Guy Bomford Prize Lecture

Physical modeling of gravity field variations to explore mechanisms of great earthquakes

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GNSSs have detected postseismic crustal deformations due to megathrust earthquakes that occur in island-arc trench systems. Such crustal deformation data have been interpreted by combining three mechanisms: afterslip, poroelastic rebound and viscoelastic relaxation. It is seismologically important to determine the contribution of each mechanism because it provides frictional properties between the plate boundaries and viscosity estimates in the asthenosphere which are necessary to evaluate the stress behavior during earthquake cycles. However, the observation sites of GNSSs are mostly deployed over land and can detect only a small part of the large-scale deformation, which precludes a clear separation of the mechanisms. To extend the spatial coverage of the deformation area, recent studies started to use satellite gravity data obtained by GRACE and GOCE that can detect long-wavelength deformations over the ocean.

To make the best use of the gravity data, a theory on global deformation is required, which treats the self-gravitation effect rigorously. The governing equations for a self-gravitating viscoelastic sphere were already given by Peltier (1974) to model postglacial rebounds. The same framework has been applied to postseismic relaxation. However, those governing equations has been solved only for special cases such as the incompressible case (the divergence of the displacement field is zero) until recently, due to some mathematical difficulties.

A first difficulty is that denumerable infinite sets of eigenmodes appear in the compressible case. The conventional root-finding procedure in the Laplace domain encounters technical difficulties for identifying these modes. To avoid this, Tanaka et al. (2006) evaluated the sum of the contributions from these modes by applying the numerical inverse Laplace integration to a radially stratified viscoelastic earth with many layers. Later, Cambiotti et al. (2011) and Tanaka et al. (2015) solved the same governing equations using a modal and a time-domain approach, respectively. Theoretical studies show that the effects of compressibility exceed 10% with respect to the incompressible case.

A second difficulty is the presence of unstable modes. The unstable modes for realistic earth models like PREM have geological time scales, so in practice they contribute only to the coseismic elastic deformation. If excluding these modes, the computed coseismic deformation disagrees with the result obtained by an elasticity dislocation theory (Sun & Okubo, 1993). A fundamental solution to this problem could be obtained by considering higher-order terms omitted in the governing equations or modifying the initial state of the earth model, which needs further studies.

To include 3-D viscoelastic structures is also important when modeling postseismic deformations by megathrust events (Pollitz et al. 2008). Most spherical models do not consider strong lateral heterogeneities in mantle viscosity, in particular due to a subducting slab. Ordinary finite-element methods can consider such effects. However, the self-gravitation effect is often treated only approximately because the model domain does not cover the whole earth. Tanaka et al. (2015) developed a spectral finite-element approach that allows 3-D viscosity distributions and the self-gravitation effect to be considered in a more natural way without approximating the governing equations of Peltier. In this approach, much larger lateral viscosity variations can be handled than by perturbation techniques to compute global deformations.

The developed approach was applied to the postseismic deformation of the 2004 Sumatra–Andaman earthquake.

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The spatial patterns of gravity change generated by the above three mechanisms clearly differ from one another. A comparison with the satellite gravity data revealed that both afterslip and viscoelastic relaxation were occurring. Recent new satellite gravity data may also be able to identify the effects of the slab on postseismic relaxation, which could exceed 20% of the coseismic change in some cases.

Recent seismological studies indicate that non-tidal decadal variations in the ocean bottom pressure with only 100 Pa could modify a long-term triggering probability of non-volcanic tremors, when combined with rapid tidal stress changes (Tanaka et al., EPS, 2015). Tremors can be triggered by much smaller stress changes due to the low effective normal stress than ordinary earthquakes. Moreover, the non-linear frictional law amplifies the superimposed tidal effects in periods with low OBPs. This means that plate subduction speeds can slowly fluctuate in the transition zone as a result of the interaction between the ocean and the plate interface. To explore this phenomenon, future satellite gravity missions are expected to monitor ocean bottom pressures in coastal areas near the plate boundaries more precisely. Global geodesy which views surface fluids and the solid earth as a system may play a more and more important role, also in studying inter-seismic deformation.

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