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Effect of fluids on dynamic fault motion during large earthquakes; where we are and where to go?

T. Shimamoto (1), C. A. J. Wibberley (2), K. Mizoguchi (1) and H. Noda (1)

(1) Division of Earth and Planetary Sciences, Graduate School of Science, Kyoto University, Kitashirakawa-oiwakecho, Kyoto, 606-8502 Japan
(shima@kueps.kyoto-u.ac.jp/fax.81-75-753-4189)

(2) Department of Geosciences, University of Nice-Sophia Antipolis, 250, rue A. Einstein, 06560 Valbonne, France.

High-velocity friction of faults, i.e., frictional properties of faults at high velocities and large displacements, have been receiving increasing attention in order to understand what controls dynamic fault motion during large earthquakes. High-velocity friction is highly nonlinear for which frictional heating plays crucial role and past slip history determines current frictional properties. Recent progress in high-velocity friction studies on (1) frictional melting, (2) thermal pressurization and (3) high-velocity weakening of fault gouge are rapidly filling the gap between field/laboratory studies on faults and seismological/geodetic studies on earthquakes. Permeability and concentration of shearing deformation within fault zones determine relative significance of those processes. Physical processes during frictional melting are now understood reasonably well [Hirose and Shimamoto, 2002], and the frictional melting problem have been solved as a Stefan problem with moving boundaries [Satomi and Shirono, 2003, 2004; Matsuzawa and Takeo, 2004]. In this presentation, I will focus on the later two problems with an emphasis on the effects of fluids on the dynamic fault motion.

A very important advancement was made by Wibberley who has shown that thermal pressurization analyses based on measured transport properties of a MTL fault zone in Mie, Japan, yields slip weakening distance, D_c, of the same order of value as that determined seismically. Analysis was further refined by Noda who has solved, in collaboration with J. Andrews, dynamic rupture propagation incorporating thermal pressurization. On the other hand, Mozoguchi conducted first high-velocity gouge experiments using a rotary-shear testing machine at slip rates to 1 m/s and demonstrated

dramatic weakening of fault gouge at high velocities. The initial frictional coefficient of 0.6 to 0.8 for Nojima fault gouge reduces down to around 0.2 at high slip rates and large displacements. He further combined this gouge behavior with thermal pressurization analysis and demonstrated that slip-weakening behavior of a fault is determined primarily by thermal pressurization when permeability is below about 10^{-18} m^2. However, when permeability is greater than about 10^{-16} m^2, both transport and slip-weakening properties of a fault affect the gross slip-weakening behavior. Thus, mechanical behavior of a fault at high slip rates must be predicted by combining the high velocity weakening of gouge and thermal pressurization process.

Our group at Kyoto University has now accumulated data on transport properties of about 10 fault zones which shows considerable variation of fault-zone permeability, but a common feature is that the combined analysis is needed at shallow portions above a few to several kilometers. Thermal pressurization appears to dictate fault properties below these depths, but a big uncertainty is the transport properties of cohesive fault rocks at depths. If permeability of cohesive fault rocks, expected at great depths, increases dramatically at the initiation of fault slip as in the case of fracturing of intact rocks, thermal pressurization process might become less effective again towards greater depths. Thus, the effects of large shearing deformation on the transport properties of cohesive fault rocks need to be studied in the future for the final evaluation of thermal pressurization at great depths. Also, tribochemical effects on high-velocity friction, i.e., the effects of interfacial chemical changes promoted by frictional heating under fluid-rich environments, are very important area for future systematic studies. Despite these unexplored areas, seismic fault motion is being predicted now based on the measured properties on fault zones. The transition from ordinary friction to high-velocity friction, poorly explored at present, should control the nucleation phase of earthquakes. Thus for earthquake prediction studies, this is probably the most important area for systematic studies in the near future.