Earthquake cycle models for the 2011 Tohoku giant earthquake

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The 2011 Tohoku earthquake M9.0 has the following observational characteristics; 1) The source region extends to a large one with a size of 200 km x 500 km. 2) There exists an area with extremely large coseismic slip over 50 m in the shallow Off-Miyagi region close to the Japan Trench. 3) Tsunami deposit surveys suggested the reoccurrence time of this M9 earthquake is 450-800 years. 4) Within the source region, M7-class evens occurred with recurrence times of several decades in the deep Off-Miyagi and Off-Ibaraki areas, and the seismic coupling in these areas was estimated to be around 30 %. 5) A foreshock occurred on March 9 two days before the event and its coseismic and afterslip stress perturbation may contribute to the occurrence of the giant event. 6) Land GPS surveys suggest that the plate coupling in the Off-Fukushima area has been changed from strong to weak ones around 2005 several years before the occurrence of this giant event.

First, I review several quasi-dynamic earthquake cycle models for this giant earthquake; the standard asperity model with a strong patch (SA) (Kato and Yoshida,2011), the hierarchical asperity model (Hori and Miyazaki, 2011) (HA), the asperity model with new two state variables (Shibazaki et al.,2011) and the asperity model with TP (thermal pressurization) (Mitsui et al., 2011), which explain the above characteristics of M9 cycle, that is, the shallow patch accumulates slip deficit for several hundred years and produces extremely large coseismic slip in an area and the huge rupture region, while M7 earthquakes occur with recurrence times of several years in this rupture area. Further, SA and HA models have been compared in some details by Ohtani et al. (2012). On the other hand, there have been proposed some dynamic rupture models; slip weakening model with TP (Mitsui et al., 2012), overshoot model (Ide et al., 2011) and multi-scale dynamic rupture model (Aochi and Ide, 2011). Most of quasi-dynamic earthquake cycle models indicate some cyclicity in the M9 earthquake cycle, while dynamic models predict probabilistic occurrence of the M9 event, as suggested by Matsuzawa (2011).

Second, I show some details of the quasi-dynamic earthquake cycle models in which I have been involved among the above mentioned studies; comparison of SA and HA models by Ohtani et al. (2012) and the asperity model with TP by Mitsui et al. (2012). Kato and Yoshida (2011) examined a 2-D model and Hori and Miyazaki (2011) proposed a conceptual model. Therefore, Ohtani et al. (2012) compare both models based on a more realistic configuration of 3-D plate interface with Hierarchical matrices method which enables us to reduce the computational memories and times. In SA model, we set the strong asperity region with a recurrence time of several hundred years in the shallow Off-Miyagi and M7 asperities with recurrence times of several decades in the deep Of-Miyagi and Off-Ibaraki in the M9 rupture area with stable slip frictional properties. On the hand, in HA model, we set conditionally unstable frictional properties in all the M9 rupture area except for the strong patch and asperities as set in SA. Both models explain the observed characteristics of M9 event. Both models produce, however, quite different interseismic slip states in the M9 rupture area, and predict different activities of M 7 events in the first stage of M9 cycle. HA model show the rapid locking after cease of afterslip due to conditionally unstable slip frictional properties and lack in loading stress causes no M 7 events in the first stage of the cycle. In times, the unlocking starting in the deep portion gradually propagates to the shallow portion, and M7 events occur in the later stage of cycle. In contrast, in SA model, the stable slip in addition to afterslip in the M9 rupture area increases M7 event activities in the first stage of cycle, and in times only steady stable slip works and produces regular M7 event activities. Suito et al. (2011) suggested that the change in plate coupling in the Off-Fukushima region before the M9 event is related to the preparation process of M9 event. However, HA model produces iteratively the slow slip in the Off-Fukushima region as the unlocking propagates to the shallow region. This iterative occurrence of slow slip can be seen as the change in plate coupling. In SA model, if we set conditionally unstable property patch in the Off-Fukushima region, the same phenomenon occurs. In both models, the direct relation to the occurrence of M9 event is the occurrence of M7 foreshock. Thus, we have some ideas why the Tohoku earthquake grew up to M9.0; SA model seems to be a simple extension from a standard asperity model consisting of only M7 asperities, in which we put an especially strong asperity in addition. HA model, which has some common concepts to the multi-scale fracture models of Aochi and Ide (2011), assumes an asperity which we can call M9 asperity and hierarchal structures inside. The further observations in the first stage of cycle would make clear which the case is. One can have a doubt of the existence of a strong asperity in the shallow Off-Miyagi close to the Japan Trench. Instead of a strong asperity in Kato and Yoshida's 2-D model, Mitsui et al. (2012) consider the effect of pore fluid in the shallow fault zone. The fluid which is confined to some degree in the fault zone expands due to coseismic frictional heating, reducing effective pressure (TP: Thermal Pressurization) and then friction. Then TP results in the large coseismic stress drop and slip even without neutral rate-weakening frictional properties, which possibly enlarges the recurrence time of the cycle. With a range of permeability, fault widths, and the depth extent of effective TP, they successfully reproduce the results of Kato and Yoshida (2011). Thus, the TP is another promising candidate for producing the M9 earthquake cycle. 3D calculation with TP would be needed, though the computation is far more time-consuming.

Finally, we have just started to explore the possibilities of co-rupturing of the northern 1968 Tokachi earthquake region and the M9 Tohoku earthquake region, which means the possibilities of the giant event greater than the 2011 Tohoku earthquake. This research has just started and only research plan will be briefly presented.