Quasi-static FEM modeling of earthquake cycle at a subduction zone based on a laboratory derived friction law in a laterally heterogeneous viscoelastic medium under gravitation

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Abstract

We are developing a GeoFEM module for simulating earthquake cycle of interplate great earthquakes at a subduction zone in a 3-D laterally heterogeneous viscoelastic medium. Here, toward this final goal, we present a 2-D simulation system of quasi-static earthquake cycle following the rate and state friction law which is derived from laboratory experiments, employing a FEM code of ABAQUS instead of GeoFEM. In the 1st ACES Workshop, we presented mainly a simple earthquake cycle due to a subducting slab with artificially changing of friction on the plate interface using rather coarse FEM meshes in a laterally heterogeneous viscoelastic medium under gravitation. In this study, we reconstruct a FEM model with fine meshes in the region close to the plate interface on which we apply the rate and state friction law. We present the concept of our FEM modeling of earthquake cycle of interplate great earthquakes due to a subducting slab and the details of our system with several numerical simulation results.

Introduction

In the 1st ACES Workshop, we presented a FEM model of earthquake cycle at a subduction zone in a laterally heterogeneous viscoelastic medium under gravitation (Hirahara,1999)[2]. There, we discussed a way to extend the simulations of earthquake cycle based on a laboratory derived friction law in a homogeneous elastic medium, which have been long executed since the work of Tse and Rice(1986)[4] to include the effect of laterally heterogeneous viscoelastic medium under gravitation. This inclusion is essential especially for subduction zones where the subducting slab produces the thermally inhomogeneous viscoelastic structures. Our previous FEM model has rather coarse sized meshes and is a discrete model in a sense discussed by Rice(1993)[3]. We reconstruct a FEM model with fine meshes in the region close to the plate interface on which we assign a distribution of frictional parameters, whose sizes are satisfied with the condition of continuous medium. This work is involved in the project where we are developing a GeoFEM module for simulating earthquake cycle. In the project, we developed a parallel computing FEM code for simulating earthquake cycle kinematically with an assigned amount of slip on the plate interface in a large scale 3-D viscoelastic medium. The details of developing status is presented by Iizuka et al.(2000), Suito et al.(2000) and Hyodo et a;.(2000) in this workshop. Along with these developments, several numerical techniques, which we obtained in developing the ABAQUS model described in this paper, will be useful for developing a GeoFEM module of earthquake cycle simulation following a friction law in a large scale 3-D viscoelastic medium. Here, we present the concept of our FEM modeling of earthquake cycle at a subduction zone, and the details of our model with preliminary numerical simulation results.

Quasi-static 2-D FEM model of earthquake cycle in Northeast Japan

2-D FEM model

We show the concept of our modeling and the details of earthquake cycle simulation using 2-D FEM model we developed for Northeast Japan. In Northeast Japan, the Pacific plate is subducting beneath the Japan Islands with a rate of 9 cm/yr, which produces repeated interplate earthquakes with a recurrence time of a hundred years along the Japan trench. The laterally heterogeneous structure in this region resulted from the subduction of Pacific slab has been clearly revealed by seismic tomography and several viscoelastic FEM models exist. Following previous models, we construct our 2-D FEM model in Fig.1. The model consists of the elastic upper crust and subducting slab and the viscoelastic lower crust and mantle wedge. For viscoelastic property, we use a standard linear solid model that is close to the Maxwell solid. The Maxwell time of the medium is 5-30 years.

Master-slave modeling of slab interface

We model the upper interface between the subducting slab and the mantle wedge using the master-slave technique implemented in ABAQUS. We set the master nodes in the slab and the slave ones in the mantle wedge. Due to a motion of subducting slab, the slip between the slab and the mantle wedge becomes large beyond several meshes over earthquake cycles. The master-slave technique allows a large amount of slip, which is suitable for earthquake cycle modeling over a thousands years.

Earthquake generation problem as a contact problem with friction

We model the generation problem of interplate earthquakes on the upper slab boundary as a contact problem with friction on an interface. In ABAQUS, we can specify any friction law using a user subroutine FRIC. We use the rate and state friction law. The user-subroutine FRIC gets the slip and the normal stress from ABAQUS and puts back the frictional shear stress, which is calculated following the friction law in FRIC. As in Fig.1, following Kato and Hirasawa (1997)[1], we assign a distribution of frictional parameters on the slab interface with a negative a-b region at depths of 5-60 km where unstable slips occur. We assume the other portion of plate-interface below a depth of 150 km and the lower boundary of the plate to have zero friction. In our previous FEM mode, we use the same mesh size in the region close to the slab interface as the ones in other regions with the size greater than 20 km. In this size of mesh, the model is expected to be discrete in a sense that each mesh on the interface ruptures independently. In our new model, we use a fine mesh of 1km size for the region close to the slab interface. This size allows the model to be continuous considering the used frictional parameters (Rice,1993[3]).

Representation of slab motion

To represent the motion of the plate, we assign displacements with a rate of 9 cm/yr in the central nodes within the subducting plate as indicated by white arrows in Fig.1.

Application of gravity

We apply gravity for 15000 years before starting simulation of earthquake cycle to stabilize the viscoelastic flow. As described previously, to get stabilized state after applying gravity, instead of Maxell solid, we employ the standard linear solid close to Maxwell solid, where the elastic stiffness of spring in parallel connected to the series of spring and dashpot is 5 % of that of another spring.

Time step control

The friction on the plate-interface changes little in the long and most of interseismic period, but suddenly changes before and after the occurrence of an earthquake. Therefore, even in a quasi-static case where the inertia term is ignored, there are two stages in the seismic cycle, the long interseismic stage with stable friction, and the stage after and before the coseismic slip with rapidly changing friction in time. We need to control properly the step size of time increment widely ranging from several years to mill-seconds. ABAQUS has capability of "automatic time step control". However, since this function of auto-time step control does not watch the change of internal variable in FRIC, the results obtained using only ABAQUS auto-time step control are not satisfactory. We are now controlling the time step in the computation taking into account the amount of slip velocity, which leads to small time step and too much CPU time. We need to improve the time step controlling reflecting the change of internal variables of state and slip velocity in the friction law.

Preliminary results

The fine mesh used in this study shows a quite different slip history from the one used in the coarse mesh previously reported. Though CPU time is greatly increased, in calculation using the fine mesh size, the calculation is greatly stabilized and a slow rise slip occurs, while the rather unstable slip frequently occurs in the case of the coarse mesh.

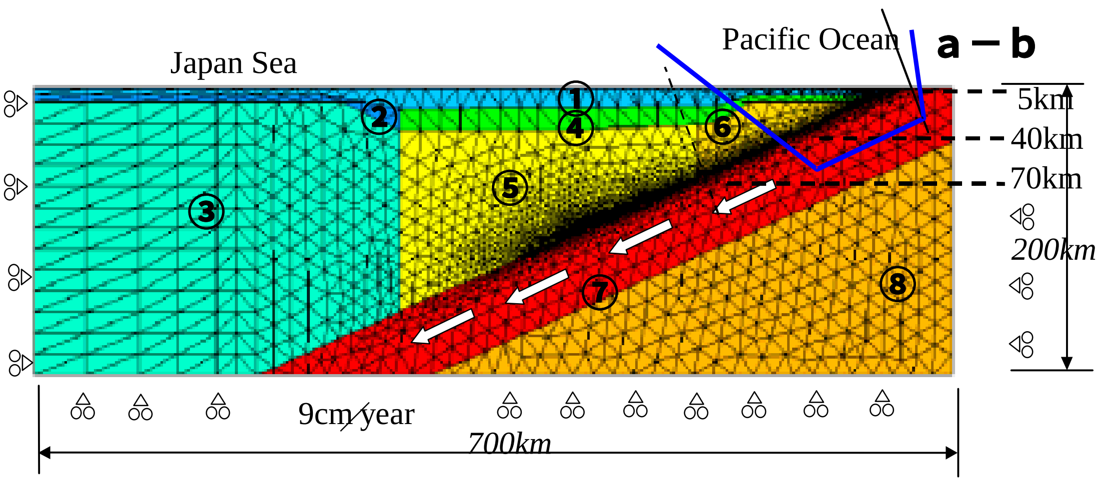

Fig.1 FEM model of Northeast Japan

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