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Acoustic monitoring of internal state of faults with gouge affected by slip and loading history

K. Nagata, M. Nakatani and S. Yoshida

Earthquake Research Institute of Tokyo University, 1-1-1 Yayoi, Bunkyo, Tokyo, Japan
(nagata@eri.u-tokyo.ac.jp / Fax: +81 03-5689-7234)

The internal state of faults, which controls fault strength, varies within an earthquake cycle. It is generally accepted that the strength decreases with slip on the fault (slip-weakening) and increases after the slip (healing), due to the variation of fault state. Recently, an acoustic technique to monitor such changes of fault state by measuring acoustic transmissivity of the fault is developing in laboratories. A stick-slip experiment of *Chen et al.* [Int. J. Rock Mech. Min. Sci. Geomech. Abst., 1993] showed that the amplitude of acoustic waves transmitted through an interface between two rough solid surfaces increases during stick period and decreases upon slip. *Yoshioka and Iwasa* [Tectonophysics, 2006] reported that the increase of amplitude is proportional to the logarithm of stationary contact time, presumably due to the increase in real contact area of the interface. *Nagata et al*. [EOS Trans. AGU, 2006] showed that these changes of amplitude are well related to frictional strength, which is considered to be proportional to real contact area [e.g. Dieterich and Kilgore, PAGEOPH, 1994], throughout complex slip history. These studies suggest the possibility of monitoring temporal change of fault strength by observing amplitude of seismic waves transmitted through or reflected by the fault. However, all the studies above are on interfaces between two bare surfaces, while natural faults usually contain a layer of crushed rock (gouge). Although an experiment of Yoshioka [EOS Trans. AGU, 2004] was performed on a gouge layer and showed that the acoustic transmissivity changes with shear loading and dramatically decreases with a miniscule precursory slip, the applied normal stress in the experiment was very low (a few kPa). We present here how acoustic transmissivity of a simulated gouge layer changes in slide-hold-slide experiments

under some normal stresses up to 10 MPa.

The experiments were performed on layers of simulated fault gouge (crushed quarts powder) in a double-direct shear apparatus. We continuously measured the amplitude of acoustic waves transmitted through the slip interfaces. Since the wavelength in the bulk medium (5 mm for P wave, 3mm for S wave) is much longer than the gouge-layer thickness ($<$0.5mm), the macroscopic acoustic property comparable to frictional strength can be observed. The change in the thickness of the gouge layer was also measured in the experiments.

In the hold period, where shear stress was reduced from steady-state sliding and kept constant, the transmitted amplitude increased in two ways. First, it increased instantly with the reduction of shear stress. Second, it increased proportionally to the logarithm of the hold time. The increase in the amplitude with shear stress is corresponding to that of frictional strength observed as peak stress during reloading phase after hold period [*Nakatani*, JGR, 1998]. Although time-dependent increase of frictional strength was observed only when the reduction of shear stress was small, that of amplitude was observed regardless of the shear stress. This is probably because the mechanical coupling in the gouge layer obtained by the time-dependent strengthening had been lost with miniscule slip before stress reached its peak as observed with the amplitude. This fast decrease of the amplitude during reloading phase seems to be less affected by shear stress itself. In the stable sliding period after peak stress, the amplitude decreased with slip to steady-state level in the same manner as frictional strength. These results suggest that the changes of acoustic transmissivity reflect mechanical state of fault, which controls its strength, even when the fault contains a gouge layer. The measurement of the gouge-layer thickness, which changes similarly to those of the transmitted amplitude, supports the suggestion although the sensitivity of the amplitude on the thickness seems to be different for the mechanisms to change them, i.e. stress-dependent and time-dependent mechanisms.