Simulation of Earthquake Generation Process in a Complex System of Faults: 2007

Project Representative

Kazuro Hirahara	Graduate School of Science, Kyoto University

Authors

Kazuro Hirahara	Graduate School of Science, Kyoto University
Naoyuki Kato	Earthquake Research Institute, University of Tokyo
Takashi Miyatake	Earthquake Research Institute, University of Tokyo
Kengo Nakajima	Graduate School of Science, University of Tokyo
Takane Hori	Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology
Mamoru Hyodo	The Earth Simulator Center, Japan Agency for Marine-Earth Science and Technology
Kachishige Sato	Natural Science, Tokyo Gakugei University
Jun Inn	Advanced Simulation Technology of Mechanics
Noa Mitsui	Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology
Keisuke Ariyoshi	Department of Oceanfloor Network System Development for Earthquakes and Tsunamis, Japan Agency for Marine-Earth Science and Technology
Bunnichiro Shibazaki	International Institute of Seismology and Earthquake Engineering. Building Research Institute
Tomoshi Miyamura	College of Engineering, Nihon University
Yutaka Nakama	Fuji Research Institute Cooperation
Takashi Kanai	Faculty of Environmental Information, Keio University

The purpose of this project is to produce simulation models for generating interplate and intraplate earthquakes in a complex system of interactive faults in northeast and southwest Japan, respectively.

At present, in quasi-static earthquake cycle simulations which mainly deal with the long-term slow deformation process of earthquake cycle including a quasi-dynamic treatment of dynamic rupture process, we use simply a homogeneous elastic half-space medium. For the Nankai trough earthquake cycle in southwest Japan, as already reported, using a flat plate interface, we succeeded in reproducing the rupture segmentation and their complicated interactions similar to the actual historical earthquake sequences, but could not reproduce the one in the case for the realistic 3-D curved plate configuration. Even in the flat interface case, we could not reproduce the large variation of recurrence intervals and sizes observed in the actual historical Nankai earthquakes. In this report, we propose a new model with heterogeneous fracture surface energy distribution on the plate interface, in which the simulated recurrence intervals and sizes can vary significantly. Furthermore, episodic slow slip events also occur in this new model.

As a simulation based on a viscoelastic FEM model in southwest Japan, we estimated the temporal stress change (ΔCFF: Coulomb failure function) on the active inland faults, which is caused by the subduction of the Philippine Sea plate and the great earthquakes along the Nankai trough. Newly adding inland earthquake faults occurring after the 1946 Nankai earthquakes, we show again a possibility that we estimate the period with the high probability of earthquake occurrence on each fault during the current Nankai trough earthquake cycle.

For dynamic rupture simulation, we performed the FEM calculation of dip slip dynamic rupture in a bending fault.

Keywords: quasi-dynamic earthquake cycle simulation, Philippine Sea plate, Nankai trough, frictional parameter, asperity, fracture surface energy, slip response function, inland earthquake, temporal stress change

1. Introduction

The Niigataken Chuetsu-oki Earthquake (M6.8) occurred in July 2007, following the Noto Peninsula earthquake (M6.9) in March 2007. These earthquakes are the inland or the intraplate earthquakes occurring on active inland faults whose recurrence times are larger than 1,000 years. In southwest Japan, the activities of inland earthquakes tend to increase 50 years before and 10 years after the occurrence of M8-class interplate earthquakes along the Nankai trough which are caused by the subducting Philippine Sea plate. Also in northeast Japan, where the Pacific plate is subducting, the inland earthquakes tend to occur before and after the occurrence of large interplate earthquakes with the recurrence interval of 100 years.

In this project, we aim at simulating earthquake generation cycles of both interplate and inland earthquakes to understand the complex sequences of earthquake occurrence and also to provide us basic information on the future earthquakes. Constructing detailed regional heterogeneous viscoelastic FEM models in northeast and southwest Japan, respectively, we simulate earthquake generation cycle in a regional scale. These are, however, our final goals. At present, we mainly simulate the large interplate earthquake cycles in a simple homogeneous elastic half-space medium.

Our simulation of earthquake cycle consists of two processes; quasi-dynamic and dynamic rupture ones. In the quasi-dynamic earthquake cycle simulation, we simulate quasi-static slow stress accumulation and quasi-dynamic slip evolution on plate interfaces or inland faults due to relative plate motions based on a laboratory-derived rate- and state-dependent friction law. In this simulation, we employ the boundary integral equation method. Namely, we divide the plate interface into fine cells with the sizes of around 1 km x 1 km, and calculate slip response functions for each cell in a homogeneous elastic half space. Then, using these slip response functions, we integrate a quasi-dynamic equation of motion combined with a friction law with an adaptive time step Runge-Kutta algorithm. In dynamic simulation, we simulate earthquake rupture propagation based on slip-dependent friction law as a contact problem and directly use the master-slave method for treating contact interfaces in GeoFEM.

So far, for the Nankai trough great earthquake cycle in southwest Japan, using a flat plane interface, we have investigated the effect of frictional property reflecting the plate configuration on the earthquake cycle using a simple plane fault in a semi-infinite homogeneous elastic medium and successfully reproduced the complicated earthquake cycle along the Nankai trough [1] [2]. Then, we extended this approach with the same heterogeneous frictional distribution to include the actual curved 3-D interfaces of the subducting plates, but we could not succeed in reproducing the observed complex sequences. Even in the former model, we could not reproduce the observed large variation of recurrence intervals and sizes. In this report, therefore, we propose a new frictional model to produce such an observed large variation.

For viscoelastic simulation, we have examined the temporal stress changes on inland active faults in southwest Japan due to the plate subduction and the earthquake slips, employing slip response functions calculated for the 3-D viscoelastic FEM model in southwest Japan. This simulation suggests that we possibly estimate the period with high probability of earthquake occurrence on inland faults. In northeast Japan, we are constructing a large scale FEM model, which is skipped in this report.

For simulation of dynamic rupture propagation, we continue the performance test of contact analysis code implemented in GeoFEM. So far, we have introduced an effective damping scheme to prevent some oscillations in slip velocity due to numerical dispersion. In this year, we execute dynamic rupture simulation on a bending dip slip fault. Our simulation results on rupture propagation pattern, slip rate time functions, and conditions of rupture arrest are roughly consistent with a previous numerical simulation using a boundary integral equation method [3]. However, some discrepancy exists possibly due to rough mesh sizes and/or unstable computations of stresses around the fault bend. After more careful examinations, we will report the results of dynamic rupture simulation in the near future.

2. New model of quasi-dynamic simulation of earthquake cycle with heterogeneous fracture surface energy distributions on the plate interface for reproducing the large variation of recurrence intervals and sizes observed in the actual Nankai trough and other subduction zone great earthquake cycles

2.1 Assigned heterogeneity in frictional property on the plate interface based on a rate- and state-dependent friction law: Previous models

We have so far simulated quasi-dynamic earthquake cycles driven by the subducting plate, based on a laboratory-derived rate- and state-dependent friction (RS) law. The RS law includes three frictional parameters a, b and L, which are to be assigned on the plate interface. The parameter a is related to the rate dependence, and the parameters b and L to the frictional surface state. The parameter a-b controls the evolution of slip behavior. Namely, in a simple mass-spring model, the case of a-$b > 0$ shows the stable sliding, and the case of a-$b < 0$ and of the spring stiffness weaker than a critical one gives stick-slip behavior similar to earthquake cycle. Laboratory experiments show the value of a-b for granite becomes negative in a temperature range of 100–350°C and positive in other temperature ranges (e.g. [4]). The temperature at the bottom of seismogenic zone is estimated to be about 350˚C, corresponding to the depth where the value of a-b changes from negative to positive.

Accordingly, we set the value of a-b to be negative in the depth range of seismogenic zone in earthquake cycle simulations, as in the Nankai trough great earthquake cycle simulation (e.g. [1], [2]) where M8 class asperities exist. However, in the Hyuganada region west of the Nankai trough, there are M6-7 class asperities. Also in northeast Japan, the M7 class asperities are distributed. In these cases of distributed M7 class asperities, the negative a-b values are assigned in the asperities, and other regions have positive a-b values even in the depth ranges where the temperature is 100–350˚C. Then, the interactions of asperities have been investigated with numerical simulations and successfully reproduced the variation in recurrence time and afterslip distribution etc. (e.g., [5], [6]). In these circumstances, it is difficult to extend the Nankai trough model of [2] to the Huganada region.

Furthermore, though we mentioned that we could successfully reproduce the characteristic features of the last three earthquake sequences along the Nankai trough using a heterogeneous frictional distribution in a flat plane model [2], the model could not unfortunately reproduce the large variation of recurrence interval and size observed in the 1707 Hoei, 1854 Ansei and 1944 and 1946 Showa Nankai great earthquakes. Recently, the investigation of tsunami deposit shows that the hyper-cycle of the Hoei-type giant Nankai earthquake may exist and the recurrence intervals of this hyper-cycle are 300–400 years and 700 years (e.g., [7]). Also in other subduction zones, such hyper-cycles in addition to usual great earthquake ones have been suggested [8]. For simulating such hyper-cycles, it seems to be necessary to take different approaches from previous ones.

Lastly, a variety of slow slips have recently been observed. Afterslip occurs in the region between asperities when each asperity ruptures separately. In the same region, the coseismic slip occurs, when several asperities rupture simultaneously to grow up to a giant earthquake. Episodic long-term slow events seem to occur in specific regions. For simulating such slow events, special fault constitutive laws have been introduced in some studies.

2.2 Proposed new model

From above mentioned, it is necessary to construct different models from previous ones, which reproduce the large variation of recurrence interval and size and also the variety of slip evolution on the plate interface in a unified scheme. Here, we propose the model with heterogeneous distribution of fracture surface energy on the plate interface.

In RS law, the frictional parameter L is the characteristic slip distance during which the friction reaches the new level after the slip rate is changed. Numerical simulations show that this parameter L is correlated with the slip weakening distance Dc in the slip weakening law, which is usually used in dynamic rupture propagation researches and the seismic wave analyses (e.g. [9]). Dc characterizes the roughness of sliding surfaces and is related to the surface fracture energy. Accordingly, the frictional parameter L is related to fracture surface energy.

According to the temperature dependence of the parameter a-b obtained in experiments, we set a-$b < 0$ in the seismogenic zone depth as in the case of Nankai trough simulation of [1]. Namely, the parameter a-b is set to be negative both inside and outside of asperities in the seismogenic zone depth. In the seismogenic zone, we assign different values of L in asperities and in other regions, respectively. Namely, we do not model the asperities as heterogeneities in a-b but in L related to fracture surface energy.

As in the simulation of [1], a subducting plate is simply modeled by a flat thrust fault plane in a three dimensional homogeneous isotropic elastic half space. Fault size is 600 km × 240 km. The fault is divided into 3 km × 3 km sub-faults and slip response function for each sub fault is calculated. The slip direction is fixed in dip direction and convergence rate is 5 cm/yr. The rate dependent parameter of $(a$-$b)\ \sigma^{\mathrm{eff}}$ depends only on the depth as shown in Fig. 1(a), where σ^{eff} is effective normal stress. In order to simplify the model setting, we treat two asperities with similar scale as shown in Fig. 1(b). The background of the asperity has about one order higher value in L (2.5 m).

Figure 2 shows the resultant temporal variation of cumulative slip at three positions shown in Fig. 1(b). In the simulation, a giant earthquake and great earthquakes occur alternately. The former ruptures almost the whole seismogenic zone, and the latter rupture two asperities separately. Slip

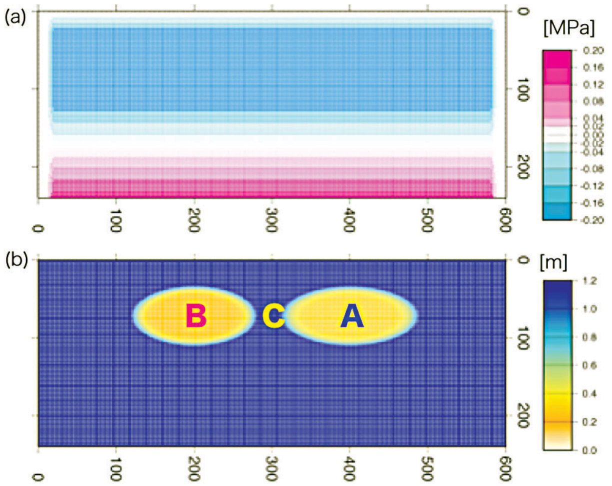

Fig. 1 (a) Distribution of $(a\text{-}b)\,\sigma^{\mathrm{eff}}$ values on a fault plane. No heterogeneity in horizontal direction excluding near the edge.
(b) Distribution of L values on a fault plane. A, B and C indicates the position, where cumulative slip is shown in Fig. 2.

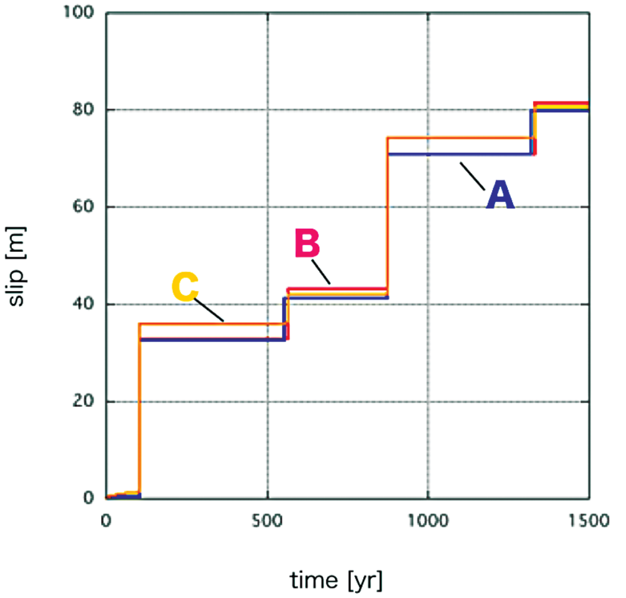

Fig. 2 Temporal variation of cumulative slip at three positions shown in Fig. 1(b).

amount at the center of one of the asperities is several times larger for the giant earthquake (more than 30 m) than for the great earthquakes (less than 10 m). Recurrence interval also varies significantly (roughly twice after the giant earthquake). Such a large variation in recurrence interval is difficult to reproduce in usual earthquake cycle simulations using the heterogeneous distribution of $(a\text{-}b)\ \sigma^{\mathrm{eff}}$.

Furthermore, significant afterslip occurs around asperities after large earthquakes (Fig. 3(a)). Stress versus slip velocity curve shows similar pattern to that estimated from afterslip of the 2003 Tokachi-oki earthquake using GPS data [10]. Episodic slow slip events also occur near the deeper edge of the asperities before the giant earthquake (Fig. 3(b)). Although the duration of the slow slip event is much longer than the real one such as the Tokai slow slip event, stress-slip relation shows similar pattern to that estimated from GPS data [11].

Thus, the earthquake generation cycle simulation with heterogeneous L distribution, which corresponds to fracture surface energy, can qualitatively reproduce various slip patterns actually observed on the plate boundaries. Earthquake cycle simulations with a wide range of distributed L values have been already executed (e.g., [12]), but they focused on statistical properties of seismicity. Here, we focused on the larger scale asperity interaction. One important aspect of our results is that slip pattern and recurrence time interval can significantly differ from each earthquake cycle. Such large variations in earthquake generation cycles have been revealed recently based on a variety of observation data not only in the Nankai subduction zone but also in many other subduction zones.

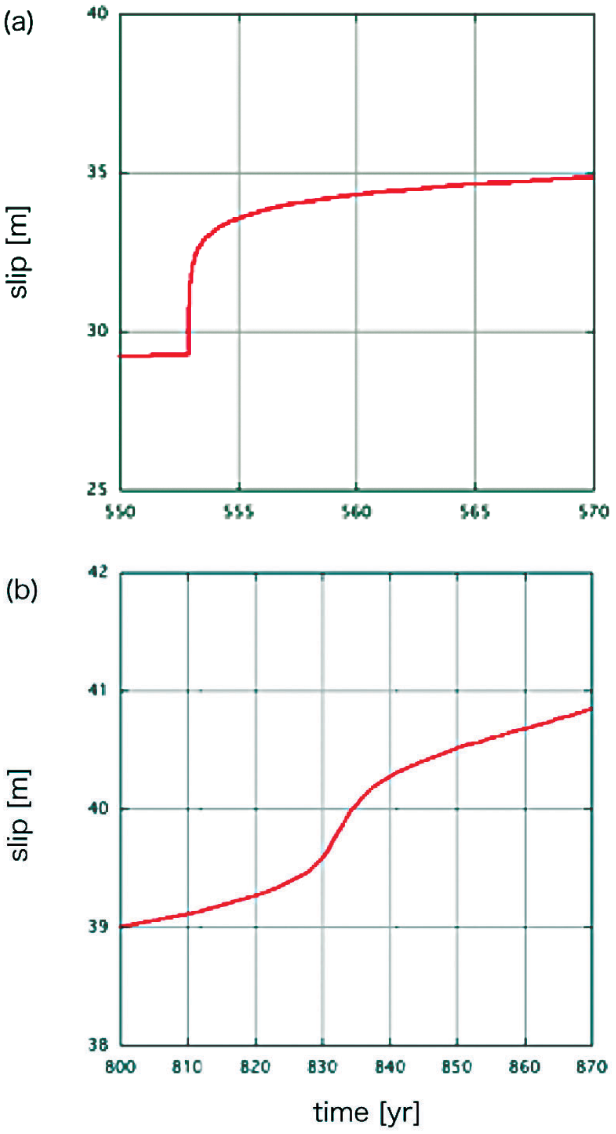

Fig. 3 (a) Cumulative slip for afterslip after a large earthquake at a position in the transition zone.
(b) Cumulative slip for a slow slip event before a great earthquake.

3. Temporal stress changes on inland faults in southwest Japan in a viscoelastic medium during the Nankai trough earthquake cycles

In our project, we constructed a viscoelastic FEM model with 3,563,520 elements in southwest Japan. To investigate the effect of viscoelastic stress interaction between the interplate and the intraplate earthquakes, we simulated the temporal stress changes on inland faults due to the subducting Philippine Sea plate and the interplate earthquake slips, using slip response function calculated by GeoFEM [13]. The inland earthquakes in southwest Japan are caused by east-west compressive stress, but stress perturbation due to the subduction of the Philippine Sea plate and the earthquakes along the Nankai trough might control the occurrence time of inland earthquakes [14]. As in the last year report, we simulated the temporal change of Coulomb failure function ΔCFF. Though we know the occurrence times of Nankai earthquakes, we have no idea of slip amounts except for the last events. Therefore, we assumed the coseismic slip amounts based on slip and time predictable models [15], and showed the slip predictable model better explains the occurrence of the 1891 Nobi earthquake.

In this report, we add the simulation of ΔCFF on 11 inland earthquake faults occurring after the 1946 Nankai earthquake. We show the results based on the slip predictable model in Fig. 4. Generally, on the stress shadow faults whose ΔCFF decrease at the great interplate earthquakes, the inland earthquakes occur after the recovery of ΔCFF. For the faults whose ΔCFF increase at the Nankai great earthquakes, the earthquakes occur around the peak of ΔCFF, except for the earthquakes occurring in the Japan Sea side of the Chugoku region (e.g., 1983 Tottori-ken Chubu and 2000 Tottori-ken Seibu earthquakes). Accordingly, the same results are obtained as reported for old inland earthquakes last year. The occurrence of inland earthquakes is partly controlled by the viscoelastic stress interaction due to the Philippine Sea plate subduction and the Nankai trough great earthquakes. Therefore, we can estimate the probability of the occurrence of the inland earthquake on respective active faults within the current Nankai trough great earthquake cycle, if we accumulate more accurate information on the strike and dip of the active fault and also the viscoelastic structure in the mantle wedge.

In Introduction, we refer to the 2007 Noto Peninsula and Niigata-ken Chuetsu-oki earthquakes, but these are located too far from the Nankai trough, and hence stress changes are so small that we can not relate the occurrences to the Nankai trough earthquakes.

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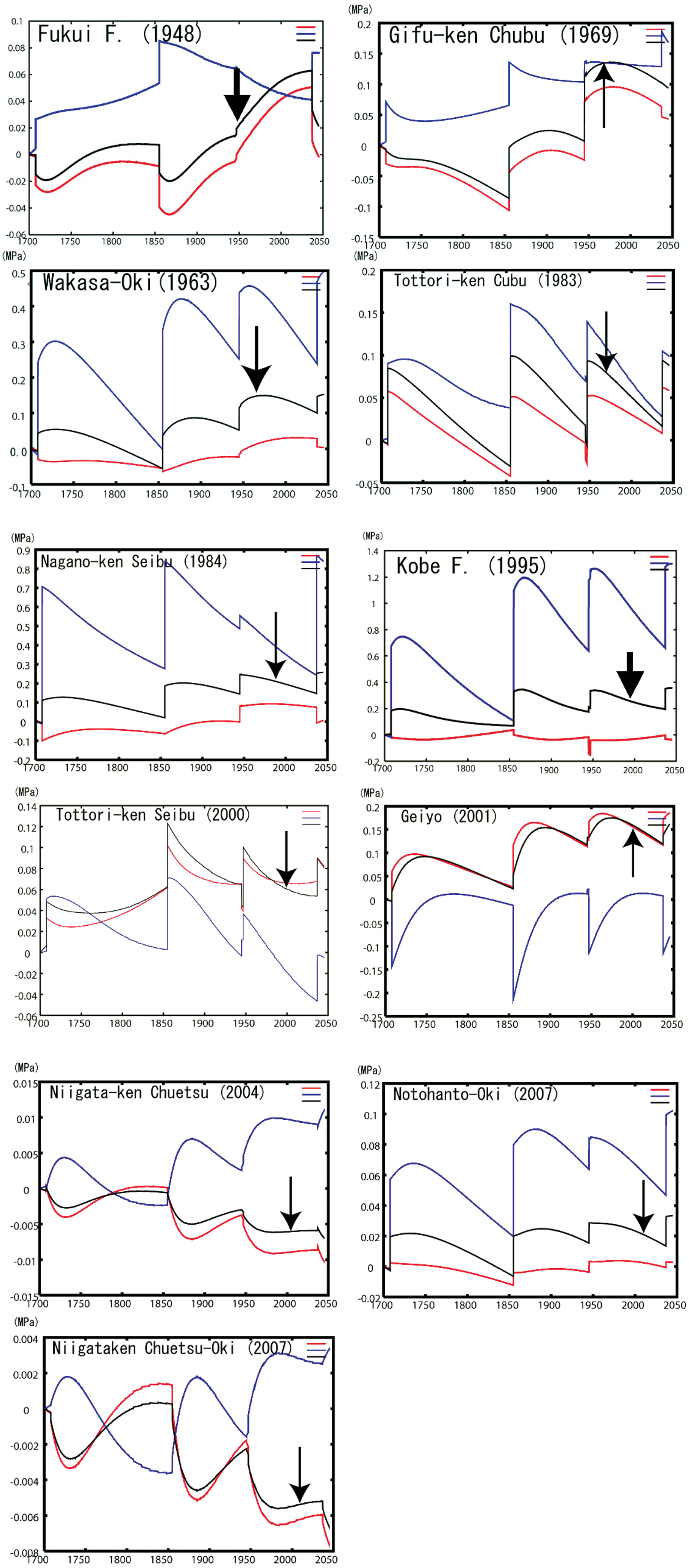

Fig. 4 Temporal changes of normal stress ($\Delta\sigma$, blue; positive in tension), shear stress ($\Delta\tau$, red), and ΔCFF (= $\Delta\tau + \mu'\Delta\sigma$, μ' = 0.3, black) for 11 inland earthquake faults occurring after 1946 Nankai earthquake.
Arrows indicate the occurrence time of inland earthquakes.

複雑断層系の地震発生過程シミュレーション; 2007

プロジェクト責任者
平原　和朗　京都大学大学院理学研究科

著者
平原　和朗　京都大学大学院理学研究科
加藤　尚之　東京大学地震研究所
宮武　隆　東京大学地震研究所
中島　健吾　東京大学大学院理学系研究科
堀　高峰　海洋研究開発機構　地球内部変動研究センター
兵藤　守　海洋研究開発機構　地球シミュレータセンター
里　嘉千茂　東京学芸大学教育学部
殷　峻　先端力学シミュレーション研究所
光井　能麻　海洋研究開発機構　地球内部変動研究センター
有吉　慶介　海洋工学センター
芝崎文一郎　建築研究所
宮村　倫司　日本大学工学部情報工学科
仲間　豊　富士総合研究所
金井　崇　慶應義塾大学環境情報学部

東北日本および西南日本における3次元不均質粘弾性FEMモデルを構築し、複雑断層系における海溝型巨大地震ならびに内陸地震の発生過程のシミュレーションを行うことを目的として、開発を進めている。これまで、均質半無限弾性体における準静的地震サイクル計算では、南海トラフ巨大地震発生サイクルシミュレーションにおいて、平面境界の場合に、実際に歴史地震履歴に見られる規模の変化や発生間隔の変化を定性的に再現することができている。ところが、この不均質摩擦パラメータ分布を用いて計算したところ、3次元プレート形状モデルでのシミュレーションでは、これらがうまく再現されなかった。また、平面モデルにおいても、最近の南海トラフの地震間隔が150年および90年と大きく変ることも再現できていない。そこで、今年度の研究では、摩擦パラメータa-bは室内実験で得られたように温度すなわち深さにのみ依存するとし、破壊表面エネルギーに関係した摩擦パラメータLの不均質を与えてアスペリティーを表現する新たなモデルを構築し、再来間隔やサイズの大きな変化を再現することに成功した。また、余効変動や長期的スロースリップも再現することができた。粘弾性モデルを含むシミュレーションでは、西南日本内陸活断層における、フィリピン海プレートの沈み込みと南海トラフ巨大地震による応力変化(ΔCFF)を、1946年南海地震以降に発生した内陸地震を追加して調べた。その結果、南海トラフ巨大地震によるΔCFFが正の活断層では、南海トラフ地震時からΔCFFがピークを迎えるまでに、内陸地震が発生し、逆に、ΔCFFが負の断層では、南海地震後低下したΔCFFが回復した後に、その内陸活断層で地震が発生しているように見えることが分かった。このように、内陸活断層により今の南海地震サイクルのどの次期に地震発生する確率が高くなるかを予測できる可能性がある。

キーワード：準動的地震サイクルシミュレーション, フィリピン海プレート, 南海トラフ, 摩擦パラメータ, アスペリティー, 破壊表面エネルギー, すべり応答関数, 内陸地震, 応力の時間変化