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Quasi-dynamic earthquake cycle simulation in a layered viscoelastic medium

HIRAHARA, Kazuro[1*], SHIKAKURA, Yosuke[1], OHTANI, Makiko[1], HYODO, Mamoru[2], HORI, Takane[2], HASHIMA, Akinori[3]

[1]Grad. School Science, Kyoto University, [2]JAMSTEC, [3]Grad. School Science, Chiba University

Earthquake cycle simulations, based on laboratory-derived rate and state friction laws, have been executed to successfully reproduce historical interplate earthquake cycles at subduction zones. Most of these simulations have assumed half-space homogeneous elastic media. At subduction zones, however, there exists a viscoelastic mantle wedge, which produces several-decades-lasting stress relaxations and postseismic deformations after interplate earthquakes. Tsunami deposit surveys suggested that the 2011 Tohoku earthquake has a recurrence time of several hundred years, and hence such a giant earthquake cycle with a long recurrence time should be affected by viscoelastic stress interactions. And there has been reported the increase of inland earthquake activity before and just after the occurrence of an interplate earthquake. Viscoelastic stress interaction in the mantle wedge would play an important role in these interplate and inland earthquake activity interactions.

In quasi-dynamic earthquake cycle simulations, we first divide a plate interface into N small cells (faults) and numerically obtain slip evolution in each cell by balancing the stress due to slip deficits from all cells with the frictional stress obeying a rate and state friction law. In a viscoelastic medium, the stress is calculated by the hereditary integral of time-dependent SRF(slip response function) and the slip deficit rate. This requires all past slip rate histories in memory and leads to huge memory storage and computations, compared with the elastic case where the stress is obtained by the simple product of the temporally constant elastic SRF and the slip deficit.

We introduced a new method of stress calculation without the heredity integral using memory variables which has been developed in FD calculations of dissipating seismic wave filed in inelastic media (Hirahara et al., 2011). There, we approximate SRF with M relaxation functions, and introduce the M memory variables, each of which satisfies a first-order differential equation in time. Stress is obtained by the product of (the slip deficit - sum of memory variables) and SRF. The slip deficit in elastic cases is replaced by (the slip deficit - sum of memory variables) , and we can keep the same scheme of stress calculation as that in elastic ones. Because of keeping the same scheme, the method for reducing computational costs in elastic cases (Ohtani et al., 2012) works also in viscoelastic ones. In their method, they introduced the H-matrices method to reduce the computational costs of product of the elastic SRF matrix (NxN) and the slip deficit vector (N) from $O(N^2)$ to O(N) - O(NlogN). The stress calculation in viscoelastic cases requires additionally NxM relaxation function parameters approximating SRF and NxM memory variables compared with the elastic cases, and also NxM first order differential equations. This means the extra computational cost is O(NxM), and we found M=2 is generally adequate for approximating SRF.

To examine the performance of our method in viscoelastic cases, we simulate the 2011 Tohoku earthquake cycle in a 2D viscoelastic structure, which consists of a 40-km-thick elastic lithosphere and the underlying Maxwell viscoelastic mantle wedge. We assume a plate interface with the dip of 20 degrees. Following Kato and Yoshida (2011), we set the seismogenic zone with velocity weakening property down to a depth of 55 km on the plate interface extending totally to 100 km depth. We calculate SRFs following Fukahata and Matsu'ura(2005,2006) and Hashima et al.(2008). SRFs in the mantle wedge decay to zero in time, while those in the elastic layer keep some level. This produces slip evolution in the seismogenic zone in the mantle wedge, which is quite different from that in the elastic case, as well as the difference of recurrence time.

Keywords: Earthquake cycle, Simulation, Layered viscoelastic media, H-matrices method, Memory variables