Viscoelastic Inversion of Crustal Deformation Data

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Abstract

We developed a new geodetic inversion method. The method is formulated for a 3-dimensional layered half space with elastic or Maxwell viscoelastic rheology. We can estimate spatio-temporal slip distribution on a fault surface with an arbitrary configuration based on time-dependent geodetic data such as GPS. With this method, we can deduce both stepwise coseismic fault slip and interseismic slip deficit simultaneously. The new method is tested using a simulated distribution of fault slip and the inversion analysis successfully reproduced the original fault slip distribution. Such an inversion method is applicable to a data assimilation process for numerical simulations intending crustal activity forecast.

Introduction

Recently established continuous GPS networks are providing precise records of surface deformation in the vicinity of seismogenic zones. Such information is very useful in understanding and forecasting physical processes of a coseismic fault rupture, a postseismic stress relaxation, an interseismic stress accumulation, and possibly a preseismic acceleration of fault slip. Generation of a large earthquake is a highly complicated process in a heterogeneous medium, in which various interactions are of essential importance. Such an earthquake generation process shows a nonlinear behavior. A small deviation of initial conditions, even if the deviation itself is less than the observational error, may cause a quite different result. In order to make a successful forecast with numerical simulations, consecutive supply of observational information is essential. Computer simulations for a crustal activity forecast thus require data assimilation process. Here we present a new method for data assimilation based on geodetic inversion. This new method is developed taking a viscoelastic effects of the asthenosphere into account. By applying a Bayesian approach with the maximum likelihood method, we can estimate optimally smoothed distribution of coseismic as well as interseismic slip distribution on the fault surface.

Viscoelastic inversion

Kinematic description of an earthquake cycle can be achieved by obtaining a spatio-temporal slip distribution on the fault surface. Crustal deformation data can be used to estimate an actual slip distribution through an inversion procedure. Because of viscoelastic nature of the Earth's asthenosphere, crustal deformation related to an earthquakes cycle is time-dependent and reflects both coseismic stepwise displacement due to previous large earthquakes and interseismic steady de-

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formation for tens of years. Thus we need to incorporate viscoelastic effects of the Earth properly in order to estimate slip distribution on the fault. Matsu'ura et al. (1998) formulated such an inversion method for 2-dimensional case. Here we present an extension of the method by Matsu'ura et al. (1998) to a 3-dimensional case and an arbitrary configuration of fault surfaces.

Formulation

Surface displacement of the Earth is represented in a form of heredity integral.

$$u_i(\boldsymbol{x},t) = \int_{-\infty}^{t} d\tau \int_{\Sigma} d\xi_1 d\xi_2 G_{ik}(\boldsymbol{x},t;\boldsymbol{\xi},\tau) \Delta \dot{u}_k(\boldsymbol{\xi},\tau) \tag{1}$$

Here, $u_i(\boldsymbol{x},t)$ is surface displacement, Σ is the boundary surface, $\Delta \dot{u}_k(\boldsymbol{\xi},\tau)$ is the slip rate distribution on the fault surface, and $G_{ik}(\boldsymbol{x},t;\boldsymbol{\xi},\tau)$ is a viscoelastic response function of surface displacement due to a unit fault slip.

Slip distribution on a plate boundary surface can be described as follows.

$$\Delta u_k(\boldsymbol{\xi},\tau) = V_k^{pl}(\boldsymbol{\xi})\tau + \Delta u_k^p(\boldsymbol{\xi},\tau) \tag{2}$$

The first term in the right side represents a steady part, describing the plate motion. V_k^{pl} is a velocity of the plate motion and is estimated based on geologic as well as geodetic observations. The second term is to be estimated by inverting the geodetic data. From (1) and (2), we obtain

$$u_i(\boldsymbol{x},t) = u_i^s(\boldsymbol{x}) + u_i^p(\boldsymbol{x},t)$$

$$u_i^p(\boldsymbol{x},t) = \int_{-\infty}^{t} d\tau \int_{\Sigma} d\xi_1 d\xi_2 G_{ik}(\boldsymbol{x},\boldsymbol{\xi},t-\tau) \Delta \dot{u}_k^p(\boldsymbol{\xi},\tau) \cdot \tag{3}$$

Here, it should be noticed that the steady deformation part $u_i^s(\boldsymbol{x})$ does not change in time. We parameterize the perturbed part of the slip distribution using a functional expansion.

$$\Delta \dot{u}_k^p(\boldsymbol{\xi},\tau) = \sum_{l=1}^{L} \sum_{m=1}^{M} \sum_{n=1}^{N} a_{klmn} T_l(\tau) X_m(\xi_1) Y_n(\xi_2) \tag{4}$$

From (3) and (4), we obtain an observation equation as follows.

$$u_i^p(\boldsymbol{x},t) = \sum_{k=1}^{2} \sum_{l=1}^{L} \sum_{m=1}^{M} \sum_{n=1}^{N} a_{klmn} \Phi_{klmn}(\boldsymbol{x},t)$$

$$\Phi_{klmn}(\boldsymbol{x},t) = \int_{-\infty}^{t} d\tau \int_{\Sigma} d\xi_1 d\xi_2 G_{ik}(\boldsymbol{x},\boldsymbol{\xi},t-\tau) T_l(\tau) X_m(\xi_1) Y_n(\xi_2) \tag{5}$$

By using B-spline functions as bases, we can narrow the range of integrals. The linear observation equation can be solved with appropriate a priori constraints. We applied a priori constraints that the slip distribution is smooth both in time and space. Akaike's Bayesian Information Criterion (ABIC) is used to achieve an optimal smoothness of the distribution.

Numerical example

We analyzed simulated crustal deformation data as a numerical example. The surface deformation data are calculated based on a computer simulation of earthquake cycle at a transcurrent plate boundary by Hashimoto and Matsu'ura (2000) (Fig. 1). 3-dimensional displacements are calculated at 40 points with 1 year sampling for 77 years (t=157.0 – 234.0) and the number of observation data is 9360. The fault plane is vertical, 120km long and 45km wide. The observation points are selected only from a single side of the fault plane and we cannot resolve the relative plate motion. Thus we estimate interseismic slip deficit and coseismic fault slip. We placed 20*9 bicubic B-splines to describe the spatial distribution of slip (rate), and 17 triangular B-splines for temporal distribution. In addition, since there are 3 seismic events during the period, coseismic

slip distributions for those events are simultaneously estimated. Fig. 2 shows an inversion result of slip distribution. Except for the accumulation of fault slip due to the plate motion, the spatio-temporal pattern of the slip distribution is well reproduced, demonstrating the effectiveness of the inversion method. Because of limited resolving power of the surface deformation data, the estimated slip distribution is a little over-smoothed. And we have to wait for several tens of years to obtain precise GPS displacement data for such a long period. However, we can apply this method to conventional geodetic data for the last 100 years. Although the estimated slip distribution may be too smoothed, such an estimate will provide a rough constraint on the slip distribution for the last 100 years, which numerical simulation results must satisfy in order to forecast crustal activity in the near future.

Acknowledgments

References

[1] Matsu'ura, M., Nishitani, A., and Fukahata, Y., 1998, *Slip history during one earthquake cycle at the Nankai subduction zone, inferred from the inversion analysis of levelling data with a viscoelastic slip response function,* Eos Trans. AGU, **79**(45), Fall Meet. Suppl., F891.
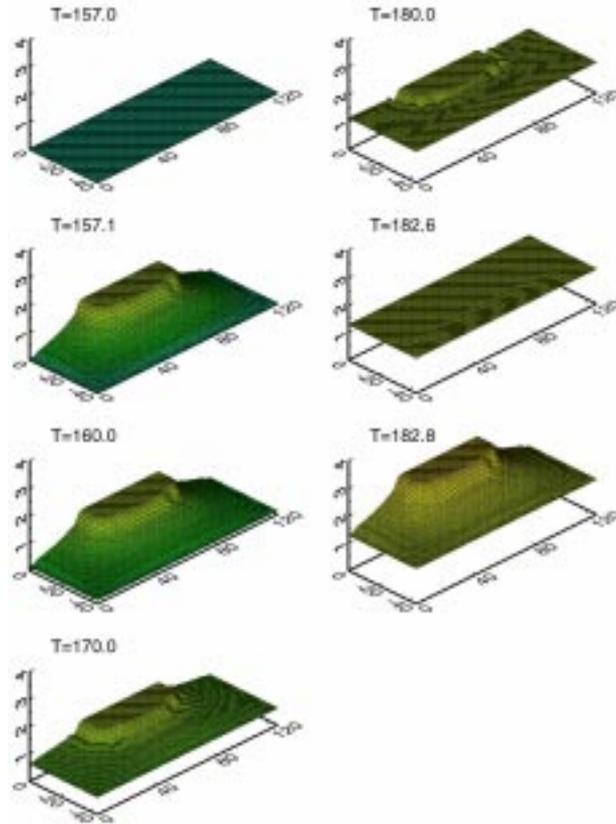[2] Hashimoto, C., and Matsu'ura, M., 2000, PAGEOPH, in press.

Figure 1: Assumed distribution of fault slip (unit in meter). Effects of steady plate motion are included.
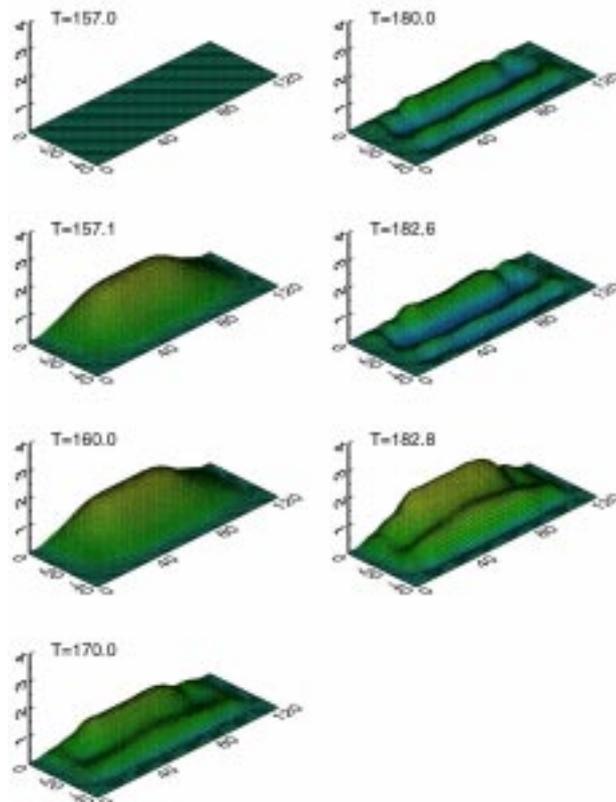

Figure 2: Slip distribution on the fault plane obtained by viscoelastic inversion. Plate motion effects are not included.