Simulation of Earthquake Generation Process in a Complex System of Faults

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We construct regional 3-D heterogeneous viscoelastic FEM models in northeast and southwest Japan, respectively, and simulate generation processes of interplate and intraplate earthquakes in a complex system of interactive faults. For this purpose, the module of earthquake cycle simulation in a parallel FEM code, GeoFEM, which has been developed for solving large-scale problems in solid earth physics, has been installed in Earth Simulator and tuned. In this year, we vectorize the viscoelastic loop in GeoFEM earthquake cycle simulation module. So far, we have tried to simulate quasi-static earthquake cycle by using a contact analysis code of GeoFEM. We found, however, this approach is difficult in real complex 3-D plate configurations. Instead, we take a boundary integral equation approach, that is, we calculate slip response functions with GeoFEM and integrate quasi-static equation of motion with a rate- and state-dependent friction law, applying plate motion. We develop a parallel code of such an approach. Assuming plane faults in a semi-infinite elastic medium, we simulate two quasi-static earthquake cycle simulations in northeast and southwest Japan. In northeast Japan, we simulate complex earthquake cycles due to the interaction of two asperities off Sanriku. Another simulation is a large scale one for the Nankai trough great earthquake cycle. Corresponding to the configuration of the subducting Philippine Sea plate, we assign the distribution of frictional parameters, and take into account the convergence rate change along the Nankai trough. Our simulation suggests a possibility that the Nankai trough great earthquakes always initiate their ruptures off the Kii peninsula, where the dip angle of the Philippine Sea plate is large, as in the cases of the 1944 Tonankai and the 1946 Nankai earthquakes. We develop a code of quasi-static earthquake cycle simulation in a viscoelastic medium, and a viscoelastic GeoFEM code for calculating slip response functions. A prototype FEM model of southwest Japan is constructed using CHIKAKU software. For dynamic rupture simulation, we test a fundamental problem using a GeoFEM contact analysis code.

Keywords: quasi-static earthquake cycle, GeoFEM, plate, asperity, Off-Sanriku, Nankai trough

Report of our result:

The Japan Islands is located in a subduction zone, where four plates, such as the Pacific, the Philippine Sea, the North America and the Amur plates, are converging. From the east, the Pacific plate is subducting beneath northeast Japan along the Kuril and the Japan trenches, while the Philippine Sea plate descends beneath southwest Japan along the Nankai trough. These subducting plates produce M8-class great interplate earthquakes with a recurrence time of 100 years. There are active faults in inland areas, where M7-class inland earthquakes occur with a recurrence time longer than 1000 years. These two type of earthquakes cause great disasters in Japan. Subduction of plates produces also strong lateral variations in the structure beneath the Japan Islands. We have tried to simulate earthquake generation cycle in a regional scale such as northeast and southwest regions primarily based on FEM analyses, which are capable of easy handling the lateral heterogeneities.

We have so far developed a contact analysis code of GeoFEM (Iizuka et al., 2002) for simulating quasi-static earthquake cycle. We found, however, this approach has some problems when it is applied for real complex 3-D configurations of subducting plate interface, especially for the Philippine Sea plate. Instead, we take an approach of boundary integral equation method which seems to be more appropriate for complex 3-D interfaces. The detailed procedure is the following. First, we divide the interface into cells with the sizes of around 1 km × 1 km, and calculate slip response functions for each cell in a viscoelastic FEM model using GeoFEM. Then, using these slip response functions, we integrate a quasi-static equation of motion combined with a laboratory derived rate-and state-dependent friction law with an adaptive time step Runge-Kutta algorithm. We developed a parallel and vectorized code of this approach for Earth Simulator. We tested this code for two realistic earthquake cycle simulations with a plane interface in a semi-infinite uniform elastic medium. These results of simulations are gephysically interesting and described in detail in the last sections.

For calculation of slip response functions, we vectorized the viscoelastic loop of GeoFEM. And we developed also a code for simulating quasi-static earthquake cycle in a viscoelastic heterogeneous medium using calculated slip response functions. A proto-type FEM model in southwest Japan was constructed using CHIKAKU software. This FEM model will be further refined for calculating slip response functions in a viscoelastic medium. For dynamic rupture simulation, we tested some fundamental problems using GeoFEM contact analysis code. As stated above, we have obtained gephysically interesting results which provide important implications for earthquake generation processes even using simplified models. We give detailed descriptions of results for elastic plane interface earthquake cycle simulations in the followings.

(1) Interaction of two asperities off Sanriku, northeast Japan

Recent source inversion studies of both old and recent earthquakes have revealed the existence of several patches of asperities, whose sizes correspond to those of the M7 earthquakes along the Japan trench (Yamanaka and Kikuchi, 2004). The asperities are defined by regions with large coseismic slips, and the locations and the sizes do not seem to be changed in time. The asperities are considered to be locked in the interseismic period, while their surrounding regions are slipping. Off Sanriku, northeast Japan, we had the 1968 Tokachi-Oki earthquake with the magnitude of 7.9, and the 1994 Sanriku-Haruka-Oki earthquake with the magnitude of 7.5, whose source areas are overlapping. And in this region, we had a previous earthquake in 1931. This earthquake sequence with different magnitudes was a puzzling problem, but source inversion studies solved this problem. There are two asperities, and one shallow asperity breaks in 1931 and 1994, while both shallow and deep asperities break in 1986. We simulated such an interaction of asperities.

We set a 18˚ westward dipping 256 km × 256 km plane plate interface with a cell size of 1 km × 1km, assuming the convergence rate of the Pacific plate is 8 cm/yr. Referring to Kato (2003a), after several trail searching of frictional parameter distribution, we found an appropriate distribution of a–b in a rate- and state-dependent friction law in Fig. 1. The characteristic distance of L is taken to be 5 cm except

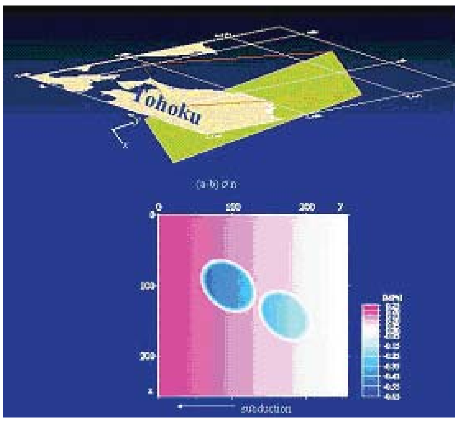

Fig. 1 Frictional parameter distribution Blue and red indicate negative and positive (a-b) σ n, respectively.

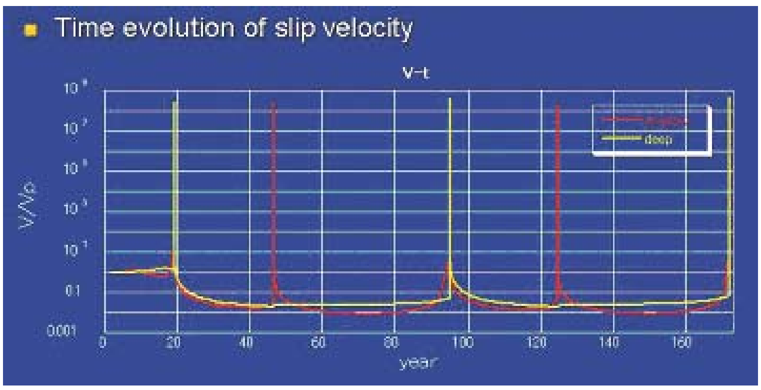

Fig. 2. Time evolution of slip velocities. Red and yellow curves indicate slip velocities at sites of shallow and deep asperities, respectively.

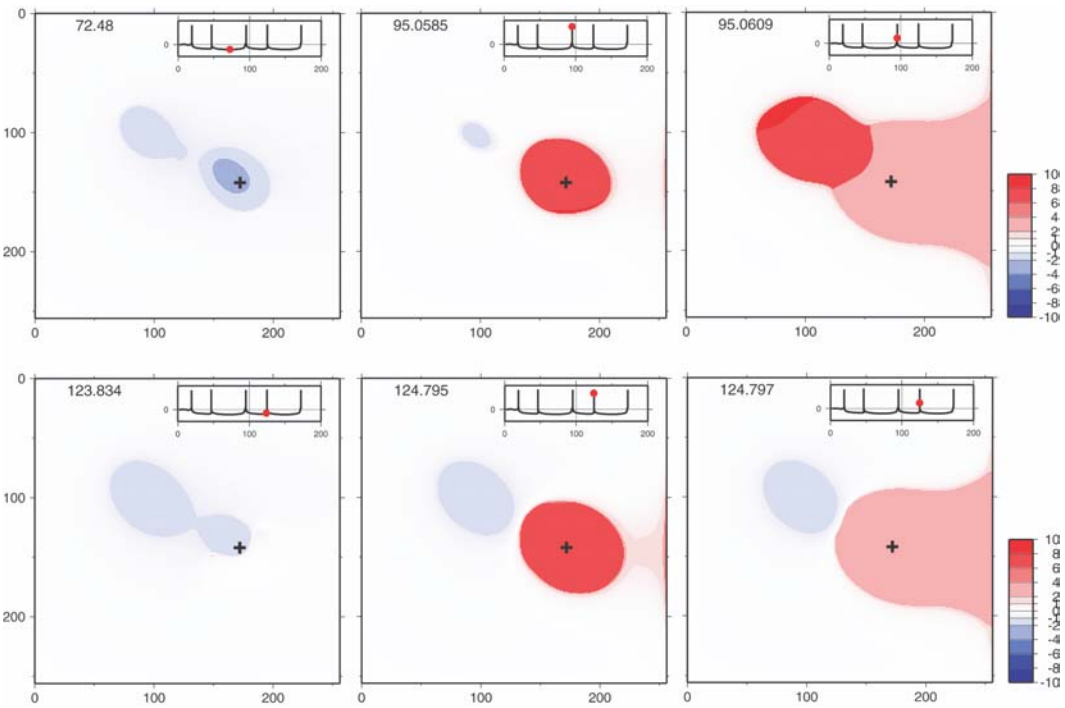

Fig. 3 Spatio-temporal evolution of slip velocity log(V/Vpl). Red means high slip velocity, while blue indicates locked state. The upper and lower figures show the double-asperity and the single-asperity beak cases, respectively. The inserted slip velocity evolution corresponds to the velocity at a site shown by a cross (+) in each figure. It is to be noted that the size of the deeper locked asperity in the single asperity break case is larger (lower middle figure) than that in the double asperity break case (upper middle figure).

for 15 cm in the deep asperity. Then, we obtained an alternate occurrence of double and single asperity breaks. For 145-year simulation with 4000 time steps, the computational time is 5.7 hours using 32 nodes. In Fig. 2, the time evolution of slip velocity at sites of shallow and deep asperity regions. Fig. 3 shows spatio-temporal distribution of slip velocity.

As shown in Fig. 2, the double and the single asperity breaks alternately. The single shallow asperity breaks after about 25 years of the double asperity beak, and both shallow and deep asperity break after about 50 years of the single asperity break. In the double asperity break case, the shallow asperity first beaks and high slip velocity extends to the deep asperity region, while the high velocity slip stops in the single asperity beak case. Close look at Fig. 3 shows that the size of the locked blue region in the deep asperity is different for the cases of the single and double asperity break. The size in the single break (lower middle figure) is larger than that in the double break (upper middle figure). If precise movement of the ocean floor can be measured by GPS-acoustic ocean floor geodesy in future, these difference of locked state would be monitored. Then, the validity of our model would be clarified.

This simple example shows how to assign the distribution of frictional parameters based on the asperity distribution which is estimated from a variety of geophysical investigations, though the difficulty increases when considering complex interactions of a number of asperities.

(2) Nankai trough great interplate earthquake generation cycle simulation

The Philippine Sea plate is younger than the Pacific plate, and then the thin Philippine Sea plate is subducting with a 3-D complicated configuration along the Nankai trough beneath southwest Japan. The interplate earthquakes along the Nankai trough repeatedly occur with a recurrence time of 90–150 years. The last events are the 1944 Tonankai and the 1946 Nankai earthquakes. The epicenters of both events are located off the Kii peninsula.

We tried to simulate the earthquake cycle using a simple plane interface in a semi-infinite homogeneous elastic medium, taking into consideration the complicated configuration of the Philippine Sea plate. Fig. 4 shows the depth-dependent distribution of A–B [(a–b) σ n] used in the simulation. In the map, are drawn the contour depths of the upper interface of the Philippine Sea plate, which are estimated from the distribution of sub-crustal earthquakes and recent explosion studies of seismic velocity structure. The regions at depths of 25–60 km and of 0–8 km are the stable sliding ones with positive (a–b), while the region at depths of 8–25 km is the locked and coseismic rupture region with negative (a–b). Around the Kii peninsula, the Philippine Sea plate is sub-

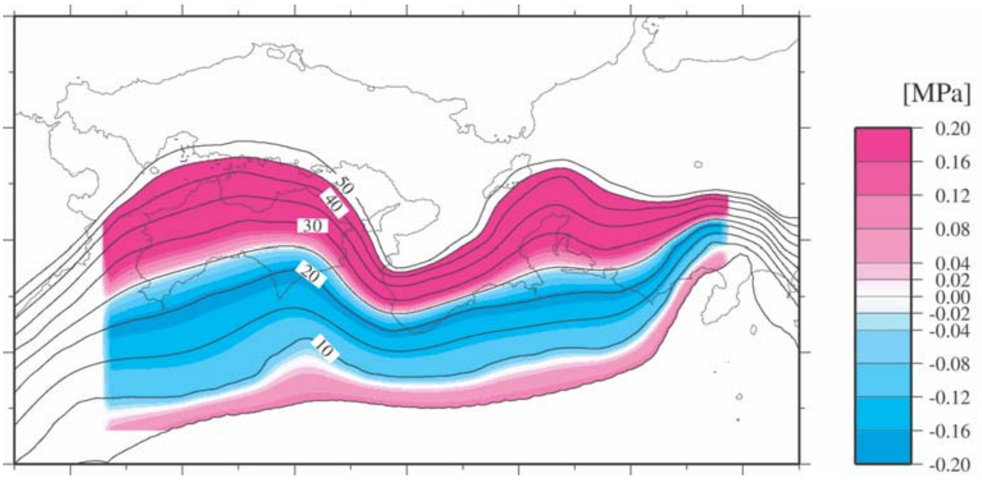

Fig. 4 Distribution of A–B [(a–b) σ n] The contour depths of the Philippine Sea plate are also drawn.

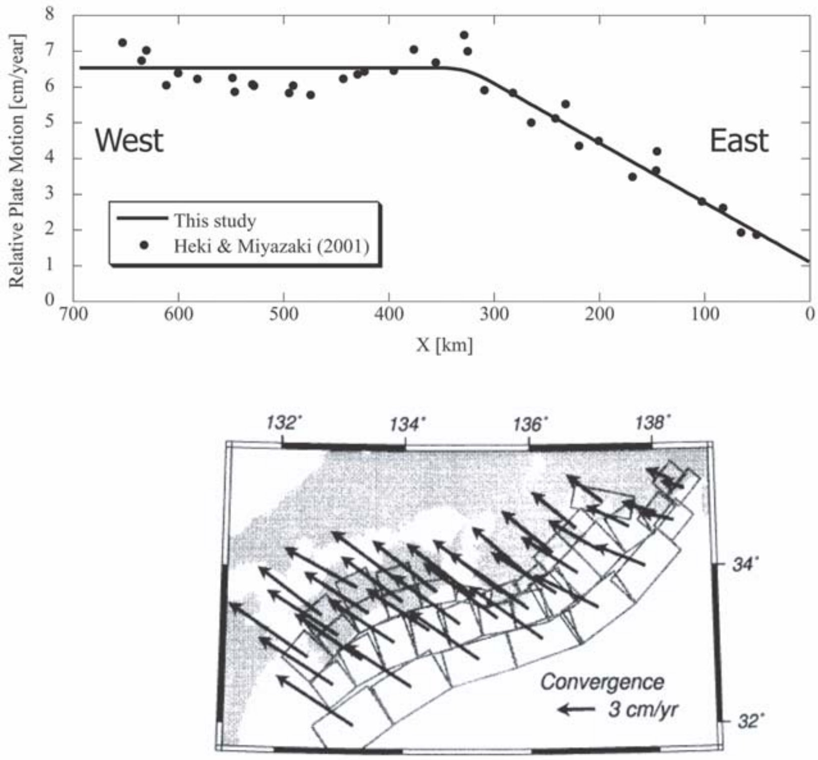

Fig. 5 Convergence rate of the Philippine Sea plate used in the simulation (upper). The rate is changed around the Kii peninsula. The lower figure shows the estimated rate from GPS data (Heki and Miyazaki, 2001).

ducting steeply compared with other regions except for the eastern region. The locked region is determined by the depth. Accordingly, the width of the locked region is narrowest around the Kii peninsula. Characteristic distance L is taken to be 20 cm at depths of 0–20 km and linearly changes in the deeper portions. We set a 691.2 km x 311.94 km plane interface and divided the plate into 1.20 km × 1.22 km cells.

The convergence rate of the Philippine Sea plate along the Nankai trough is estimated based on GPS observation data (e.g., Heki and Miyazaki, 2001). Fig. 5 shows the convergence rate which is taken from the estimated rates in cells. The convergence rate is increasing from 1 cm/yr in the east to 6.5 cm/yr in the west.

For three earthquake cycles in 380 years with 3000 time steps, the computational time is 5.4 hours using 128 nodes. Fig. 6 shows the snap shots of one earthquake cycle. During an interseismic period after healing, the slow slip region is invading the locked region from the deeper and the upper portions, and the locked blue region becomes to be narrower in time. Especially, the locked region disappears firstly around the Kii peninsula, because the locked region here is the narrowest along the Nankai trough except for the eastern portion due to the high dip angle of the Philippine Sea plate. Then, preslip occurs and the seismic rupture initiates off the Kii peninsula. The rupture propagates bilaterally toward the east and the west. The rupture velocity is 1.5 km/sec. After the rupture finishes, the fault region becomes to heal. In our simulation such an earthquake cycle is iterated.

The 1944 Tonankai earthquake initiates the rupture off the Kii peninsula and the rupture propagates eastwards, and two years later the rupture of the 1946 Nankai earthquake also starts off the Kii peninsula and propagates westwards. Fig. 7 shows an enlarged snap shot of preslip stage. The preslip area before the high speed rupture is located off the Kii peninsula. Close look at Fig. 7 shows the rupture starts in the western portion of the preslip area. The convergence rate of the Philippine Sea plate is abruptly changed eastwards from 6.5 cm/yr in the west of the Kii peninsula (see Fig. 5), and the rupture initiation point corresponds to the portion where the rate becomes to change.

We do not know the locations of the epicenters for old Nankai trough great earthquakes. Our simple simulation suggests a possibility that all Nankai trough earthquakes initiate off the Kii peninsula just as in the cases of the 1944 Tonankai and the 1946 Nankai earthquakes. Our simple simulation assumes a plane interface, though the real interface is a 3-D complicated one. Slip response functions are very different from real ones, and the normal stress would be changed in a 3-D configuration. A feature of narrow locked region off the Kii peninsula due to a high dip angle of the Philippine Sea plate is, however, fundamental even for the real 3-D configuration, and hence it seems to be true for the real case that all Nankai trough great earthquakes initiate their ruptures off the Kii peninsula.

In our simple simulation, the preslip occurs off the Kii peninsula. There is a possibility that preslip occurs around the Kakegawa which is located far from the epicenter of the 1944 Tonankai earthquake.Simulation of preslip or slow slip is executed by introducing another cut-off velocity into the rare- and state-dependent friction law (e.g., Kato, 2003b). In the deeper portion than the locked region, we need to use such a friction law. With a 3-D configuration of plate interface in a viscoelastic medium, we need to simulate the Nankai trough great earthquake cycle to clarify whether the observed preslip is related to the 1944 Tonankai earthquake.

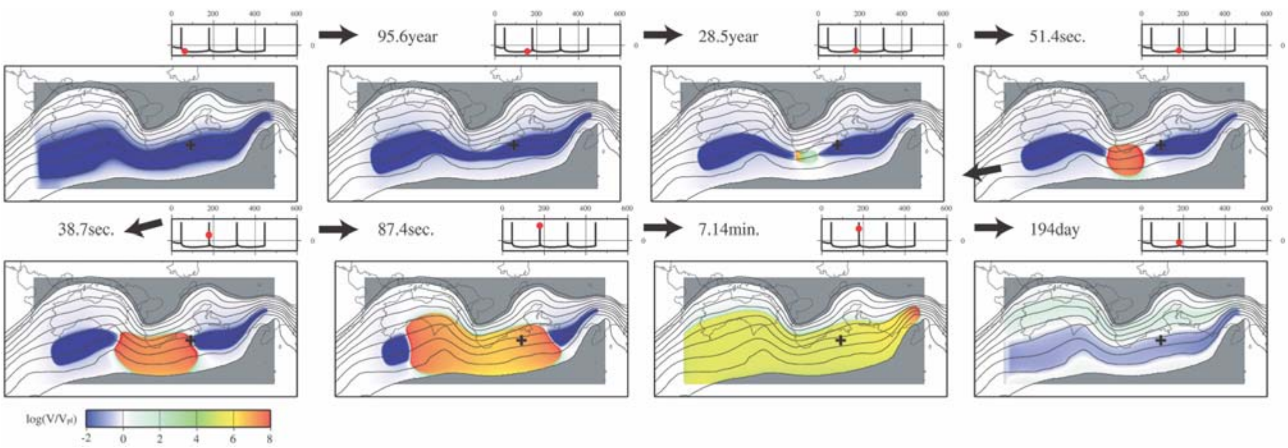

Fig. 6 Snap shots of one earthquake cycle. Red and blue indicate the high slip velocity and the locked states, respectively. The velocity plot inserted above each figure indicates that in a site shown by cross (+) in the figure, and the red circle represents the time of the snap shot.

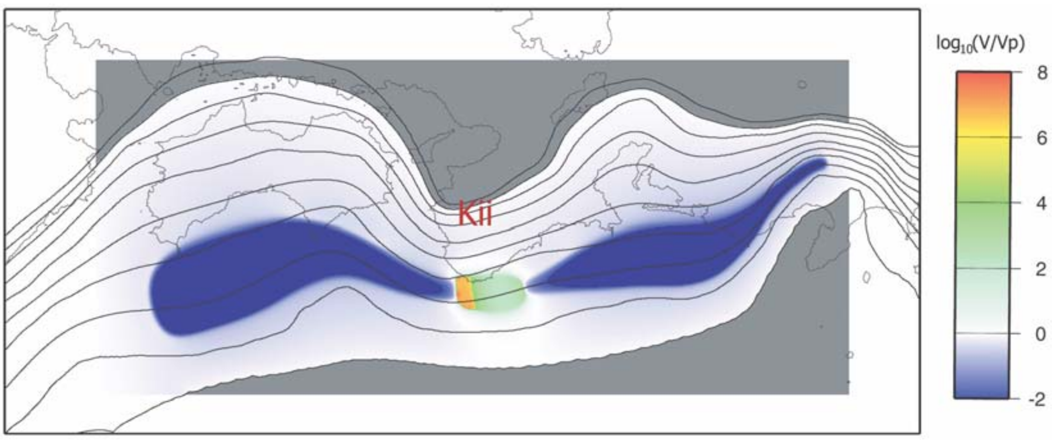

Fig. 7 Close up of the snap shot for preslip around the Kii peninsula.

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