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

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Abstract

We developed a new method of geodetic data inversion with a viscoelastic slip response function for estimating slip history at plate interfaces. By applying this inversion method to levelling data for 1893-1983 in Shikoku, southwestern Japan, we reconstructed the pattern of spatiotemporal variation in slip motion at the interface between the Eurasian plate and the Philippine Sea plate. In the deep portion ($40km < d$) of the interface steady slip proceeds at a plate convergence rate (4 mm/yr) through the entire earthquake cycle. In the intermediate depth range ($10km < d < 40km$), on the other hand, instantaneous slip of about 4 m on average occurs at the time of the Nankaido earthquake. After that, this portion keeps in stationary contact untile the occurrence of the next large earthquake. The slip motion in the shallower portion is obscure for lack of data.

Introduction

In the southwestern part of Japan, where the Philippine Sea plate is descending beneath the Eurasian plate along the Nankai trough at the convergence rate of about 4 cm/yr, large thrust-type interplate earthquakes have periodically occurred with the recurrence time of about 100 years. In this region geodetic surveys started in the 1890's and were repeated at the interval of 10-30 years since then. From comparison of these repeated geodetic measurements, the crustal deformation cycle associated with the 1946 Nankaido earthquake has been revealed (Thatcher, 1984[7]; Sagiya, 1995[5]; Fukahata et al., 1996[2]). I order to rationally explain such a deformation cycle, we must consider the effects of viscoelastic stress relaxation in the asthenosphere, as pointed out by many investigators (Thatcher and Rundle, 1984[8]; Matsu'ura and Sato, 1989[4]; Sato and Matsu'ura, 1992[6]).

$$w(x,t)=\int_{-\infty}^{t}\int_{\Sigma} G^{L}(x,t-\tau;\xi,0)\,\dot{u}(\xi,\tau)\,d\xi d\tau \tag{1}$$

with $u(\xi,t)=v_{pl}t+\Delta u(\xi,t)$

Viscoelastic Case:

$$w(x,t)=v_{pl}U_{\Sigma}(x)t+\int_{-\tau_e}^{t}\int_{\Sigma} G^{L}(x,t-\tau;\xi,0)\,\Delta\dot{u}(\xi,\tau)\,d\xi d\tau \tag{2}$$

with $U_{\Sigma}(x)=\int_{\Sigma} G^{L}(x,\infty;\xi,0)d\xi$

Elastic Case Neglecting Effects of Steady Slip:

$$w(x,t)=\int_{0}^{t}\int_{\Sigma} G^{L}(x,0^{+};\xi,0)\,\Delta\dot{u}(\xi,\tau)\,d\xi d\tau \tag{3}$$

Table 1. Theoretical expressions of surface displacements caused by slip motion on a plate boundary.

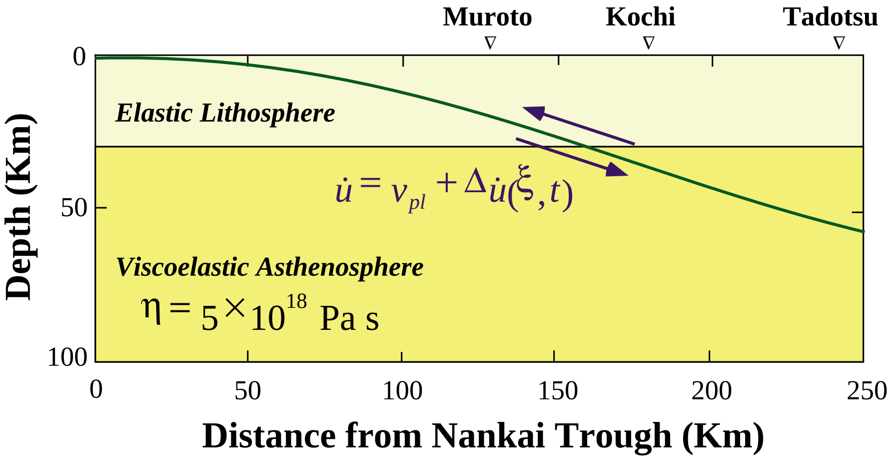

Figure 1: The structure model used for inversion analysis.

The method of geodetic data inversion

In general, the viscoelastic surface displacements caused by slip motion along a plate boundary can be written in the form of hereditary integral in Eq. (1) of Table

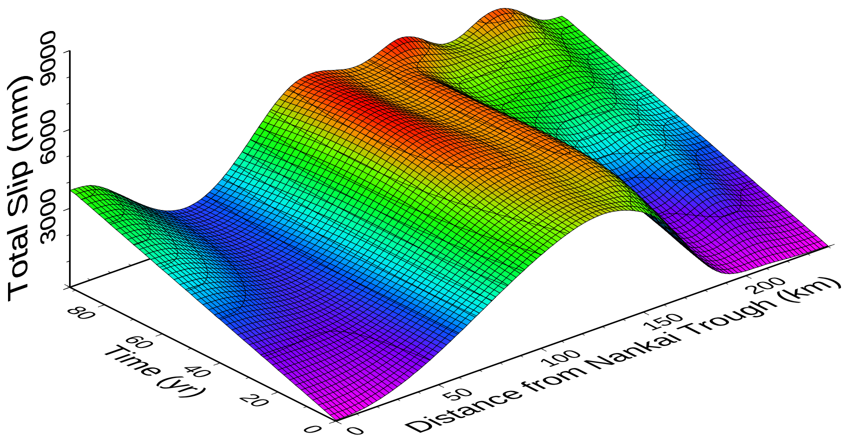

Figure 2: Slip history during one earthquake cycle inverted from levelling data with a viscoelastic response function. The distance is measured from the Nankai trough, and the time is measured from the last Nankaido earthquake.

1. Here, u indicates the total slip motion along the plate boundary Σ, and G^L is a viscoelastic slip response function. Decomposing the total slip motion into the uniform steady slip at a plate convergence rate V_{pl} and its perturbation, we can obtain Eq. (2). Here, U_Σ indicates response to the steady slip motion. If we are interested in instantaneous coseismic deformation only, of course, we can use an elastic response function, which is obtained from the viscoelastic response function by setting time $t = 0$. Our problem is to estimate the slip velocity perturbation $\Delta\dot{u}$ from observed surface displacement data by applying an inversion technique. To do so, first of all, we must parameterize the slip velocity perturbation. In practice, we represent the slip velocity function $\Delta\dot{u}$ by the superposition of a number of basis functions. In space we take cubic B-splines as the basis functions, and in time we take linear splines and delta functions. The delta function is needed for representing instantaneous coseismic slip motion. Then the model parameters to be determined in inversion analysis are the expansion coefficients.

Now we can apply the method of geodetic data inversion using Akaikes Bayesian Information Criterion (Akaike, 1980[1]) developed by Yabuki and Matsu'ura (1992)[9]. The outline of this inversion method is as follows. The first step is to describe observation equations and prior smoothness constraints. The second step is to construct a Bayesian model by combining these two different sorts of informations with Bayes' theorem. The structure of the Bayesian model is controlled by hyperparameters, and so the third step is to find the best estimates of hyperparameters by minimizing ABIC. Given the best estimates of hyperparameters, we can easily obtain the best estimates of model parameters by applying the algorithm developed by Jackson-

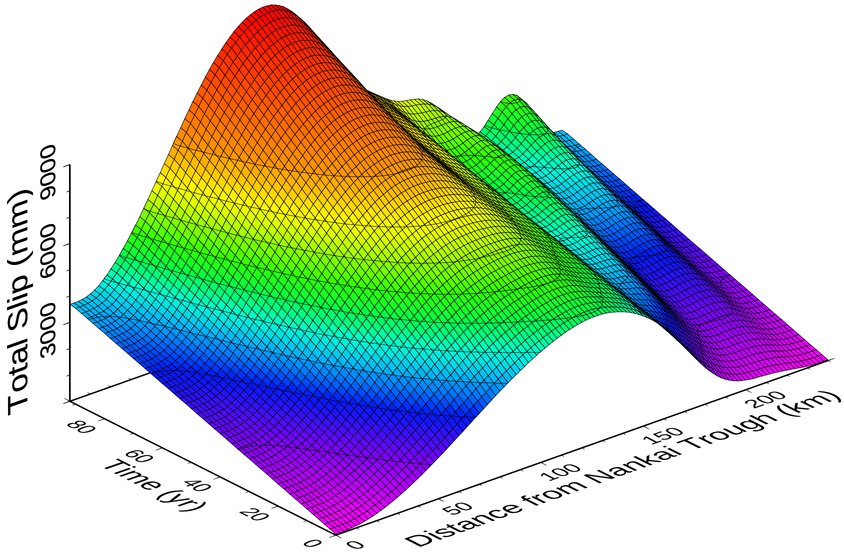

Figure 3: Slip history during one earthquake cycle inverted from levelling data with an elastic response function. The distance is measured from the Nankai trough, and the time is measured from the last Nankaido earthquake.

Matsu'ura's algorithm (1985)[3].

Results of inversion analysis

The structure model used for the inversion analysis of Nankai data is shown in Fig. 1. The model consists of the 30 km thick elastic lithosphere and the Maxwellian viscoelastic asthenosphere with the viscosity of 5×10^{18} Pa s. The geometry of the plate boundary was determined from the hypocenter distributions of earthquakes in this region . Along this plate boundary we distributed 22 cubic-spline functions. The observed data cover only the northern-half of the model region in space. As to time the observed data cover the preseismic, coseismic, postseismic, and interseismic periods of the 1946 event, and so we model the recent two cycles of Nankaido earthquakes. However, it is clear that we have not enough data to determine the slip history of these two earthquake cycles independently. And so we assume that the slip histories of these two earthquake cycles are completely the same.

On this assumption we inverted the observed displacement data and obtained the spatiotemporal distribution of slip velocity perturbation. Integrating this slip velocity distribution with respect to time, and adding the instantaneous coseismic slip and the uniform steady slip motion at 4 cm/yr, we can finally obtain the slip history during one earthquake cycle shown in Fig. 2. From this result we can see that in the deep region along the plate boundary, steady slip motion at the plate convergence rate continuously proceeds, and in the intermediate region, after the instantaneous coseismic slip of about 4 m, the plate boundary is almost completely locked through the entire earthquake cycle. As to the shallow region, the inverted result is not so reliable, because of the lack of data in sea area.

If we ignore the effects of viscoelastic stress relaxation in the asthenosphere, the result of inversion analysis dramatically changes as shown in Fig. 3. In the intermediate region, continuous slip motion proceeds at a high rate (6 cm/yr) after the instantaneous coseismic slip. This continuous slip motion is of course apparent one. From comparison of these two inverted results, we can conclude that the effects of viscoelastic stress relaxation in the asthenosphere is very essential to correctly understand the crustal deformation cycle in subduction zones.

References

[1] Akaike, H., 1980, *Likelihood and the Bayes procedure. In: J. M. Bernardo, M. H. DeGroot, D. V. Lindley and A. F. M. Smith (Editors), Bayesian Statistics.* University Press, Valencia, pp. 143-166.

[2] Fukahata, Y., C. Honsho, and M. Matsu'ura, 1996, *Crustal movements on Shikoku, southwest Japan, inferred from inversion analysis of levelling data using ABIC,* Tectonophysics, **257**, 239-252.

[3] Jackson, D. D. and Matsu'ura, M., 1985, *A Bayesian approach to nonlinear inversion,* J. Geophys. Res., **90**, 581-591.

[4] Matsu'ura, M. and Sato, T., 1989, *A dislocation model for the earthquake cycle at convergent plate boundaries,* Geophys. J. Int., **96**, 23-32.

[5] Sagiya, T., 1995, *Crustal Deformation Cycle and Interplate Coupling in Southwest Japan,* Ph.D. Thesis, University of Tokyo.

[6] Sato, T. and Matsu'ura, M., 1992, *Cyclic crustal movement, steady uplift of marine terraces, and evolution of the island arc-trench system in southwest Japan,* Geophys. J. Int., **111**, 617-629.

[7] Thatcher, W., 1984, *The earthquake deformation cycle at the Nankai Trough, southwest Japan,* J. Geophys. Res., **89**, 3087-3101.

[8] Thatcher, W. and Rundle, J. B., 1984, *A viscoelastic coupling model for the cyclic deformation due to periodically repeated earthquakes at subduction zones,* J. Geophys. Res., **89**, 7631-7640.

[9] Yabuki, T. and Matsu'ura, M., 1992, *Geodetic data inversion using a Bayesian information criterion for spatial distribution of fault slip,* Geophys. J. Int., **109**, 363-375.