Joint estimation of parameters and initial conditions of numerical models of fault slip using data assimilation methods

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Numerical models of the evolution of fault slip based on rate- and state-dependent friction laws have been widely used to simulate variety of seismic and aseismic fault slip behavior during the earthquake cycle, including earthquakes, afterslip, slow slip events, and steady aseismic creep. In these numerical models, the evolution of slip and shear stress on faults are governed by the force balance equations and friction law equations for many subdivided fault patches. The friction law equations include parameters that describe frictional properties of the fault. Previous studies have shown that these parameters, which are often called friction parameters, as well as initial conditions of the model, are one of the major governing factors in determining the evolution of fault slip. Although several studies have proposed methods to estimate friction parameters with fixed initial conditions based on GNSS data [Fukuda et al., 2009; Kano et al., 2013, 2015], it has been difficult to constrain the friction parameters and initial conditions simultaneously. In this study, we develop methods to simultaneously estimate the friction parameters and initial conditions of the rate-state friction model of fault slip using data assimilation methods.

In this study, we employ a two-dimensional planar fault in a three-dimensional elastic half-space. The evolution of slip rate and shear stress on the fault is governed by the force balance equation and rate- and state-dependent friction law. We assume that time-series of displacements at stations on the ground surface are observable. We employ the ensemble Kalman filter and smoother (EnKF) and adjoint method to simultaneously estimate cumulative slip, slip rate, and frictional state variable for each subdivided fault patch and friction parameters.

We conduct synthetic tests to assess the validity of the proposed methods. In these synthetic tests, we focus on afterslip, which is transient, decelerating, aseismic slip triggered by stress changes due to a large earthquake. We impose an earthquake using a circular crack with constant stress drop and calculate coseismic shear stress changes on the fault. Slip rate and frictional state variables immediately after the earthquake are determined based on the calculated coseismic shear stress changes. Using these slip rate and frictional state variables as the initial condition, we employ the rate-state friction model to simulate the evolution of afterslip assuming that the fault has a velocity-strengthening frictional property. We then compute displacement time series at stations on the ground surface using the simulated slip history. Finally, we add normally distributed observation errors to generate simulated data. This simulated data set is used in the synthetic tests.

For the case of the EnKF, we find that the prediction step of the EnKF becomes numerically unstable if some of the initial ensemble members have values significantly different from the true values. These numerical instabilities occur when, for example, the initial ensemble members are randomly generated. In contrast, if the initial ensemble members have similar values to the true values, such numerical instabilities do not occur and consequently the EnKF can successfully be implemented. These results indicate that it is important to develop a method to generate appropriate initial ensemble to successfully implement the EnKF for our model. We will also show the results obtained from the adjoint method in the presentation.

Keywords: data assimilation, fault slip, friction parameters

