弾性・非弾性歪み解析を用いた地殻内応力蓄積・解放の評価：2016年熊本地震への適用

Crustal stress accumulation and release estimated from elastic/inelastic strain analysis: the 2016 Kumamoto earthquake

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To understand the mechanism of earthquake generation, it is important to observe stress accumulation and release in the crust. For interplate earthquakes, we can observe them through interseismic slip-deficit and coseismic slip at the plate interface estimated from geodetic observations (e.g. Hashimoto et al., 2009 Nature Geo.). For crustal earthquakes, however, there is no alternative physical quantity to appropriately represent the stress accumulation and release in the crust, like slip motion at the plate interface for interplate earthquakes, and hence it is difficult to comprehensively evaluate them.

We developed a method to estimate the stress accumulation and release from GNSS data by using the physics-based elastic/inelastic strain analysis proposed by Noda and Matsu'ura (2010 GJI). First, a 3D distribution of moment density tensor for a volume source in the crust is estimated from observed GNSS displacement data, and then elastic and inelastic strain distributions are calculated from the estimated moment density tensor distribution. The elastic strain field is converted into changes in the crustal stress field using a constitutive equation for elastic medium. We finally obtain the 3D distribution of stress accumulation and release by comparing the stress changes with the tectonic (background) stress field.

In the present study, to demonstrate the performance of the method, we applied the method to coseismic displacement data in the 2016 Kumamoto earthquakes, including the foreshock on Apr. 14 and the mainshock on Apr. 16. The displacement data were obtained from the difference between the GEONET daily coordinate data (GSI) before and after the events. We took a volume of a rectangular cuboid as a model region and represented the 3D spatial distribution of moment density tensor by the superposition of basis functions: the bicubic B-spline functions for horizontal distribution; the first-order splines for vertical distribution.

To obtain a stable solution, we assumed a normalized moment tensor and formulated an inversion problem to estimate the distribution of scale factor of the moment tensor from the GNSS data. Based on an idea that the total moment tensor of inelastic deformation is proportional to the tectonic stress field (Terakawa and Matsu'ura, 2008 GJI), six elements of the normalized moment tensor can be determined from the tectonic stress field. In this study, we approximated it by the sum of F-net seismic moment tensor solutions (NIED) of events that occurred in the model region before the foreshock. We solved the inversion problem according to Noda and Matsu'ura (2010).

The estimated moment density tensor distribution was smoothly distributed around the source region with a length of about 60 km, a width of about 20 km, and a depth range of 0-20 km, and it shows two peaks corresponding to the Futagawa and Hinagu faults. The total moment was 5.6×10^{19} (N m), which was roughly equal to the estimations in the previous studies using waveform inversion and geodetic data

inversion (e.g., Kubo et al., 2016 EPS; Fukahata and Hashimoto, 2016 EPS).

To compare with the result, we also estimated fault slip distribution on two fault planes with an inversion method by Yabuki and Matsu'ura (1992 GJI). The tensor of stress changes calculated from the elastic/inelastic strain analysis was basically close to that calculated from the fault plane model. On the other hand, the amplitude of stress changes from the strain analysis was about 50 % smaller than that from the fault plane model. The underestimation of stress changes might be mainly caused by the smoothly spreading distribution of the estimated moment density tensor.

Finally, we evaluated the stress accumulation and release due to the Kumamoto earthquakes from the stress changes and the approximated tectonic stress field by using the shear-strain energy change (Saito et al., 2017 AGU). The spatial variation of the shear-strain energy change calculated from the strain analysis was consistent with that from the fault plane model, though the amplitude is about half of that from the fault plane model. Additionally, the region where the shear-strain energy change was positive (i.e., stress accumulation) agreed well with the distribution of aftershocks.

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