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Influence of slip rate on the evolution of permeability in simulated fault rocks

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Fluid transport properties in fault zones are important parameter to understand dynamic slip mechanism of the fault zone and pore pressure fluctuations observed near surface during earthquake. Permeability is the dominant property that affects the generation of fluid pressure in the fault zone during the earthquake, and it can be dramatically changed by the fracture generation and shear deformation at a high slip rate. Evolution process of permeability had been previously investigated under low strain rate and low slip velocity in laboratory experiments, though permeability evolution at high slip rate is not well understood. In this study, we carried out friction tests at slow to high slip rates. Then we measured permeability and elastic velocity of rock samples used for friction tests. In addition, we observed deformation structures in the micro-focus CT system and thin sections.

We used Berea Sandstone (porosity = 20-22%), Indian Sandstone (14-15%), and Aji Granite (1%) in our experiments. Friction tests were performed by using the rotary-shear testing apparatus. A pair of cylinders of 25 mm diameter was sheared, and Teflon sleeve was used to cover the simulated fault plane to prevent newly formed gouge materials from leaking. In all tests, we applied a constant normal stress of 2 MPa, and samples were rotated to 2 m of total slip displacement. We applied a constant slip velocity from 0.13 mm/s to 1300 mm/s. Elastic velocity was measured at atmospheric pressure by the instrument for the ultrasonic wave velocity measurement of rock samples. Permeability was measured at high confining pressure of 5 to 120 MPa and fluid pressure of 0 to 2 MPa. Distilled water was used as the pore fluid, and the transient pore pressure pulse method and the steady state flow method are used to evaluate the permeability.

Friction coefficient gradually reduced with slip displacement in a low slip rate, though, unstable friction that fluctuated rapidly is observed above slip rate of 0.4 m/s. Friction is reduced with an increase of slip rate in all rocks. Permeability in Berea sandstone decreased as slip rate increased, and the permeability decreased by 1 order of magnitude ($5*10^{-15}$ m^2 at 10 MPa) from initial permeability ($4*10^{-14}$ m^2). Permeabilities in India sandstone and Aji granite did not change below slip rate of 0.1m/s, though the sharp increase of permeability was observed at high slip rate. Permeability in India sandstone increased by 5 times after high velocity test from $2*10^{-17}$ m^2 to 10^{-17} m^2, and that in Aji granite increased by 3 orders of magnitude from $4*10^{-20}$ m^2 to $4*10^{-17}$ m^2. P wave velocity in Aji granite decreased with an increase of slip velocity, and the other rocks did not show velocity dependence on the P wave velocity. Fine grained gouge layer was formed at slip surface in all specimens and the thickness of the gouge zone was increased with an increase of slip velocity. Fractures were clearly observed in micro-XCT images in host rocks at the slip velocity above 0.4 m/s.

Slip velocity dependence on the permeability may be related to the formation of gouge and fractures. In Berea Sandstone, newly formed gouge layers might have reduced bulk permeability, and newly formed fractures generated permeability in Indian Sandstone and Aji Granite. Gouge layers are developed in Indian sandstone and Granite, they did not influence on net permeability change because permeability of gouge layer might be similar to that of host rock. Our results imply that the permeability of the fault zone will decrease during earthquake if the initial permeability is high, and impermeable fault rocks may show rapid increase in permeability at high slip rate. Thermal pressurization, which is one of the fault weakening mechanisms, had thought to be effective in impermeable fault zones, though our results suggest that this weakening process may become ineffective due to sharp increase of permeability at high slip rate.