Simulation of Earthquake Generation Process in a Complex System of Faults: 2008

Project Representative

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In this project, we aim at simulating the generation of interplate and intraplate earthquakes in a complex system of interactive faults in northeast and southwest Japan, respectively.

We use simply a homogeneous elastic half-space medium at present, to simulate quasi-static earthquake cycles based on a laboratory-derived rate and state friction law, in which the long-term slow deformation process is mainly dealt with, though including a quasi-dynamic treatment of dynamic rupture process.

First, we show the simulation of short-term slow slip events and low-frequency tremors recently observed in southwest Japan. Based on so called asperity model in which asperity patch has stick-slip frictional property, while the other areas have stable sliding ones, we set small asperities chained along the trench at the depth of 30 km beneath a large mega-thrust asperity patch on a plate interface. Then, our simulations successfully reproduce short-term slow slips and low-frequency events in the same asperity, and the observed migration speed, indicating that interaction between asperities may cause various types of slow slips.

Following this asperity model, as already reported, for the Nankai trough mega-thrust earthquake cycle in southwest Japan, we reproduced successfully the rupture segmentation and their complicated interactions similar to the actual historical earthquake sequences. However, it was accomplished only by using a flat plate interface, but unfortunately we could not reproduce the one in the case for the realistic 3-D curved plate configuration. And the model could not explain the large variation of recurrence intervals observed in the Nankai trough earthquakes, southwest Japan and in northern Japan. For overcoming this difficulty, last year, we proposed a new friction model with scale-dependent heterogeneous fracture surface energy.

In this year, we first apply this model to the Tokachi-Nemuro areas in northern Japan. This simulation reproduces the large earthquakes rupturing the whole two asperities which may correspond to the large events in 17th century. And the afterslip observed after 2003 Tokachi earthquake is well reproduced. Secondly, we map the last year's new friction model with two asperities on a flat plate interface onto the curved 3-D Philippine Sea plate interface for the Nankai trough earthquake cycle simulation. In spite of shortcomings caused by only two asperities and the same convergence rate set along the Nankai trough, we can simulate actually observed phenomena in the Nankai earthquake cycles such as mega-thrust ruptures confined on a single segment, a large-scale mega-thrust earthquake rupture extending over multiple segments, large variation of recurrence intervals, occurrence of afterslip, even using a 3-D curved plate interface. Thus, this new frictional model is well working even on the realistic 3-D curved interface and would be useful for simulating the complex historical earthquake cycles actually observed along the Nankai trough southwest Japan, and along the Japan trench northeast Japan.

Keywords: quasi-dynamic earthquake cycle simulation, Tokachi-Nemuro, Philippine Sea plate, Nankai trough, frictional parameter, asperity, fracture surface energy, slip response function

1. Introduction

Our purpose in this project is to construct the simulation models for 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 future earthquakes. However, we have so far been mainly constructing simulation models of interplate earthquake cycles in northeast and southwest Japan, respectively. The actual Earth shows viscoelastic behavior with delayed response to the occurrence of earthquake, which seems to be important for understanding the interaction of interplate earthquakes along trenches and intraplate ones in inland areas. For this purpose, we have constructed large-scale 3-D viscoelastic FEM models. However, since it is still formidable to simulate earthquake cycles using 3-D viscoelastic models at present, we have evaluated effects of viscoelastic properties on earthquake cycles and interaction between earthquakes. For viscoelastic simulation, in this year, we examine the mesh generation problems of FEM model construction. We have so far developed the supper parallel FEM-code, GeoFEM [1]. GeoFEM can employ only hexahedra meshes for their high-precisions. It is, however, takes time to construct these meshes in case of the large-scale model including complicated 3-D plate interfaces. Therefore, we decide to extend GeoFEM to use also tetrahedron meshes. This is a technical problem, which is skipped in this report.

For realistic simulations of earthquake cycle, we have simply used a homogeneous elastic half space model. Namely, we divide the plate interface into fine cells with the small sizes of several hundred meters, 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 rate and state friction law with an adaptive time step Runge-Kutta algorithm.

Following so called asperity model, we set heterogeneous frictional parameters representing several asperity patches with stick-slip frictional behaviors and other stable sliding regions on a plate interface, and then by applying relative plate rates, simulate interplate earthquake cycles based on a rate and state friction law. We have successfully simulated asperity interactions such as those in the Sanriku, northeast Japan (e.g. [2]).

In this report, first, using this kind of asperity model, we show simulation results of short-term slow slips and low-frequency tremors recently observed at a depth of 30 km in southwest Japan. There exist several models for the occurrence of slow slip events such as [3] who introduced a velocity cut-off into a rate and state friction law. In our model, using an ordinary rate and state friction law, we set small asperities chained along the trench at the depth beneath a large asperity corresponding to a great earthquake patch. Our simulations successfully reproduce short-term slow slips and low-frequency events in the same asperity, and the observed migration speed, indicating that interaction between asperities may cause various types of slow slips.

Along this direction, we have simulated the earthquake cycles in northern and southwestern Japan to reproduce some features actually observed in historical great earthquake cycles [4], [5]. We could not, however, reproduce the observed large variation of recurrence intervals and sizes in earthquake cycles. Last year, we proposed a new frictional model to produce such an observed large variation based on the heterogeneous distribution of fracture surface energy, and gave a simple example on a flat interface. In this year, we proceed with this approach and apply this new frictional model to simulations of mega-thrust earthquake cycles in the Tokachi-Nemuro areas, northern Japan and also along the Nankai trough, southwest Japan.

For simulation of dynamic rupture propagation, we have developed a contact analysis code implemented in GeoFEM. In this year, we execute dynamic rupture simulation on a realistic dip slip fault. Our simulations show some physically plausible results. However, since the results seem to be still basic ones, we will skip the report of the dynamic rupture simulation.

2. Simulation of short-term slow slips and low-frequency tremors observed in southwest Japan

Recently, various types of slow earthquakes have been globally observed in subduction zones. Especially, in southwest Japan, we have found long-term slow slip events (LSSE), short-term slow slip events (SSSE) and low-frequency tremors (LFT). LSSE and SSSE have the duration times of 0.5 – 5 years and of 2 – 5 days and the recurrence intervals of several years and of 3 – 6 months, respectively (e.g., [6]). In the next section, we refer to LSSE, which occurs in confined regions, the Tokai and the Bungo regions. In this section, we focus on SSSE and LFT, whose occurrences seem to be inter-related. They occur at a depth of 30 km beneath the mega-thrust earthquake asperity patch, and migrate laterally along the trench at a speed of about 5 ~ 15 km/day.

2.1 Simulation model

Figure 1 shows the model of a flat plate interface with a dip angle of 15 degrees and the relative plate rate of 4 cm/year, where the divided cell number is 1024 (in strike) × 195 (in dip). We set the distribution of the frictional parameter *a*-*b* as shown in Fig. 2, and the periodic boundary condition is applied in the strike direction of the trench. A large asperity with negative *a*-*b* (blue) and the characteristic length (*L*) of 4 cm is set in the dip direction distance of 30 – 100 km. And we set two types of chained asperities at the depth of 30 km corresponding to the dip direction distance of around 110 – 120 km. One is the middle-sized asperities with the radius of 5 km and *L* of 0.1 cm, and the other is the small-sized ones with the radium of 2.5 km and *L* of 0.05 cm. Here we use the slowness version of the rate and state friction law. According to [7], we assign the reduced effective normal stress σ in the dip direction distance of 110 – 120 km at the chained asperities

$$\sigma = (1/10)\,(\rho - \rho_w)\ g\ \ z \qquad (1)$$

where ρ, ρ_w, g and z are rock and water densities, gravitational acceleration and the depth, respectively.

2.2 Results and discussion

In the interseismic period of the large asperity earthquake cycle with the recurrence interval of 180 years, aseismic slips occur at the depth of 30 km and propagate laterally at the depth. Figure 3 shows the snap shots of slip rates in the interseismic period around 100 years before the occurrence of large earthquake, which represent the successive rupture of chained asperities. These chained rupture seems to look like propagating aseismic slips. The recurrence interval of the middle asperities is 1.1 – 1.6 years and larger than that of the small ones, 0.5 – 0.8 years. The propagating speed is 0.03 ~ 3 km/day. Furthermore, in regarding to the propagating direction, the chained ruptures of small asperities tend to propagate bilaterally, while that of middle asperities unilaterally. In the case of small and nearby asperities, since aseismic slip surrounds the asperity and the rupture starts in the center of asperity, the propagation becomes bilateral. On the other hand, in the case of middle-sized asperity, the aseismic slip intrudes into the edge of the asperity and the rupture starts at the edge, and hence, the propagation becomes unilateral.

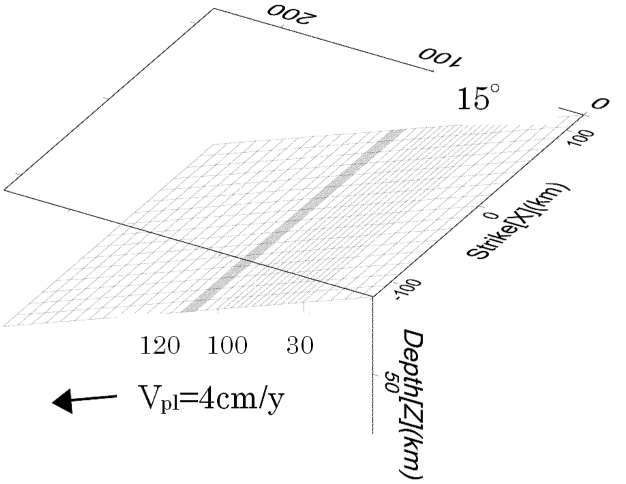

Fig. 1 Model of plate interface.

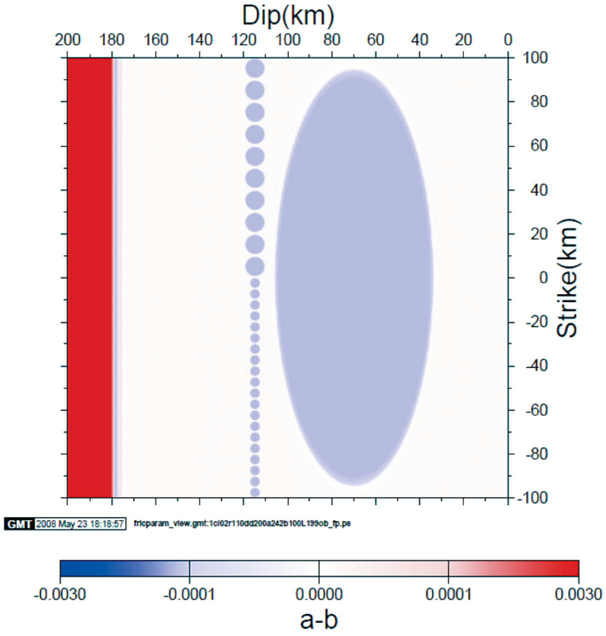

Fig. 2 Distribution of a-b on the plate interface.

In the west of Shikoku region, the recurrence interval of SSEs and LFTs seems to be smaller and the propagation is bilateral, while there are observed the longer recurrence interval and the unilateral propagation of SSEs and LFTs in the northern Kii peninsula. These observations lead us to consider that the size of asperity in the northern Kii peninsula is larger than that in the western Shikoku region, and then the rupture segment tends to be longer in the northern Kii peninsula.

Thus, our simulation succeeds in reproducing various types of slow earthquakes including low-frequency events and rapid slip velocity in the same asperity, indicating that interaction between asperities may cause the low-frequency events. Our simulation also shows chain reaction along the trench with a propagation speed consistent with observations

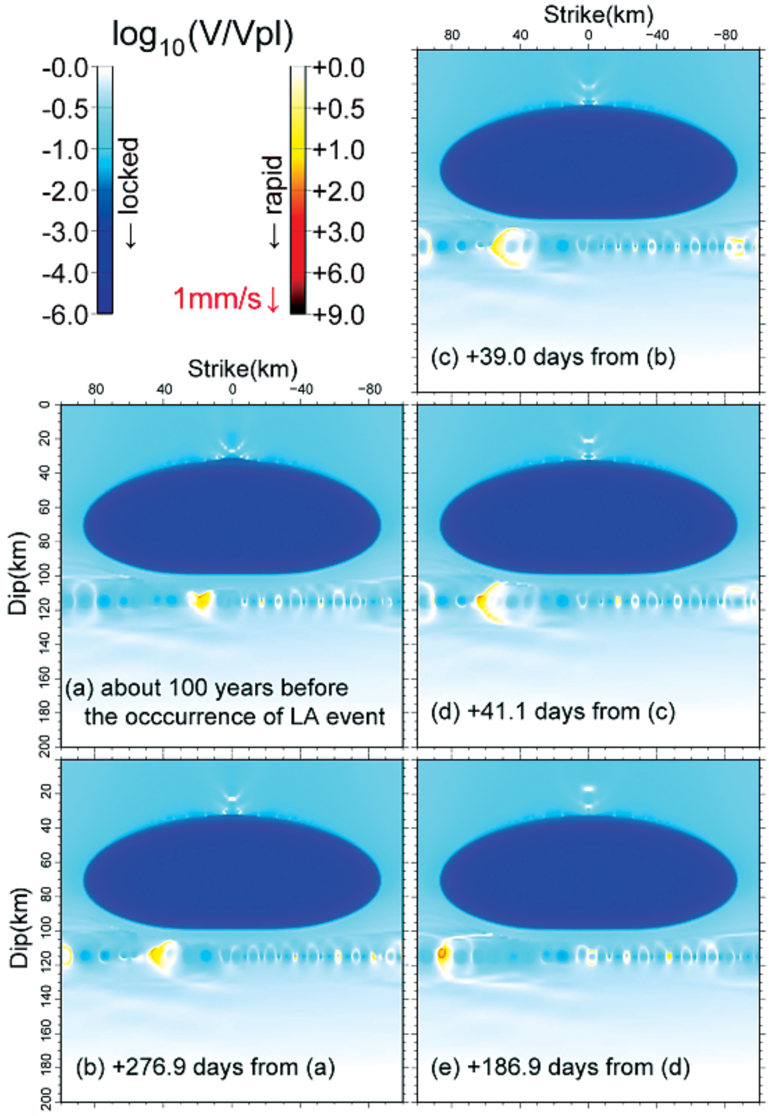

Fig. 3 Snap shot of slip rates showing successive rupture of chained asperities at (a) 100 years before the occurrence of large asperity rupture, (b) +278.9 days, (c) +39.0days, (d) +41.1 days, (e) +186,9 days.

in order level, which suggests that the interactions also explain the observed migration of slow earthquakes.

3. Earthquake cycle simulation with scale-dependent heterogeneity in fracture surface energy

As reported last year, we proposed a new earthquake cycle model. Following [8] and [9], locally consumed fracture energy *Gc* depends on the size of the local asperity and *Gc* is basically proportional to slip weakening distance *Dc*. Such scale dependence and heterogeneity in *Gc* and *Dc* have been introduced in nucleation and rupture dynamics, but not in earthquake generation cycle models with laboratory-derived rate and state friction laws. Based on [10]'s concept for this friction law, state variable can be interpreted as fault strength. Hence, frictional parameters *B* and *L*, which control state evolution, determine strength drop amount and slip weakening distance *Dc* during high speed slip, respectively.

In the usual asperity model, we set the stick-slip frictional property with A-$B < 0$ in the asperity and the stable sliding one with A-$B > 0$ in the surrounding other areas at the seismogenic zone depths. According to the experimental result of [11] using wet granite, however, the frictional property shows stick-slip behavior in the temperature range of 100 – 350˚C , which corresponds to the seismogenic zone depths. Hence, we might set the conditionally unstable frictional property with A-$B < 0$ but with large fracture energy (large *L*) outside of the asperities at the seismogenic zone depths. The new frictional model adopts the latter view of frictional parameters.

3.1 Small asperity case for the Tokachi-Nemuro areas in northern Japan

Thus we introduce scale-dependent heterogeneity in *L* distribution in our model. On the other hand, only depth dependence in *B* is assumed, as shown in Fig. 4a (*A* is constant for simplicity). Here we assume relatively small two asperities with comparable distance of their diameter (Fig. 4b). This asperity distribution is similar to the Tokachi and Nemuro earthquakes observed in northern Japan (Fig. 4c).

In the 17^{th} century, a large event seemed to rupture both asperities and caused large tsunami [12]. The simulation results in Fig. 5 show that large variation in time interval between the largest event, which ruptures the whole seismogenic zone including two asperities, and regular events. Such earthquake occurrence pattern is similar to that in the Tokachi-Nemuro areas. In our simulation, the whole area rupture occurs after the two events recur at each small asperity, although we do not have long enough data for recurrence of the 17^{th} century type earthquakes.

At a site located between the two asperities, slip pattern varies during earthquake cycles for the whole area rupture, as shown in Fig. 6. During the rupture of the whole area, coseismic slip occurs also in this site and its slip amount is large. After the rupture, that portion becomes locked. Then slow slip starts around the occurrence of events at small asperities. Finally, significant afterslip occurs after the second events at small asperities. Afterslip occurs around the asperities, which is similar to that after the 2003 Tokachi-oki earthquakes (Fig. 4c). We will apply our model to realistic plate geometry and boundary condition in the near future,

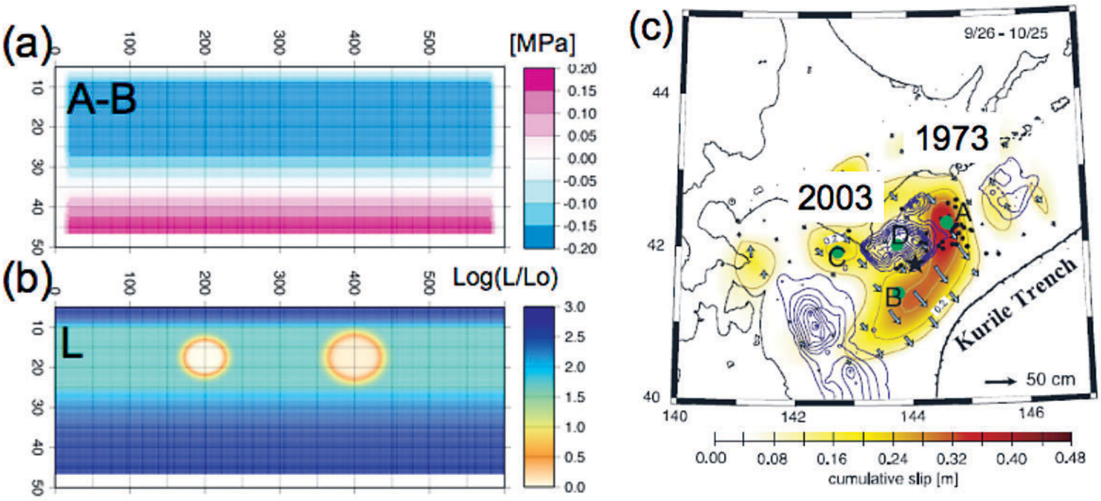

Fig. 4 (a) Distribution of *A*-*B* values on a fault plane. No heterogeneity in horizontal direction excluding near the edge. (b) Distribution of *L* values on a fault plane. Smaller patch has smaller *L* value and for the background the value is much larger. (c) Colored contour indicates afterslip of the 2003 Tokachi-oki earthquake. Black contour shows coseismic slip distribution of the 2003 Tokachi-oki and 1973 Nemuro-oki earthquakes. Modified from [13].

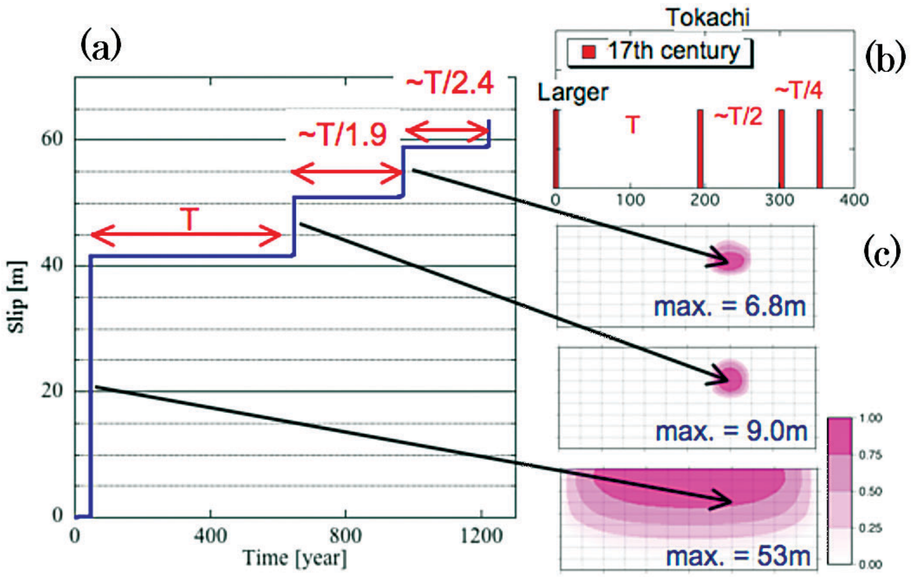

Fig. 5 (a) Cumulative slip variation in a small asperity. Time intervals of earthquakes are shown in red relative to that just after the largest event. (b) Time interval variation in historical earthquakes in Tokachi area. (c) Coseismic slip distribution for each event.

and also try to reproduce quantitatively the slip pattern in Tokachi region.

3.2 Large asperity case for the Nankai trough mega-thrust earthquake in southwest Japan

We have set the value of *a-b* to be negative in the depth range of seismogenic zone in earthquake cycle simulations in the Nankai trough great earthquake cycle simulation (e.g. [4], [5]) where M8 class asperities exist. This model using a flat plate interface with laterally changing seismogenic zone widths successfully reproduced the qualitative features observed in the last three great Nankai earthquakes [5]. Using a realistic 3-D curved plate interface, however, we could not succeed in simulating the observed features. And, even using the flat plate model, which explained the features qualitatively, could not reproduce quantitatively the features such as large variations of recurrence intervals. Therefore, last year, we introduced a new friction model to reproduce large variation of recurrence intervals. But the model was a flat plate interface. Therefore, we try to set a new frictional model on a 3-D curved interface of the actual Philippine Sea plate. It is to be noted, however, that, in the model, we do not intend to reproduce the features actually observed in the Nankai earthquakes, but we simply map the previous two-asperity model used on the flat plate interface last year onto the 3-D curved plate one.

Figure 7 shows the distributions of frictional parameters on the actual interface of the 3-D Philippine Sea plate. The upper figure indicates the distribution of *L*, and large two asperities have smaller *L* compared with the other areas with larger fracture energy at seismogenic zone depths. As you notice in this model, we have no asperity corresponding to the Tokai one. As shown in the lower figure of Fig. 7, the frictional parameter *A*-*B* is dependent only on the depth. The actual plate convergence rate is changing along the Nankai trough, namely, increasing westwards, but at present we set the same rate of 4 cm/year along the Nankai trough.

Figure 8 shows the simulated accumulation of slips at two sites indicated by crosses, and coseismic slip distribution corresponding to three earthquakes. In this model, only the asperity corresponding to the Tonankai segment (Tonankai asperity) breaks independently, but the Nankai asperity cannot break independently but the rupture extends over both two asperities, when the Nankai asperity breaks. This may be caused by setting the same convergence rate along the Nankai trough. The stressing rate off the Kii peninsula is so high due to the high dip angle there that the rupture starts there. Off the Shikoku region, the stressing rate is not so high due to low dip angle that the rupture cannot start independently. Since the actual rate in the western region is larger than in the eastern one, these shortcomings would be improved if we set the westward increasing rate.

In spite of these shortcomings, it is to be noticed that this model successfully reproduce the large variation of recurrence interval from 170 to 80 years as indicated by the blue line in Fig. 8. This amount of change is comparable to that from 150 to 90 years actually observed in the last three Nankai earthquakes. And also note that we can succeed in rupturing the whole two asperities on a curved 3-D plate interface. This cannot be realized in the old asperity model.

Finally, we show the afterslip evolution in the deeper portion beneath the mega-thrust asperity in Fig. 9. This afterslip follows the rupture of the eastern Tonankai asperity. Though we do not show here, this model can reproduce the long-term slow slips such as the Tokai and the Bungo ones. Thus, our new friction model with scale-dependent heterogeneity in fracture surface energy would be very powerful for reproducing a variety of slip properties.

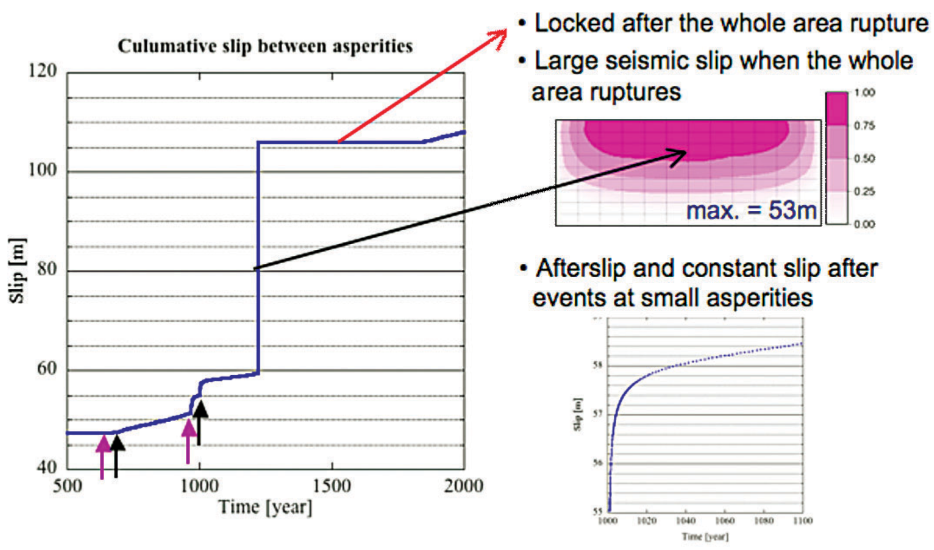

Fig. 6 Cumulative slip variation at a site located between the two small asperities. Small arrows indicate events at the small asperities.

In this report, we show very preliminary models based on the new frictional model with scale-dependent heterogeneity in fracture surface energy. If we set asperities and boundary conditions such as plate rates corresponding to the observed ones, this model would reproduce some of complex features observed in the historical earthquake sequences to provide information of value on the future great earthquakes.

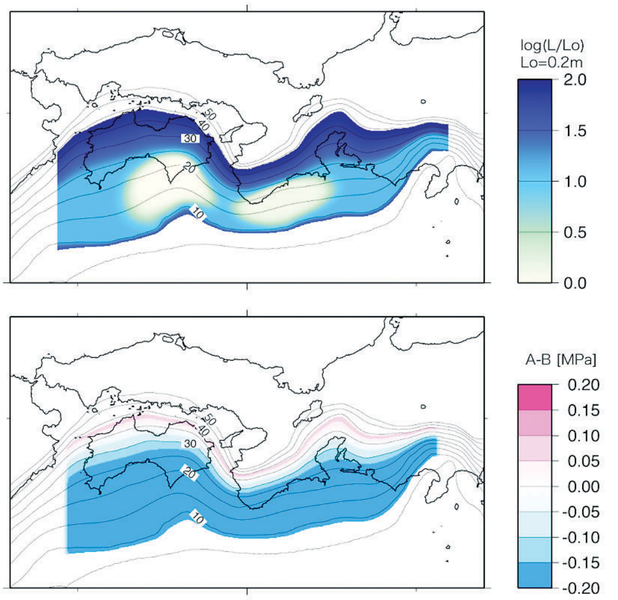

Fig. 7 Distribution of *L* (upper) and of *A-B* (lower) on the actual 3-D Philippine Sea plate interface.

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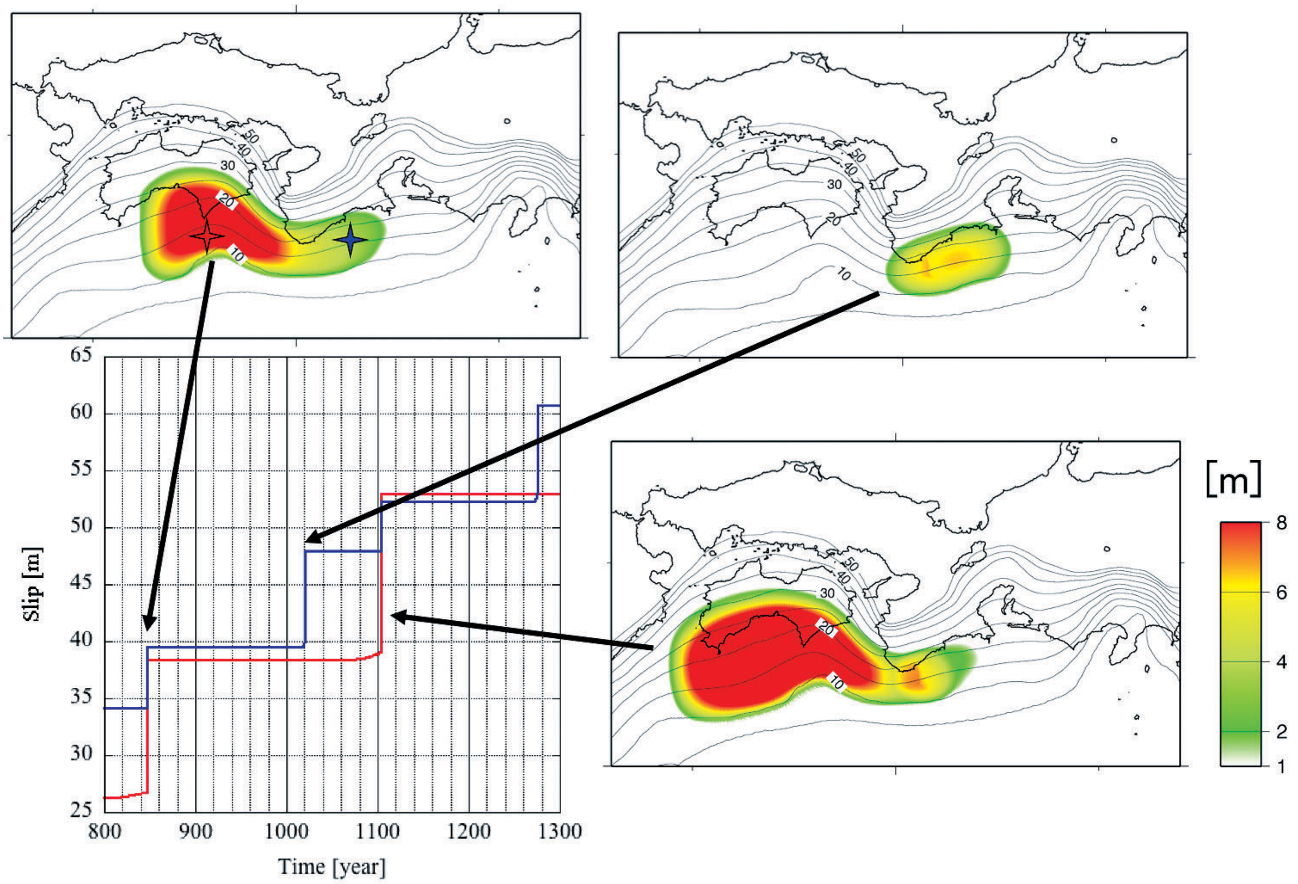

Fig. 8 Accumulated slips (lower left) at two sites indicated by crosses in the upper left figure. The blue and red lines correspond to that of accumulated slip at the eastern and the western site, respectively. Three figures showing coseismic slip distributions correspond to those at the times indicated by arrows, respectively.

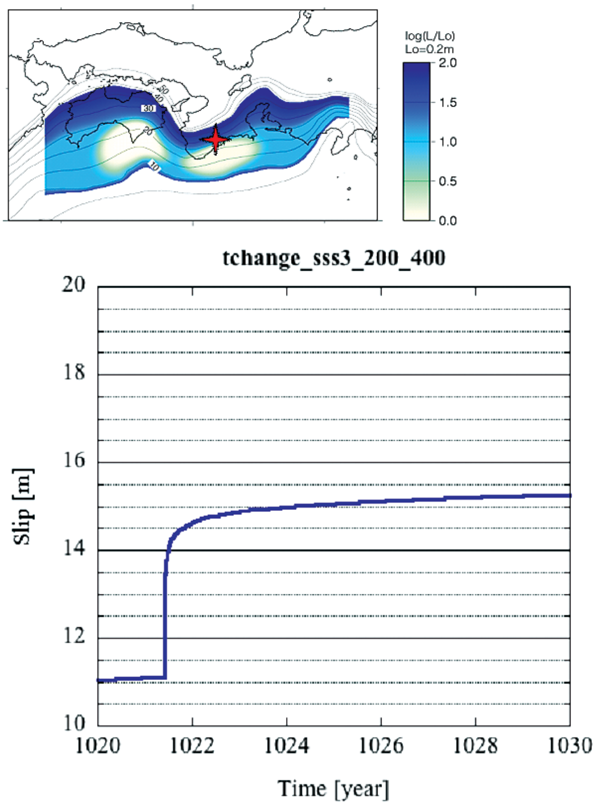

Fig. 9 Afterslip evolution after the eastern asperity earthquake (Tonankai earthquake) at the site indicated by cross in the upper figure.

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複雑断層系の地震発生過程シミュレーション; 2008

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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、実際的なシミュレーションでは、均質半無限弾性体における準静的地震サイクル計算法を用いてきた。まず、アスペリティー域に固着—すべり、他の領域に安定すべりの摩擦特性を与える、アスペリティーモデルを用いて、西南日本で最近発見された、短期的スロースリップ(SSSE)と低周波微動(LFT)のモデリングをおこなった。巨大地震に対応する大きなアスペリティーの下部に小さなアスペリティーパッチを連ねて置き、地震サイクルシミュレーションを実行した。その結果、観測された繰り返し間隔や移動速度を説明する、小アスペリティーの連動破壊が実現できた。これは、SSSEやLFTが小アスペリティーの連動破壊によって生じている可能性を示唆している。

アスペリティーモデルを用いた、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、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、昨年度の研究では、規模依存の破壊エネルギーの不均質分布を与えるという新たなモデルを提案した。今年度は、このモデルをまず十勝沖地震に適応した。その結果、17世紀に発生した可能性のある、2つのアスペリティーを含む広い領域を破壊する巨大地震を発生させることができた。また、2003年十勝沖地震後に観測された余効変動と同様に、1つのアスペリティーの破壊後には余効すべりを発生させることができた。次に、昨年度の平面モデルでの摩擦モデルを、沈み込むフィリピン海プレートの3次元形状を考慮して取り込み、シミュレーションを実行した。2つのアスペリティー(実際には、東海、東南海、南海の3つ)や南海トラフに沿って一定の沈み込む速度を与えていることに起因する不備はあるものの、観測されている繰り返し間隔の大きな変化に匹敵する倍半分の変化がシミュレートでき、また、3次元形状を考慮したうえで、連動破壊が実現できた。このように、この新たな摩擦モデルを用いて、観測に対応するアスペリティー配置や沈み込む速度を与えれば、過去の地震発生履歴や複雑な破壊様式を再現し、将来発生する巨大地震について貴重な情報を与えうる可能性が開かれたと言える。

キーワード: 準動的地震サイクルシミュレーション, 十勝—根室, 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