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Fault Constitutive Laws and Earthquake Generation Processes

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In the last decade, there has been great progress in the physics of earthquake generation; that is, the introduction of laboratory-based fault constitutive laws as a basic equation governing earthquake rupture and quantitative description of tectonic loading driven by plate motion. The fault constitutive law plays the role of an interface between microscopic processes in fault zones and macroscopic processes of a fault system, and the plate motion connects diverse crustal activities with mantle dynamics. An ambitious challenge for us is to develop realistic computer simulation models for the entire earthquake generation process on the basis of micro-physics in fault zones and macro-dynamics in the crust-mantle system.

In general, the earthquake generation cycle consists of tectonic loading due to relative plate motion, quasi-static rupture nucleation, dynamic rupture propagation and stop, and restoration of fault strength. The process of earthquake generation cycle is essentially governed by a coupled nonlinear system, consisting of elastic and viscoelastic slip-response functions that relate fault slip with stress changes in surrounding media and fault constitutive laws that govern the progress of seismic and aseismic slip on faults. The driving force of this system is relative plate motion.

At present we have two different types of laboratory-based constitutive laws, one of which is the slip-dependent law (Ohnaka et al., 1987; Matsu'ura et al., 1992), and another is the rate- and state-dependent law (Dieterich, 1979; Ruina, 1983). So far these two constitutive laws have been regarded as incompatible concepts. Actually, they are complements each of the other, because the slip-dependent law is based on rather high slip-rate experiments, while the rate- and state-dependent law is based on very low slip-rate experiments. Recently, by integrating the microscopic effects of abrasion and adhesion of rock surfaces in contact, Aochi and Matsu'ura (1999, 2002) succeeded in deriving a slip- and time-dependent fault constitutive law that rationally unifies the slip-dependent law and the rate- and state-dependent law. This can be regarded as generalization of the slip-weakening type of fault constitutive law derived by Matsu'ura et al (1992).

In the slip- and time-dependent fault constitutive law the slip weakening results from the abrasion of surface asperities that proceeds irreversibly with fault slip. On the other hand, the restoration of shear strength after the arrest of faulting results from the adhesion of surface asperities that proceeds with contact time. At the limit of high slip-rate the unified constitutive law is reduced to the slip-weakening law. At the limit of low slip-rate it shows the log t strengthening of faults over the wide range of contact time t. In the steady state with a constant slip-rate V, the shear strength has the negative log V dependence, known as the velocity weakening. Another interesting property that expected from the unified constitutive law is the gradual increase of the critical weakening displacement Dc with stationary contact time. Since Dc has a linear dependence on the upper fractal limit of fault surfaces, the gradual increase of Dc means the gradual increase of the upper fractal limit associated with the restoration of fault surfaces to the original fractal structure in the order of increasing wavelength. From the analysis of stick-slip experiments and seismological observations with a theoretical model of rupture nucleation, Shibazaki and Matsu'ura (1998) have pointed out that actual faults have a hierarchic fractal structure characterized by a scale-dependent Dc. The slip- and time-dependent constitutive law suggests that such a hierarchic fractal structure of faults will be destroyed by the sudden occurrence of earthquake rupture and gradually restored with time during the inter-seismic period.