stress level at an adjacent strong asperity. When the stress level averaged over a whole fault is high, larger pre-slip may occur.

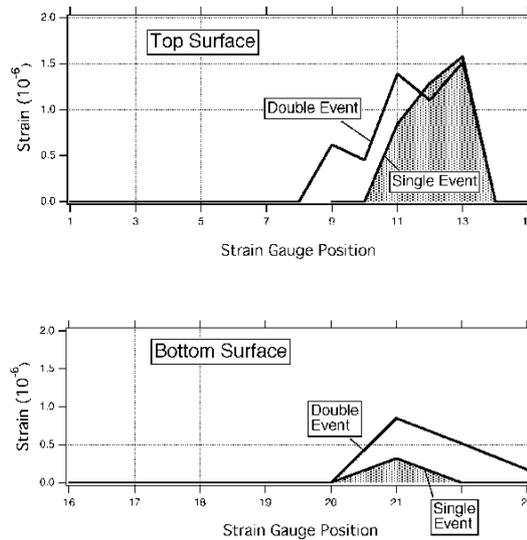


Figure 3: Comparison of nucleations before double event and before single event. Quasi-static stress drops during the nucleation process are shown. Larger nucleation appears before the double event than before the single event.

Both final event size and the magnitude of pre-slip appearing around a weaker asperity may be controlled by the stress accumulated at an adjacent stronger asperity. In this case, there could ap-

pear a correlation between the final event size and the magnitude of the precursory slip. Further study is needed to understand the underlying physics causing such a phenomenon.

Summary

In the present study, two asperities with different strengths were generated as a result of geometric roughness with a long wavelength of the fault surface, and of heterogeneous normal stress distribution. The positions of the asperities did not vary during the cycles of several events. The experimental results demonstrated that single asperity failure and double asperity failure occur alternately when the strength of one asperity is sufficiently higher than that of the other asperity. The accumulated stress level at the stronger asperity determines whether a single or double event will occur. For the triggering of a rupture, it is necessary that stress at the strong asperity accumulate to a certain level just prior to the failure of the weak asperity. If insufficient stress is accumulated, the strong asperity will not be ruptured, resulting in a single event.

References

- [1] Dieterich, J., 1981, Potential for geophysical experiments in large scale tests, *Geophys. Res. Lett.* 8, 653-656.
- [2] Nagai, R., and M. Kikuchi, 1999, Comparison of the source process of the 1968 Tokachi-Oki and the 1994 Sanriku-Haruka-Oki earthquakes, *Progr. Abstr. seism. Soc. Jpn*, P071.
- [3] Ohnaka, M., and Y. Kuwahara, 1990, Characteristic features of local breakdown near a crack-tip in the transition zone from nucleation to unstable rupture during stick-slip shear failure, *Tectonophysics*, 175, 197-220.
- [4] Mogi, K. and H. Mochizuki, 1990, Measurements of precursory strains prior to sudden slips along a heterogeneous artificial fault using a new double-shear type loading machine, *extended absts, International symposium on earthquake source physics and earthquake precursors, Tokyo*, 43-47.