
Summary of Session 4.2:

Physical scale dependencies, observed scaling relations and simulation

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The earthquake rupture, or more generally, rupture phenomena themselves are inherently scale-dependent, so that the scale dependency is of critical importance for physical modeling and simulation of a large earthquake, and eventual modeling for earthquake prediction. The major issues discussed in the session were:

1. how scale-dependent physical quantities are scaled in terms of the underlying physics,
2. how earthquakes are prescribed by geometric and structural properties of the seismogenic layer and the fault zone, and
3. how large earthquakes are distinguished from small earthquakes.

The main outcomes of the session are summarized below. The issue of how scale-dependent physical quantities are scaled in terms of the underlying physics is a key to quantitative modeling and simulation of the earthquake generation process. To solve this problem, we first of all need to know whether or not the earthquake rupture is governed by any constitutive law. If the earthquake rupture is governed by a constitutive law, then it must be addressed how the governing law should be formulated. It has been demonstrated that laboratory-scale shear rupture is governed by a constitutive law. Ohnaka emphasized that the constitutive law for earthquake rupture should be formulated as a unifying constitutive law that governs both frictional slip failure and shear fracture of intact rock mass, because earthquake rupture is a mixed process between what is called frictional slip failure and fracture of intact rock mass. He also emphasized that the law should be formulated so as to scale scale-dependent physical quantities inherent in the rupture consistently, and thereby a unified comprehension should be provided for shear rupture of any size scale - small scale in the laboratory to large scale in the Earth as an earthquake source. Dieterich discussed how the earthquake rupture nucleation zone size can be scaled in terms of the rate and state dependent constitutive law, and he showed a numerical simulation result of earthquake sequences of foreshocks, mainshock, and aftershocks to explain patterns of earthquake clustering such as foreshocks and aftershocks. Ohnaka showed that scale-dependent physical quantities inherent in the rupture, including the nucleation zone size, are scaled consistently in terms of the

governing law if the governing constitutive law for earthquake rupture is formulated as a slip-dependent law. Shaw discussed the constraints a number of earthquake behaviors place on earthquake physics, together with modeling efforts being done to try to simulate realistic earthquake behavior. He also discussed how data assimilation in the context of the physics of earthquakes could work.

The issue of how earthquakes are prescribed by geometric and structural properties of the seismogenic layer and the fault zone was addressed by Aki, and Fujii & Matsu'ura. The seismogenic layer and the fault zone include characteristic lengths of various scales departed from the self-similarity. The depth of seismogenic layer, fault segment size, fault zone thickness, barrier or asperity size are representative examples of such characteristic length scales. For instance, if large earthquakes which result in the rupture over the entire depth of seismogenic layer are compared with small earthquakes that end up as local rupture within the seismogenic layer, it is easily understood that earthquakes are prescribed by the depth of seismogenic layer. In fact, Fujii & Matsu'ura showed that the seismic moment of inter-plate large earthquakes (that resulted in the rupture over the entire depth of seismogenic layer) obey a scaling law different from the scaling law for the moment of intra-plate smaller earthquakes (that ended up as local rupture within the seismogenic layer). Aki pointed out that there are a range of characteristic length scales between the fault zone thickness and the depth of seismogenic layer. The fault zone thickness has been estimated from guided wave as a few hundred meters in California, and the depth of seismogenic layer has been estimated to be roughly 15 km. Aki showed that observed scaling relations are well explained in terms of these characteristic length scales; for instance, f_{\max} of source origin is prescribed by the fault zone thickness. He discussed that there is a minimum characteristic size of earthquake, whose magnitude is 5, in the San Andreas fault in California, and that the minimum characteristic earthquake size of magnitude 5 results from a few hundred meter fault zone thickness in California. This fact coincides with the finding by Knopoff & Lee that a magnitude distribution for mainshock earthquakes of magnitude greater than roughly 5 does not exhibit the self-similarity.

The issue of how large earthquakes are distinguished from small earthquakes is closely related to the issues summarized above. As discussed by Aki and Ohnaka, a large earthquake is prescribed by a large characteristic length scale, while a small earthquake is prescribed by a small characteristic length scale. However, there is a persistent idea that earthquake phenomena in general are explained by self-organized criticality. To what extent this idea is correct and whether or not the self-organized criticality is applicable to large earthquakes, therefore, need to be closely checked. From this point of view, Knopoff & Lee studied the self-organization of earthquakes that occurred in California, and they concluded that a magnitude distribution for mainshock earthquakes of magnitude greater than 4.7 (roughly 5) for southern California is not scale-independent (in other words, departed from the self-similarity), although aftershock distribution and mainshock distribution for magnitude less than 4.7 both exhibit self-similarity. Knopoff & Lee further concluded that individual faults show no evidence for self-organization prior to strong earthquakes. They proposed a model of aftershocks that has the following properties: 1) Gutenberg-Richter law, 2) Omori's law, and 3) aftershocks located near the rupture surface where the stress is low, rather than at the ends of the fault where the stress is high.

All the above presentations and discussions are consistent and can be unified. It can thus be concluded that we have reached a unified comprehension for the physical scale-dependencies.

