Mechanics-based scenarios for the Nankai trough subduction earthquakes: A necessary condition for earthquake generation

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Earthquake rupture scenarios for anticipated megathrust events were conventionally constructed based on empirical information on the fault parameters of past earthquakes. Now we can estimate interplate slip-deficit rate distribution at plate boundaries by using geodetic observation systems such as GNSS and can construct the scenarios based on these estimates. There are two types of approaches to construct earthquake rupture scenarios: kinematic and dynamic modeling. In the kinematic modeling, a slip model is obtained by multiplying the estimated slip-deficit rates by the accumulation time (e.g., Baranes et al. 2018 GRL; Watanabe et al, 2018 JGR). While the rupture area and seismic moment can be easily modeled, the slip model is not always consistent with the mechanics of faulting. In the dynamic modeling, on the other hand, source models are obtained via dynamic simulations (e.g, Hok et al., 2011 JGR; Lozos et al. 2015 GRL; Yang et al., 2019 JGR). The slip model is necessarily consistent with the mechanics of faulting but its disadvantage is high computational load. In particular, the high computational load becomes critical in performing parameter searches in various friction parameters.

In this study, we propose a new mechanics-based method to bridge the gap between the kinematic and dynamic modeling. The method greatly reduced the computational load by constructing the source model as a static slip distribution and then examined whether each scenario actually happens from the viewpoint of fault mechanics. We applied the method to large interplate earthquakes in the Nankai trough subduction zone.

First, we calculated shear-stress accumulation rates at the plate boundary from the estimated interplate slip-deficit rates (Noda et al. 2018 JGR). Assuming that the shear stress accumulated during interseismic period is completely released by the earthquake, we determined the stress drop distribution by multiplying the shear-stress change rates by the accumulation time. Next, we estimated the coseismic slip distribution which causes the assumed stress drop by solving an inverse problem. We constructed various scenarios by applying this procedure to different accumulation times and different rupture areas.

We then examined whether each scenario is consistent with fault mechanics in view of energy balance. The strain energy released by an earthquake is partially dissipated on the fault plane. We therefore introduced residual energy which is obtained by subtracting the dissipated energy from the strain energy. The residual energy should be positive to generate earthquakes. We estimated the strain energy (available energy) and dissipated energy (fracture energy) for each scenario assuming a slip-weakening friction law used in Hok et al. (2011 JGR). The available energy increased in proportion to the square of time, and the dissipated energy increased in proportion to time (seismic moment). While the dissipated energy is larger than the strain energy (negative residual energy) immediately after the previous event, as time passes the strain energy becomes dominant over the dissipated energy (positive residual energy) and earthquakes occur. This result suggests that the accumulation of strain energy (slip deficit) is not directly related to the earthquake generation unlike simple kinematic modeling and that a certain level of energy accumulation is required for the generation of great earthquakes.

Keywords: Earthquake scenarios , Interplate earthquakes , The Nankai trough subduction zone , Fault mechanics, Energy balance of shear faulting