Quasi-static simulation of seismic cycle of great inter-plate earthquakes following a friction law in laterally heterogeneous viscoelastic medium under gravitation

-FEM approach-

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Abstract

Recent simulation studies based on the friction law derived from laboratory experiments have successfully modeled seismic cycles of great inter-plate earthquakes in a half-space homogeneous elastic medium. However, the lateral heterogeneities in the medium and the viscoelastic properties under gravitation, which would seriously affect the simulation of seismic cycles, have not yet been examined in the previous studies. We consider the quasi-static simulation, and discuss the problems in extending the simulation in a simple elastic medium to that in a laterally heterogeneous viscoelastic medium under gravitation using Finite Element Method (FEM) with an example of 2-D modeling of seismic cycles in northeast Japan where the subduction of the Pacific plate causes the great inter-plate earthquakes. Before the introduction of complicated friction law, we examine a simple friction case, where an artificial seismic cycle, with a given constant friction in a locked portion during an interseismic period of 100 years and zero friction during the coseismic and postseismic period of 1 year, is considered. We compare this simple friction case with the rate- and state-dependent friction case both in a pure elastic medium and in a viscoelastic medium under gravitation.

Introduction

Since the work of Tse and Rice (1986)[5], recent simulation studies based on friction laws derived from rock friction experiments have successfully modeled seismic cycles of inter-plate great earthquakes. However, most of such studies have been executed assuming a half-space homogeneous elastic medium. Lateral heterogeneities of the crust and the upper mantle and viscoelastic properties would seriously affect the development of slip on the plate-interface, and the distribution of displacement and stress induced in the overlying crust and mantle wedge portion during seismic cycles. Since there exist strongly lateral heterogeneities of the viscoelastic properties in the subduction zones, where great interplate earthquakes repeatedly occur, the effects of viscoelastic heterogeneities make especially an important role on simulation of seismic cycles there. Further the self-gravity effect would be progressively important for the long period of simulation during a large number of seismic cycles in viscoelastic medium. Most of previous simulation studies, however, have not yet taken into consideration these effects of viscoelastic heterogeneities under gravitation.

Here, we discuss how to extend the simulation of seismic cycle in a half-space homogene-ous elastic medium to that in a laterally heterogeneous viscoelastic medium under gravitation. Though there are several stages in seismic cycle, for which the strategy of simulation should be changed from quasi-static to dynamic one or vice versa, we focus on the quasi-static simulation of seismic cycle in this paper.

We discuss the problems in specifically considering the simulation of seismic cycles in the subduction zone. Namely, we extend the previous studies of seismic cycles of thrust great earthquakes in homogeneous half-space elastic medium(e.g.Stewart,1988[4]; Kato and Hirasawa,1997[1]) to those in laterally heterogeneous elastic or viscoelastic medium with a subducting plate under gravitation. For this purpose, we employ the Finite Element Method (FEM). Most of previous simulation studies in simple elastic media have so far used analytical forms of stress changes due to a slip on each subdivided cell of the interface. However, there exist no analytical forms in laterally heterogeneous viscoelastic media. This is why we select FEM as a technical tool for realizing simulation, which enables us to easily handle lateral heterogeneities in the structural medium and viscoelastic properties. We discuss the technical problems in simulation of seismic cycles in a laterally heterogeneous viscoelastic medium with FEM, presenting a 2-D example in northeast Japan where the Pacific plate is subducting.

Technical problems in a quasi-static FEM simulation of seismic cycle

There exist several important technical difficulties in realizing seismic cycles using FEM. One is the introduction of the plate-interface in FEM. FEM usually analyzes a continuous medium, so that we need special techniques for introducing displacement discontinuous boundaries in the medium, such as the plate interface and the faulting surface due to an earthquake. There have so far been proposed several techniques. In seismology, the "split node technique" (Melosh and Raefsky,1981[2]) has frequently been used for representing the earthquake faulting, that is the displacement discontinuity on the earthquake fault. In this technique, fictitious double couples of forces equivalent to a given amount of displacement discontinuity are applied on the nodes adjacent to the split node as well as the split node itself. Other techniques allow the real discontinuity in displacement such as joint element method using thin laminar material and joint elements. Among these techniques, the “master-slave method” is most suitable for representing the evolving slip on the plate-interface, on which a large amount of slip is accumulated cycle by cycle. In the master-slave method, the pair of master and slave is changing during the evolution of slip, which allows a large amount of slip on the interface.

The second difficult aspect in realizing seismic cycles is the implementation of friction law in FEM. We can consider the evolution of slip on the plate-interface in seismic cycles as a contact problem with friction. Several forms of friction law derived from rock experiments have so far been proposed, and the constitutive form of friction is still a central subject of seismology. Following the friction laws derived in rock experiments, the friction is not simply divided into a static and dynamic ones, which none of FEM softwares available consider as a standard one. Therefore, FEM code for modeling seismic cycles is required that it has an option through which any friction law is easily implemented in the code.

The third one is control of time increment in computation. 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 milli seconds.

ABAQUS 2-D quasi-static simulation of seismic cycle in northeast Japan

ABAQUS

Here we employ a general-purpose FEM code of "ABAQUS" to simulate the quasi-static development of slip during seismic cycles on the interface between a subducting oceanic plate and a continental plate with laterally heterogeneous crust and mantle wedge. In ABAQUS, modeling of slip development on the fault is treated as a contact problem, and the fault is defined by the master-slave method. On the plate-interface, we define master elements in the subducting plate, and the slave ones in the overlying mantle wedge.

Furthermore, any friction law can be defined in a "user-subroutine FRIC". In this study, we use the rate- and state-dependent friction law, because this includes healing process, which enables us to simulate recurrence of earthquakes. In this law, the friction is dependent on slip velocity and state, which is changing according to an evolution law. Among several forms of this friction law which have been proposed, we use the Ruina-Dieteich's slip 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.

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.

2-D viscoelastic FEM model in northeast Japan

In this study, we construct 2-D viscoelastic model in northeast Japan with the subducting Pacific plate, where the viscoelastic structures have been studied in some details, and Kato and Hirasawa (1997) [1]simulate seismic cycles assuming a homogeneous elastic medium. Our model consists of the elastic upper crust and the viscoelastic lower crust and upper mantle wedge with Maxwell times of 5-30 years overlying the inclined elastic plate. Following Kato and Hirasawa (1997)[1], we assign a distribution of frictional parameters on the plate 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 70 km and the lower boundary of the plate to have zero friction. 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.

In the viscoelastic case, we apply gravity for 15000 years before starting simulation of seismic cycle to stabilize the viscoelastic flow. 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.

Simple friction case

We simulate simple cases of friction before the cases following the friction law. Namely, we consider an artificial seismic cycle, where the plate is subducting with a friction coefficient of a value, say 0.5, in the locked portion of the plate-interface at depths down to 60 km during the interseismic period of 100 years and the friction is suddenly changed to be zero during the coseismic and postseismic period of 1 year. And we compare the viscoelastic case with the pure elastic one in each friction case.

In the simple friction case of 0.5 and zero, after almost complete locking in the interseismic period of 100 years, the coseismic slip occurs following the postseismic slip due to elastic and viscoelastic rebound. In the initial stage of seismic cycles, the amount of coseismic and postseismic slip is 2 m, which is 20 % of the accumulated slip of 9 m during the interseismic period of 100 years. However, both of rebound slips increase cycle by cycle to reach the stable state after around 20 cycles. The slip amounts to almost all slip accumulated during the interseismic period in the last stage of simulation. In the elastic case of simple friction, the elastic rebound with the amount of 100 % of accumulated slip is not changing cycle by cycle. Next, the value of friction given in the locked portion has been changed from 0.5 to 0.0001. Down to around 0.005, the above mentioned clear coseismic and postseismic slips and the almost complete locking in the interseismic period occur. For the value of 0.001, even in the interseismic period the plate-interface with friction has not completely locked, but partially started to slip. And, for the value of 0.0001, the plate-interface has completely slipped.

Rate- and state-dependent friction case

In the rate and state friction case, it takes many cycles to stabilize the state in both elastic and viscoelastic cases. In the initial stage of seismic cycles, there appear very irregular patterns of slip in both elastic and viscoelastic cases. Though we might not have yet completely succeeded the simulation of seismic cycle in the rate- and state-dependent friction case, the preliminary results show that the quite different development of slip in seismic cycle appears in the elastic and viscoelastic cases, respectively. The recurrence time in the elastic case is shorter than that in the viscoelastic case. In the elastic case, we have got shorter recurrence time than that in a simple elastic medium of Kato and Hirasawa(1997)[1], though we use the same distribution of frictional parameters as theirs. At present, our FEM mesh size is 10 km, which is too large to obtain smooth slip history (Rice,1993[3]). In this sense, our model is not a continuous but a discontinuous model.

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