Simulation of Earthquake Generation Process in a Complex System of Faults

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Constructing regional 3-D heterogeneous models in northeast and southwest Japan, respectively, we aim to simulate generation processes of interplate and intraplate earthquakes in a complex system of interactive faults. This simulation consists of two processes; one is quasi-static earthquake cycle simulation, and the other is simulation of dynamic rupture propagation.

In quasi-static earthquake cycle simulations based on a rate- and state-dependent friction law in semi-infinite elastic media, we have so far used flat plane interfaces of subducting plates. In this year, we introduce 3-D curved interfaces of subducting plates and execute the following three simulations. 1) In the eastern Hokkaido, north Japan, we simulate great interplate earthquake cycles along the southern Kuril trench off the Tokachi to Nemuro regions, where the Pacific plate is subducting. Here, though the M8-class Tokachi-Oki earthquake occurred in 1952 and 2003, and the Nemuro-Oki in 1894 and 1973, every events have different rupture modes. In this region, the giant earthquake, which ruptured the whole region off Tokachi to Nemuro regions, is estimated to occur in the 17-th century. To understand these complex sequence of earthquake occurrence, we put three asperities with $a-b < 0$ in the Tokachi-Oki, the Akkeshi-Oki and the Nemuro-Oki rupture regions within the stable sliding plate interface with $a-b > 0$, and simulate earthquake cycle. Our simulation shows that the possible existence of asperities with a larger value of characteristic slip distance L in the Akkeshi-Oki source region, modulates the mode of rupture off the Tokachi and Nemuro regions, producing complex rupture patterns like the historical ones. 2) In southwest Japan, we simulate great earthquake cycles along the Nankai trough. So far, using a flat plane interface of the subducting Philippine Sea plate but changing the width of locked zone along the trough corresponding to the configuration of the plate, we have simulated earthquake cycles and found a possibility that the great earthquakes along the Nankai trough always start to rupture off Kii Peninsula. Assuming the frictional properties depend only on the depth, simulations with the actual 3-D curved interface of the Philippine Sea plate also confirm this conclusion. 3) One of factors for the occurrence of slow slip events has been proposed to be the slab dip change. To assure this, we use a model of slab with laterally changing dip to simulate earthquake cycle. In a transition zone from the unstable to the stable ones, we confirm the occurrence of slow slip event in the lower dip portion in the latter period of the great earthquake cycle.

Next, we evaluate the slip response function in heterogeneous media. Constructing a 3-D heterogeneous elastic FEM model in the region from the Tohoku to the Hokkaido, we compare the slip response functions with those from homogeneous models and find the 3-D heterogeneous structure affect the deformation pattern.

For dynamic rupture simulation, we improve our scheme in the FEM calculation of dynamic rupture. Therefore, in a strike slip faulting model, we can obtain the same results of dynamic rupture as those in the previous studies by different techniques, indicating our code is well working in a strike slip faulting.

Toward realistic simulation, a large-scale viscoelastic FEM model of southwest Japan is reconstructed by using CHIKAKU software.

Keywords: quasi-static earthquake cycle, 3-D curved interface, Tokachi-Oki earthquake, slip response function, Philippine Sea plate, Nankai trough, slow slip event, slab dip, heterogeneity

1. Introduction

The Japan Islands is located at the subduction zone, where are converging four plates, the Pacific, the Philippine Sea, the North American and the Eurasian (Amurian) plates. The Pacific plate is subducting beneath the northeast Japan along the Kuril and the Japan trenches, and the Philippine Sea plate descends beneath the southwest Japan along the Nankai trough. These subducting plates produce great interplate earthquakes along the Japan trench and the Nankai trough with recurrence times of 100 years. Further we have another type of earthquakes with recurrence times of longer than 1000 years, which are inland earthquakes occurring in active faults.

The main purpose in our project is to simulate earthquake generation cycles of both interplate and inland earthquakes for providing us basic information on past and future earthquakes. Since there exist strong variations in the structure beneath the Japan Islands, which are produced by the subducting plates, we construct detailed regional heterogeneous FEM models in northeast and southwest Japan, respectively, and try to simulate earthquake generation cycle in a regional scale.

Our simulation of earthquake cycle consists of two processes; quasi-static and dynamic rupture ones. In the first part of earthquake cycle simulations, 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 friction law. In this simulation, we take the following approach of boundary integral equation method. 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 3-D viscoelastic FEM model, where the plate interface is further divided, using GeoFEM, a super-parallel FEM code (Iizuka et al., 2002), which we have tuned up for the Earth Simulator. 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. In dynamic earthquake cycle 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.

Before simulation in complicated 3-D viscoelastic models, we first 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 (Hori et al., 2004; Hori, 2006). Here, we extend this approach to include the actual curved 3-D interfaces of the subducting plates in the quasi-static simulation of earthquake cycles along the southern Kuril trench, north Japan and along the Nankai trough, southwest Japan, respectively. For application of curved interface, we give another example of slow slip events (SSEs), which have recently observed by GPS observations (e.g., Hirose et al., 1999; Ozawa et al., 2002). Mitsui and Hirahara (2006) have recently proposed that the change in the slab dip is one of factors for generation of SSEs. We simulate earthquake cycles due to the subducting slab with laterally changing dip along a trench to show the effect of the dip on the occurrence of SSEs. For laterally heterogeneous media, we evaluate slip response functions in a 3-D Hokkaido elastic model. These simulations show that the lateral heterogeneity in elastic structure greatly affect the displacement fields.

For calculation of slip response function, we need to construct 3-D viscoelastic FEM models. We reconstruct the FEM model of southwest Japan by CHIKAKU software, though we do not describe here. For simulation of dynamic rupture propagation, we test the performance of contact analysis code implemented in GeoFEM using simple plane models. We introduce an effective damping scheme to prevent some oscillations in slip velocity due to numerical dispersion. This introduction of damping scheme improves our simulation of dynamic rupture propagation and gives almost the same results as those obtained by previous studies with different methods in strike slip fault models. Because of still simple problems, we skip the report here.

2. Quasi-static simulation of earthquake cycle with actual curved 3-D interfaces of subducting plates

2.1 Simulation of earthquake cycle along the southern Kuril trench in eastern Hokkaido, north Japan

In eastern Hokkaido, north Japan, great earthquakes have repeatedly occurred off the Tokachi and the Nemuro regions along the Kuril trench where the Pacific plate is subducting. Earthquakes occurred in 1952 and 2003 off the Tokachi region and in 1894 and 1973 off the Nemuro region, respectively. The tidal records observed at a station have shown different tsunami waveforms due to each earthquake since 19th century, which implies the earthquake cycle in this region is complex (Satake and Yamaki, 2005). Further, geological evidences of tsunami deposits have shown that the giant earthquake far larger than such great earthquakes, which ruptured the whole region off Tokachi to Nemuro occurred in the 17th century (Nanayama et al., 2003).

The source region of the 2003 Tokachi-Oki earthquake is overlapping with the western one of the 1952 earthquake (Yamanaka and Kikuchi, 2003). The 1952 earthquake has the tsunami source region close to the trench off the Akkeshi region (Hirata et al., 2003). The afterslip following the 2003

Tokachi-Oki earthquake extended eastwards, keeping away from the 1952 tsunami source region (Baba et al, 2006). These suggest the existence of three asperities in the Tokachi-Oki, the Akkeshi-Oki and the Nemuro-Oki source regions.

2.1.1 Model setting

For simulation, we construct the 3-D curved interface of the subducting Pacific plate down to 120 km depth estimated from the seismic explosion studies and the micro-earthquake distribution (Fig. 1), and divide the interface into 85,488 triangles with their sides of 1 km. Assuming a semi-infinite homogeneous elastic medium, we calculate slip response functions for each triangle fault. We assign the subduction rate of 8.25 cm/yr with a direction of N46.6°W, and simulate based on a rate- and state-dependent friction law using 312 PE (39 nodes).

As described before, we assume three asperities in the 2003 Tokachi-Oki, the 1952 Tokachi-Oki and the 1973 Nemuro-Oki earthquake source regions with velocity weakening of a–b<0. Other regions of the plate interface, where the afterslip has been observed, has frictional property of velocity strengthening of a–b>0 (Miyazaki et al., 2004). For the 1952 Tokachi-Oki source region off Akkeshi, we assign larger characteristic distance L of 0.5 m so that this asperity is not easily ruptured by afterslip intrusion. Figures 2a and 2b show the distribution of (a–b) σ (σ: normal stress) and L, respectively.

2.1.2 Simulation results

Figure 3 displays spatio-temporal distributions of slip velocity derived from one of simulation results. As can be seen from this figure, the asperity in the Akkeshi-Oki source region, which has larger L and hence larger fracture energy than other two asperities, modulates respective earthquake cycles, and produces a variety of rupture patters which can be seen in the historical earthquake cycles in this region; the

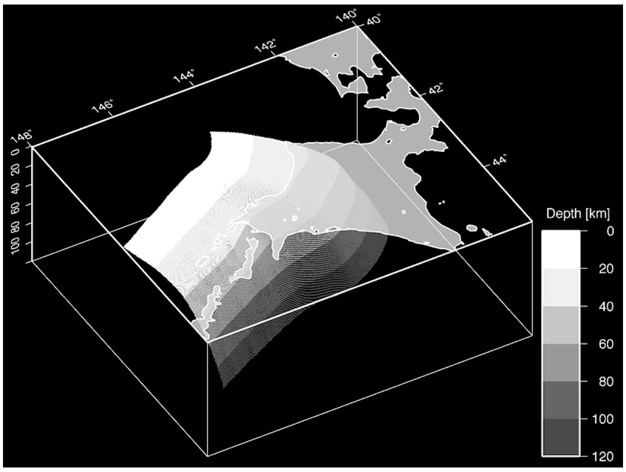

Fig. 1 Curved 3-D interface of the subducting Pacific plate beneath the Hokkaido region.

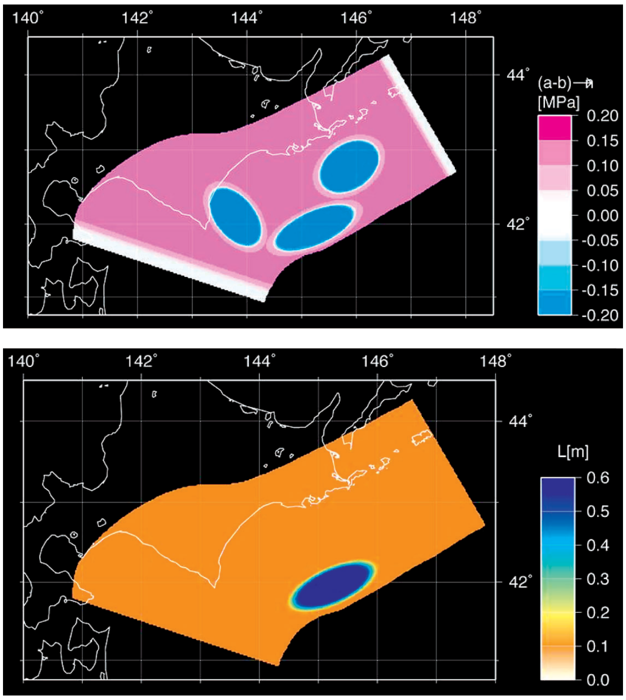

Fig. 2 (a) Distribution of (a–b) σ (upper). (b) Distribution of L (lower).

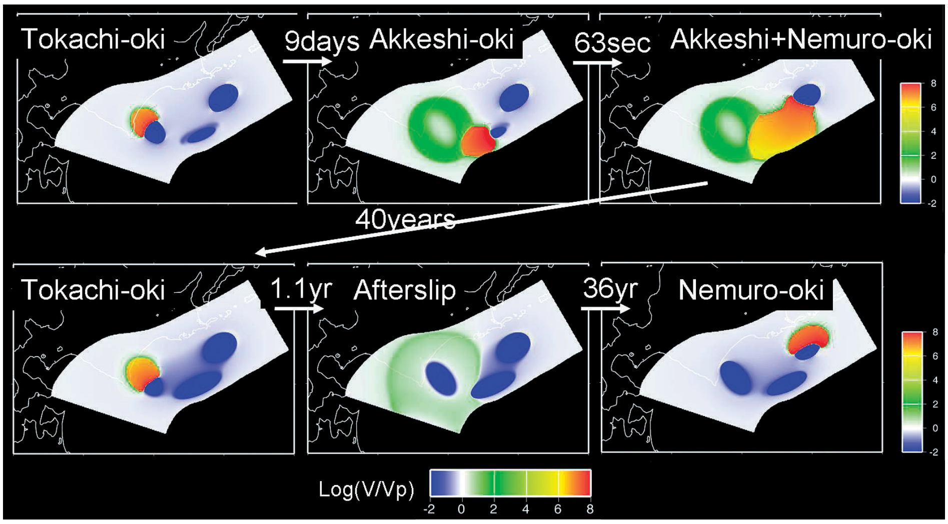

Fig. 3 Spatio-temporal distributions of slip velocity derived from one of simulations of earthquake cycle along the southern Kuril trench. Red and blue colors indicate the seismic slip and the locked state, respectively.

Tokachi-Oki and the Nemuro-Oki asperities sometimes break solely, the Akkeshi-Oki and the Nemuro-Oki earthquakes sometimes occur simultaneously, and the Akkeshi-Oki earthquake sometimes follows immediately the Tokachi-Oki one. Simulation results including those, which are not shown here, indicate that the recurrence times of the Tokachi-Oki and the Nemuro-Oki earthquakes are fluctuating and are about 40–70 and 65–75 years, respectively.

2.2 Simulation of earthquake cycle along the Nankai trough, southwest Japan

Instead of the flat plane which we have so far used, we model the 3-D curved interface of the subducting Philippine Sea plate with triangles with sides of 1 km. Assuming the frictional properties depend only on the depth, we assign the distribution of frictional parameters as shown in Fig. 4. As in our previous simulations, the convergence rate of the Philippine Sea plate varies along the Nankai trough, which is taken from Heki and Miyazaki (2001). The convergence rate is around 2 cm/yr in the Tokai region, and increases westwards and reaches 6.5 cm/yr around the west of Kii peninsula.

Figure 5 shows the slip velocity distribution when the rupture of earthquake initiates off Kii peninsula. Simulation results with the 3-D curved interface show that the earthquake always initiates off Kii peninsula and the rupture bilaterally extends to the whole focal region, which is the same conclusion in case of the flat plane interface with the changing width of the locked zone along the Nankai trough corresponding to the 3-D configuration of the plate (Hori et al., 2004). Thus, we confirm that the plate interface off Kii peninsula has higher stressing rate and the hypocenter is always located there, because the locked zone there is narrower because of its steeper dip.

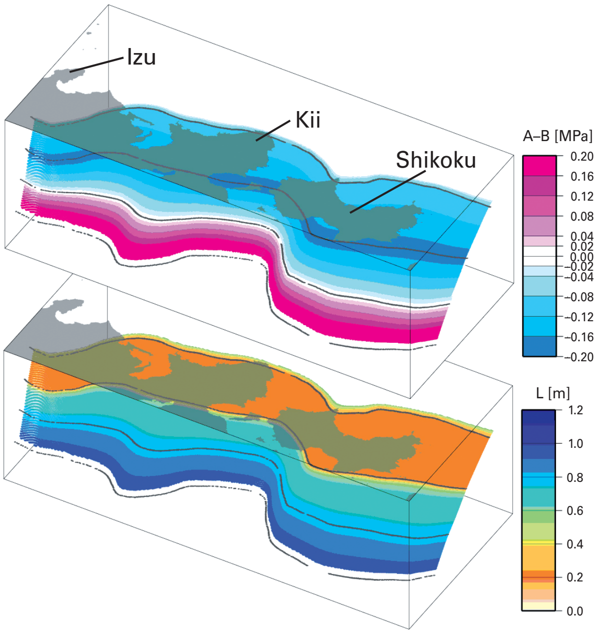

Fig. 4 3-D curved interface of the Philippine Sea plate and the distributions of A-B ((a–b) σ) (upper) and of L (lower).

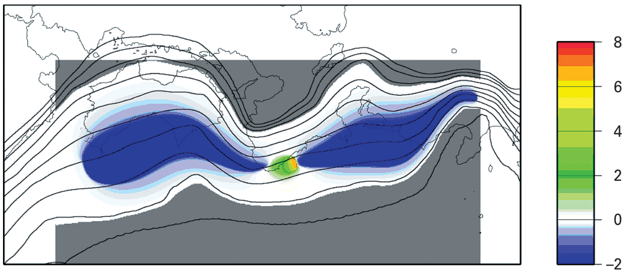

Fig. 5 Slip velocity distribution when the rupture initiates off Kii peninsula.

2.3 Occurrence of slow slip events on the curved plate interface with laterally changing dip along a trench

To examine the hypothesis that the change of slab dip is one of factors for causing slow slip events (SSEs) based on cell model simulations proposed by Mitsui and Hirahara (2006), we model the curved plate interface, whose dip laterally changes along a trench, to simulate earthquake cycles.

The plate interface has a uniform dip of 10° at depths of 5–25 km. The dip is, however, laterally changing from 10° to 25° along the trench at depths 25–40 km as shown in Fig. 6. The locked zone with a–b<0 is set to be at depths of 10-30 km as shown in Fig. 7. The characteristic distance L is taken to be

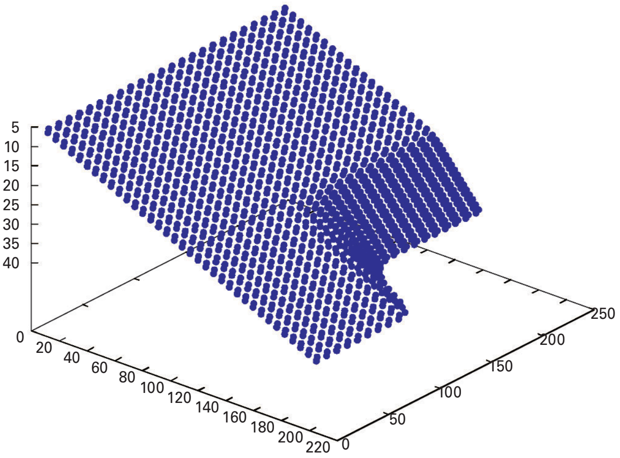

Fig. 6 Curved plate interface.

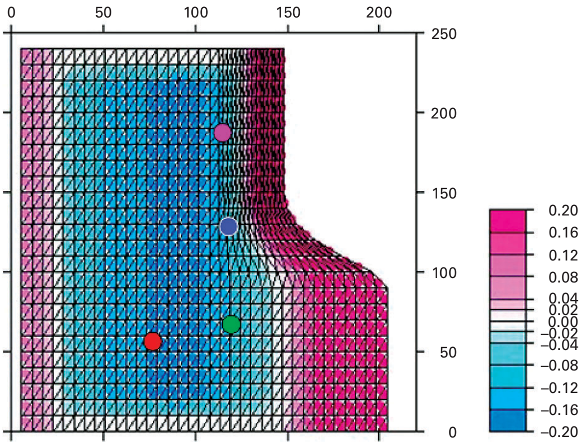

Fig. 7 Distribution of (a-b) s in MPa.
Red, light green, blue and pink circles indicate the locations whose slip velocity and slip are shown in Figs. 8 and 9.

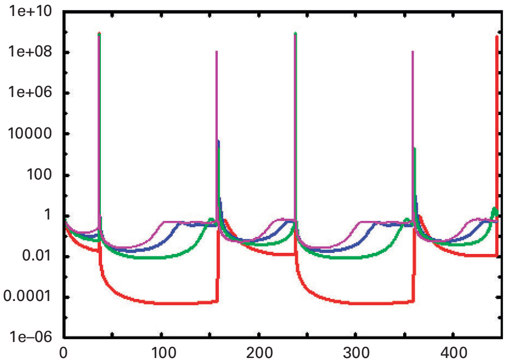

Fig. 8 Histories of slip velocity (log(V/Vp)) at the points in Fig. 7.

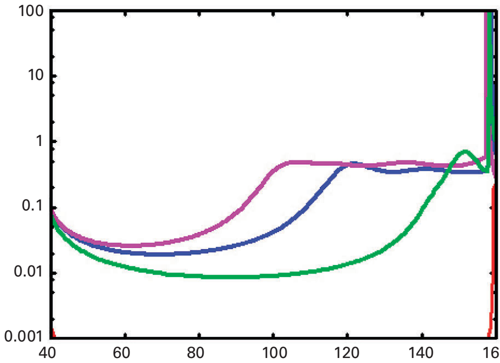

Fig. 9 Slip histories during a period of 40–160 years at the points in Fig. 7.

0.1 m everywhere. Plate convergence rate (Vp) is 4 cm/yr everywhere in the model.

Figure 8 shows the temporal changes of slip velocity at locations indicated in Fig. 7. And the histories of slip are shown in the enlarged figure of Fig. 9. The red line in Fig. 8 shows the earthquakes occur in the locked zone. The light green and pink lines show the slip velocities and slips at the points in the transition zone on the gentle and the steep side of the plate interface, and the blue one on the plate where the dip is changing. Only in the area with a gentle dip (light green point), SSEs occur during the earthquake cycle, where the plate coupling becomes weaker and locked zone becomes narrower, hence the slip velocity increases and accelerates. To the contrary, in the area with a steeper dip (pink point), the locked zone becomes narrower and slip velocity increases faster than in the area with a gentle dip, but slips at a constant rate. It is noted that, after the occurrence of SSEs, the rupture of the earthquake in the locked zone starts at a point different from that where SSEs occur. Thus, the SSEs do not trigger the rapid rupture, but the occurrence of SSEs is indicative of the temporal stage in the earthquake cycle.

3. Surface deformation in 3-D heterogeneous elastic media in the Tohoku to the Hokkaido regions, north Japan

To examine the effect of the heterogeneous elastic structure on the surface deformation, we construct a 3-D FEM model in the regions from Tohoku to Hokkaido as shown in Fig.10. The numbers of nodes and of meshes are 151,040 and 142,506, respectively. Figure 11 shows the slips assigned on the plate interface to calculate the deformation at the surface. Figure 12 displays the cross section along Y = 600 in Fig.11 where are given the material region names of the upper and the lower crust, the upper mantle and the subducting Pacific plate.

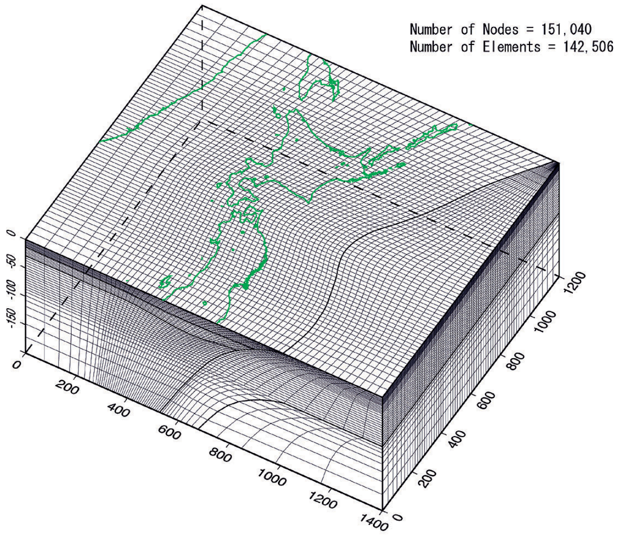

Fig.10 Elastic FEM model in the regions from Tohoku to Hokkaido.

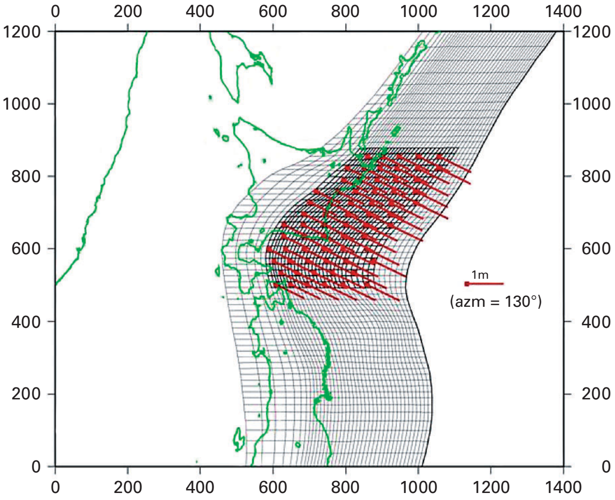

Fig.11 Iso-depth of the Pacific plate interface and small faults where slips are assigned for calculation.

In Fig.13, we compare the horizontal displacements due to a slip on the sub-fault 074 in the homogeneous model and the heterogeneous model with lower rigidity in the crust and larger rigidity in the plate. As shown in Fig.13, the results of simulation indicate that the deformation at the surface differs by 20% between the homogeneous and the heterogeneous elastic models. Though usual estimates of back slip distribution from the inversion of the surface deformation observed with GPS have assumed the homogeneous elastic medium, it would be necessary to assume the inhomogeneous model derived from seismic data. And we need to calculate the deformation associated with earthquake cycle.

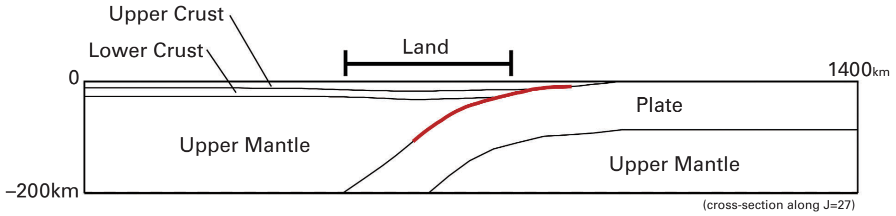

Fig.12 Cross section along Y = 600 in Fig.11 and region names.

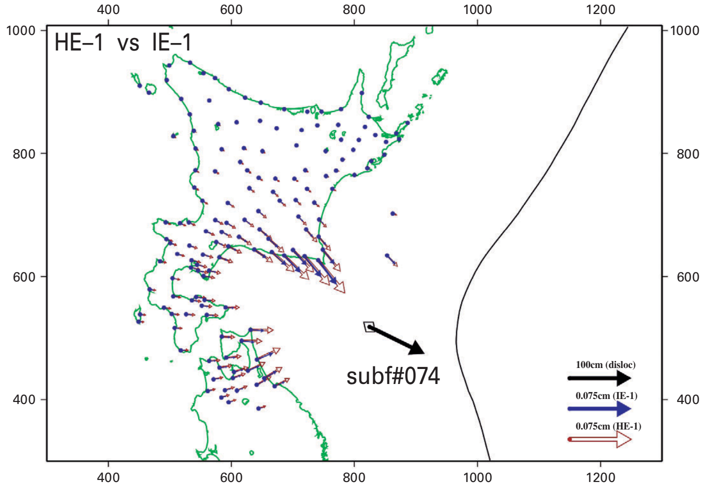

Fig.13 Horizontal displacements in the homogeneous model HE-1 and the inhomogeneous model IE1 for a slip on sub-fault 074.

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複雑断層系の地震発生過程シミュレーション

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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。準静的地震発生サイクルシミュレーションにおいては、境界要素法的解法を用い、すべり応答関数を計算し、すべり速度と状態に依存する摩擦則とカップルさせてプレート境界でのすべり速度の時空間変化を解く。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、これまで簡単のため、平面境界を用い、沈み込むプレートの3次元形状の効果は近似的に取り入れてきただけであった。そこで、今年はプレート境界面の屈曲した3次元形状をモデルに組み込みシミュレーションを実行した。まず、北海道東部における地震サイクル計算を行った。ここでは、1952年、2003年にM8クラスの十勝沖地震、1894年、1973年に根室沖地震が発生しているが、毎回異なった破壊様式を持っている。また、17世紀には十勝沖と根室沖に及ぶ全領域を破壊したと思われる超巨大地震が発生している。このように、複雑な地震発生サイクルが形作られている。十勝沖、厚岸沖、根室沖に3つのアスペリティー（a–b<0の領域）を置き、また厚岸沖のアスペリティーに大きなLを与えることによって、実際に見られている複雑な地震サイクルを部分的に再現することに成功した。西南日本の南海トラフ巨大地震サイクルでは、摩擦特性が深さのみに依存すると仮定して、屈曲したフィリピン海プレートの形状をモデル化してシミュレーションを行ったところ、破壊は毎回紀伊半島沖から始まり全領域を破壊した。これは、これまでの平面断層モデルでの結論を裏付けるもので、プレートの沈み込み角度が急な紀伊半島沖では、固着域の幅が狭く応力蓄積速度が高いため、破壊の開始点になる可能性が高いことが、確かめられた。また、プレートの沈み込み角度の変化がスロー地震の発生要因の一つであるとセルモデルから提唱されているが、プレートの沈み込み角度が海溝に沿って変化する場合にスロー地震が発生しやすいことを、連続詳細モデルのシミュレーションによって確かめた。最後に、媒質の不均質性の効果が地表変形に与える影響を評価するため、地殻やプレートを含む3次元不均質弾性FEM北海道モデルを構築し、プレートの境界にすべりを与え、生じた地表変形を均質モデルのよるものと比較したところ、20％におよぶ違いが生じた。

キーワード：準静的地震サイクル，屈曲した3次元境界面，十勝沖地震，すべり応答関数，フィリピン海プレート，南海トラフ，スロー地震，スラブの傾斜，不均質性