Simulation of Earthquake Generation Process in a Complex System of Faults

Project Representative
Kazuro Hirahara Graduate School of Environmental Studies, Nagoya University

Authors
Kazuro Hirahara Graduate School of Environmental Studies, Nagoya University
Naoyuki Kato Earthquake Research Institute, University of Tokyo
Takashi Miyatake Earthquake Research Institute, 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
Jun Inn Advanced Simulation Technology of Mechanics
Noa Mitsui Graduate School of Environmental Studies, Nagoya University
Takayuki Sasaki School of Engendering, University of Tokyo
Tomoshi Miyamura College of Engineering, Nihon University
Yutaka Nakama Fuji Research Institute Cooperation
Takashi Kanai Faculty of Environmental Information, Keio University

Constructing regional 3-D heterogeneous viscoelastic FEM 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.

This year, we mainly develop quasi-static simulation. To investigate some basic features of frictional properties in a rate- and state-dependent friction law, assuming a simple plane fault in a semi-infinite elastic medium, we simulate quasi-static earthquake cycles due to the subduction of the Philippine Sea plate (PHS) along the Nankai trough in southwest Japan. In addition to the lateral variations in convergence rate and in the frictional property reflecting its depth-dependency and the plate configuration, we assign small lateral heterogeneities in frictional property off Kii Peninsula and off the Tokai region corresponding to heterogeneous structures revealed by recent seismic surveys. This model with heterogeneities in frictional property produces segmentation of earthquake fault and complicated rupture interaction of the segments, which successfully mimic the historically recurring great earthquakes along the Nankai trough. Toward realistic simulation, a large-scale viscoelastic FEM model of southwest Japan is constructed by using CHIKAKU software.

Keywords: quasi-static earthquake cycle, asperity, segmentation, Philippine Sea plate, Nankai trough

1. Introduction

The 26 December 2004 Sumatra-Andaman Islands earthquake, the second largest earthquake since 20th century, whose moment magnitude is 9.3, generated large Tsunami, which caused devastating disaster including a heavy loss of 300,000 lives. The earthquake occurred in a subduction zone where the Indian plate is subducting beneath the Burma plate. The Japan Islands is also located in a subduction zone, where the Pacific plate is subducting beneath northeast Japan along the Kuril and the Japan trenches, and the Philippine Sea plate descends beneath southwest Japan along the Nankai trough. In Japan, we have two types of large earthquakes which cause great disaster in Japan: one is the M8-class great interplate earthquake along trenches with a recurrence time of around 100 years, and the other is the M7-class inland earthquakes on a active inland fault with a recurrence time longer than 1000 years.

We aim to simulate earthquake generation cycles for both interplate and inland earthquakes. For this purpose, we need to take into consideration the strong variation in the structure beneath the Japan Islands. As a variety of geophysical surveys such as seismic tomography have recently revealed, there exist strong variations in the structure beneath the Japan Islands, which are produced by the subducting plates.

Therefore, we construct detailed regional FEM models in northeast and southwest Japan, respectively, and try to simulate earthquake generation cycle in a regional scale.

The earthquake cycle simulation consists of two processes; quasi-static and dynamic ones. In quasi-static earthquake cycle simulations, we simulate slow stress accumulation and slip evolution on plate interfaces or inland faults due to relative plate motions based on a friction law. For 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, an 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 function treating contact interfaces in GeoFEM.

Before simulating realistic quasi-static earthquake cycles in complicated 3-D viscoelastic models, we 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, last year (Hori et al., 2004). Here, we extend this approach to the inclusion of asperities in the earthquake cycle simulation along the Nankai trough, southwest Japan. In the following, first, we show that lateral heterogeneities in frictional property play an important role in producing the segmentation of earthquake fault and the complicated rupture patterns due to segment interaction.

For calculation of slip response function, we need to construct 3-D viscoelastic FEM models. We show the FEM model of southwest Japan, which is newly produced by CHIKAKU software.

For simulation of dynamic rupture propagation, we test the performance of contact analysis code implemented in GeoFEM using simple plane models. After tuning several parts, we have successful results in comparison with the ones obtained in previous studies. Because of still simple problems, we skip the report here.

2. Quasi-static simulation of earthquake cycle along the Nankai trough, southwest Japan: segmentation of earthquake fault and complicated segment interaction in rupture

2.1. Last year's model with lateral variations in frictional property due to the configuration of subducting Philippine Sea plate

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

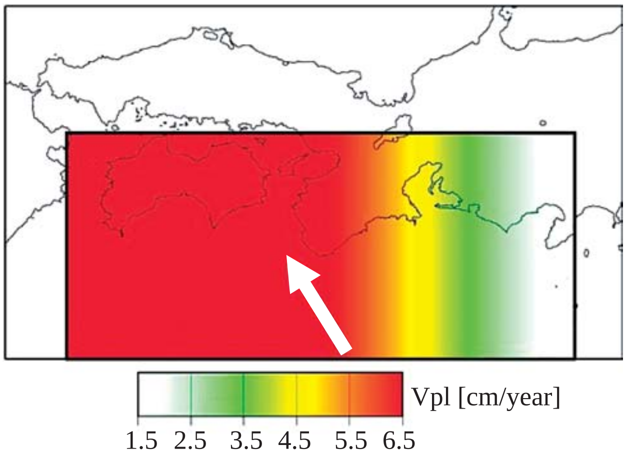

Fig. 1 Convergence rate and direction of the Philippine Sea plate along the Nankai trough assigned in the simulation

Last year, we tried to simulate the earthquake cycle using a simple plane interface in a semi-infinite homogeneous elastic medium, taking into consideration the varying convergence rate along the Nankai trough (Hori et al., 2004). We set a 691.2 km × 311.94 km plane interface and divided the plane into 1.20 km × 1.22 km cells. According to Heki and Miyazaki (2001) who estimated the convergence rate based on GPS observation data, we set the westwardly increasing rate along the Nankai trough from 1 cm/yr in the Suruga Bay to 6.5 cm/yr off Kii Peninsula and around the Shikoku region as shown in Fig. 1.

We considered also the effect of the complicated configuration of the Philippine Sea plate. Assuming the frictional parameters are dependent on the depth, they were mapped on the flat model plane, which resulted in lateral variation in frictional property corresponding to the changing dip angle of the plate. In the simulation results, the earthquake repeatedly occurred with recurrence times of around 100 years and the rupture always started off Kii Peninsula as in the case of the 1944 Tonankai and the 1946 Nankai earthquakes. Both the effects of a narrower locked area due to the larger dip angle and a faster convergence rate caused the highest stress accumulation rate in this area, promoting slip nucleation. The rupture propagated both eastwards and westwards, and broke the whole seismogenic zone every time in this model.

2.2. Model including small lateral heterogeneities in frictional property

Historical documents and seismo-archaeological data indicate, however, that the whole source region was not always ruptured and the rupture pattern was complicated (e.g. Ishibashi and Satake, 2001). The plate interface is divided into five segments A-E corresponding to geological and geophysical structures, and the source region is further grouped into three segments, the Nankai A-B, the Tonankai C-D and the Tokai E segments, respectively, as shown in Fig. 2. The rupture of the Tonankai segment C-D and the Tokai segment E usually preceded that of the Nankai one A-B. The delay times were 2 years and 32 hours for the 1944 Tonankai and the 1946 Nankai events and for the 1854 Ansei event, respectively. As in the case of the 1707 Hoei event, the rupture happened to expand to the whole source region A-E. The rupture did not always reach the Tokai segment E as in the case of the 1944 Tonankai event.

For producing the fault segmentation, we introduce small lateral heterogeneities in frictional property into our model. Off Kii Peninsula, Baba and Cummins (2005) analyzed Tsunami data to show the existence of the large coseismic slip around the epicenter of the 1946 Nankai earthquake, suggesting that fracture energy is locally high in this area. There we put larger B-A [σ_n(b-a)] and L values than those in the surroundings. Seismic surveys revealed that the low velocity region and reflective layers exist in the shallow locked zone of the Philippine Sea slab (Kodaira et al.,2004b) also off Kii Peninsula. This suggests the existence of stable sliding region, and we put a positive A-B value there. Off the Tokai region, Kodaira et al. (2004a) presented that a series of the ridge subduction occur there. Corresponding to the subducted ridge, we put larger B-A and L values than those in the surroundings. In addition to the depth-dependent frictional property which we used in the simulation last year, we put small heterogeneities in frictional property corresponding to the above mentioned so called asperities. The resultant distributions of A-B and L are displayed in Fig. 3.

Based on this model with asperities, we simulate six earthquake cycles in 667 years, where the computational time is 7.4 hours using 128 nodes. Fig. 4 shows examples of

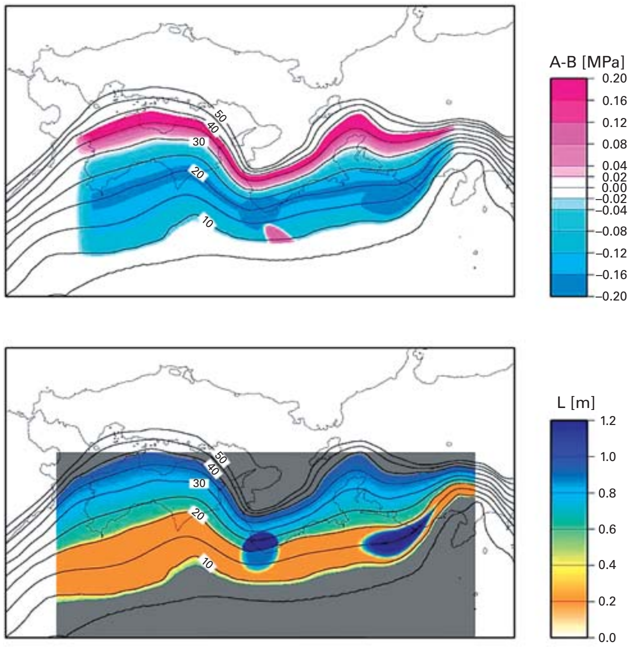

Fig. 3 Distribution of A-B [σ_n(a-b)] (upper) and L (lower) used in the simulation

snapshot of coseismic slip distribution in simulated two earthquake cycles. In the figure, the first event ruptures the Tonankai C-D and the Nankai A-B segments, leaving the Tokai one E unbroken. 110 years later, the second event occurs and the rupture extends to the Tonankai and the Tokai segments C-E, and then 6 days later the Nankai segments A-B is broken. The third event occurs 103 years after the second event. This event ruptures only the Tonankai segment C-D, and then 91 days later the Nankai segment A-B is broken. In Table 1, we summarize the interval times between successive earthquakes cyles and the complicated rupture patterns representing segment interaction in rupture.

Thus, the model with small heterogeneities in frictional property successfully simulates the fault segmentation and the complicated rupture patterns appearing in historical earthquake cycles along the Nankai trough in Fig. 2. Our

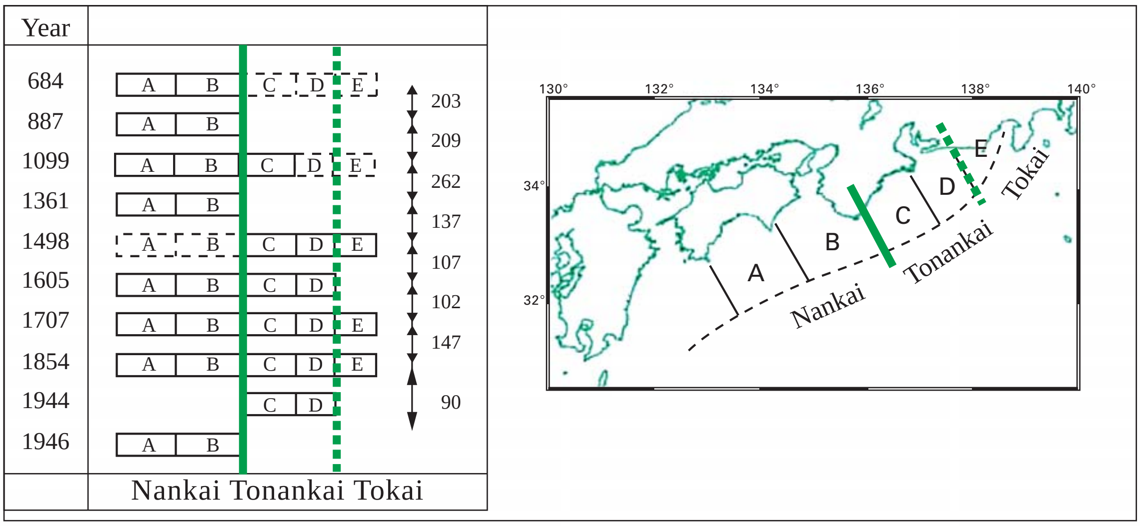

Fig. 2 Segmentation and complicated rupture pattern of great earthquakes along the Nankai trough

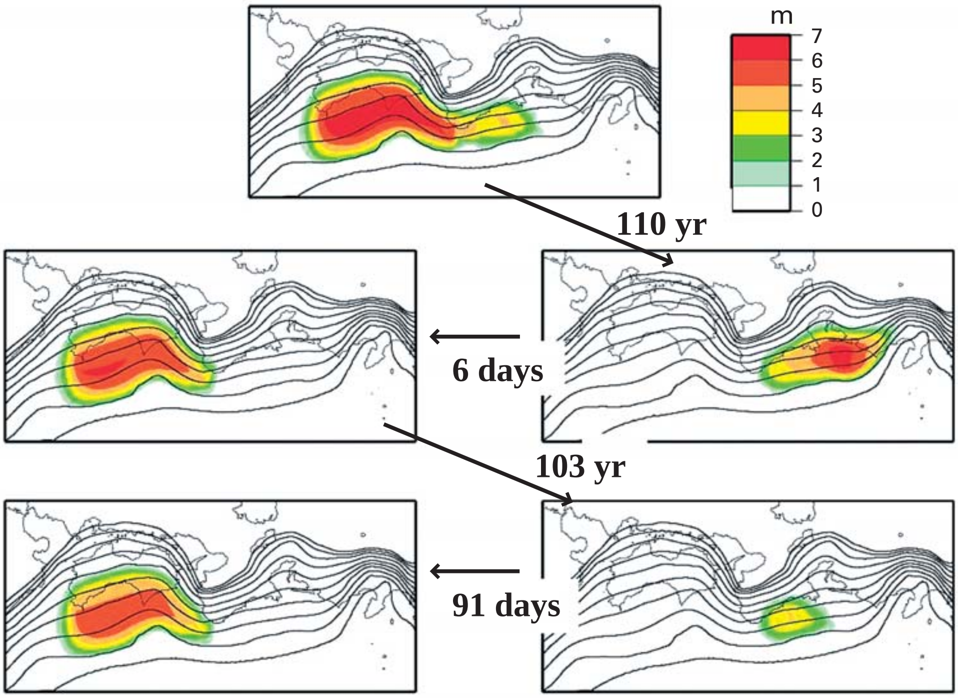

Fig. 4 Snapshots of distribution of coseismic slips whose slip velocities exceed 1 cm/s during two earthquake cycles. Arrows indicate time advance and the numerals mean time intervals between successive snapshots.

simple simulation indicates that the asperities or barriers which are small heterogeneities in frictional property make an important role in controlling the fault segmentation and the segment interaction in rupture.

Now, we discuss what roles the heterogeneities in frictional property introduced into the model are playing in controlling segmentation and rupture complexity in more details. First, we introduced the lateral variation of convergence rate along the Nankai trough and also the lateral variations in frictional property due to its depth dependency and the configuration of the subducting slab, though they were already introduced last year. Off Kii Peninsula, the locked zone width becomes narrower due to a large dip of slab and the rate is faster, both of which promote stress accumulation there and cause the rupture nucleation there. Second, also off Kii Peninsula, we introduced two regions with the larger B-A and L values at depth of 10-30 km and with the positive A-B in the shallow locked zone. They are working as barriers for westward rupture propagation and separate the fault zone into the eastern and the western segments. Third, off the Tokai region, we introduced the region with the larger B-A and L values corresponding to the subducted ridge. This is working as a barrier for eastward rupture propagation, and the rupture does not reach the Tokai segment every second time. Finally, it is noted that the larger L values assigned at depths larger than 20 km make the larger change in the interval of each earthquake cycle and in the rupture complexity between segments. This suggests that aseismic slip at depth also controls the complexity in rupture and in segment interaction during successive earthquake cycles.

Table 1 Interval times between successive great earthquakes and complicated rupture pattern during simulated six earthquake cycles Circles mean that the earthquake ruptures the segment.

Lapse time (years)	Interval	Nankai	Tonankai	Tokai
24.0	–	○	○	○
135.4	111.4 years		○	
135.5	26 days	○		
203.7	95.2 years		○	○
203.9	69 days	○		
343.4	111.2 years	○	○	
453.1	109.6 years		○	○
453.1	6 days	○		
556.1	103.0 years		○	
556.3	91 days	○		
667.1	110.8 years	○	○	○

In this study, we tentatively assigned small lateral heterogeneities in frictional property referring to the heterogeneous structures which are investigated by seismic surveys, and found the heterogeneities in frictional property play an important role in producing the complexity of earthquake cycle. Further detailed studies on heterogeneities in frictional property would be needed to make realistic simulation of earthquake cycle along the Nankai trough.

3. 3-D viscoelastic FEM model in southwest Japan

For realistic earthquake cycle simulation, we construct a large scale 3-D viscoelastic FEM model in southwest Japan by using CHIKAKU software, a mesh generation software, developed by Riken and JAERI. Fig. 5 shows the FEM meshes. The numbers of nodes and elements are 466,725 and 445,440, respectively. The mesh size on the plate inter-

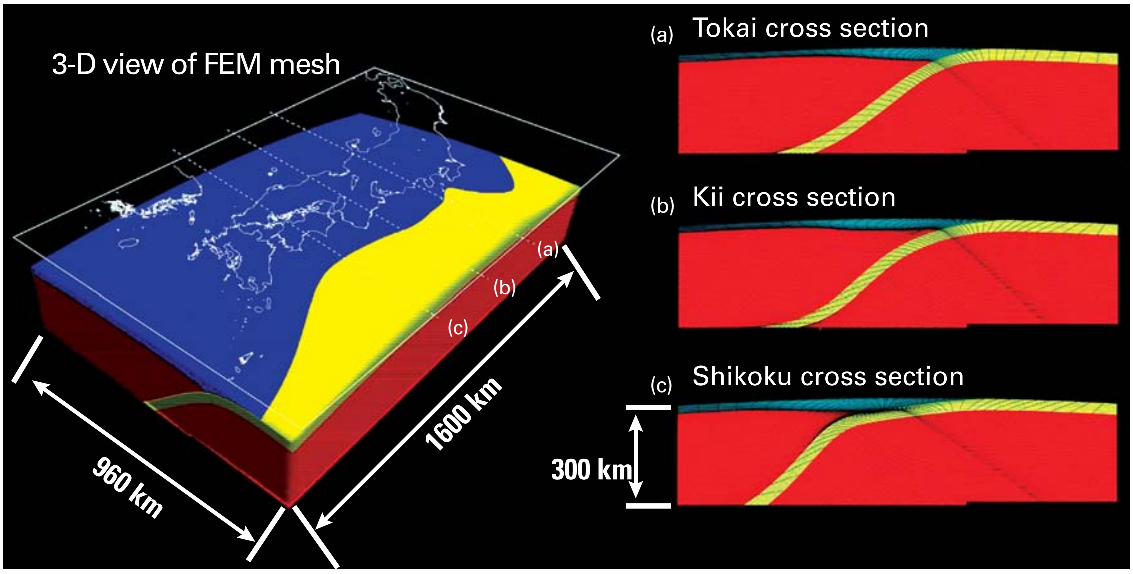

Fig. 5 Meshes of 3-D viscoelastic FEM model in southwest Japan

face is 10 km, which is too large to calculate slip response functions. Cell size should be 1 km for assuring precise calculation of slip evolution based on a rate- and state-dependent friction law. Therefore we need to subdivide the meshes of this model into smaller ones with a size of several 100 m and calculate slip responses in Earth Simulator.

References

[1] Baba, T. and P.R. Cummins, Contiguous rupture areas of two Nankai earthquakes revealed by high-resolution tsunami waveform inversion, Geophys. Res. Lett., 32, L08304, doi:/10.1029.2004GL022320, 2005.

[2] Heki, K. and S. Miyazaki, Plate convergence and long-term crustal deformation in central Japan, Geophys. Res. Lett., 28, 2313-2316, 2001.

[3] Hori, T., N. Kato, K. Hirahara, T. Baba, and Y. Kaneda, A numerical simulation of earthquake cycles along the Nankai trough, southwest Japan: Lateral variation in frictional property due to the slab geometry controls the nucleation position, Earth Planet. Sci. Lett., 228, 215-226, 2004.

[4] Iizuka, M., D. Sekita, H. Suito, M. Hyodo, K. Hirahara, D. Place, P. Mora, O. Hazama and H. Okuda, Parallel simulation system for earthquake generation: fault analysis modules and parallel coupling analysis, Concurrency Computat.: Pract. Exper., 14, 499-519, 2002.

[5] Ishibashi, K. and K. Satake, Problems on forecasting great earthquakes in the subduction zones around Japan by means of paleoseismology, Zisin 50 suppl., 1-21 (in Japanese with English abstract), 1998.

[6] Kodaira, S., T. Iidaka, A. Kato, J. Park, T. Iwasaki and Y. Kaneda, High pore fluid pressure may cause silent slip in the Nankai trough, Science, 304, 1295-1298, 2004a.

[7] Kodaira, S, S. Miura, G. Fujie, A. Ito, J. Park and Y. Kaneda, Abnormally low velocity in the uppermost mantle at a segmentation boundary between the rupture zones of the Nankai-Tonankai earthquake, PROGRAMEE and ABSTRACTS, the Seismological Society of Japan, 2004 Fall Meeting, B068, 2004b

複雑断層系の地震発生過程シミュレーション

プロジェクト責任者

平原　和朗　　名古屋大学大学院　環境学研究科

著者

平原　和朗　　名古屋大学大学院　環境学研究科

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

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

殷　　　峻　　先端力学シミュレーション研究所

光井　能麻　　名古屋大学大学院　環境学研究科

佐々木隆行　　東京大学大学院　工学系研究科

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。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、GeoFEMを用いて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解く。西南日本を例に取り、大規模弾性平面問題でこのコードの性能の評価を行った。昨年は、南海トラフ巨大地震のシミュレーションで、沈み込むフィリピン海プレートの形状に対応した摩擦パラメータ分布を与え、破壊が紀伊半島沖で始まる可能性を示した。これに加え、地震探査等から推定されている構造の不均質性に対応する摩擦特性の不均質性を、紀伊半島沖と東海沖に導入した。こういったバリアまたはアスペリティーを導入することにより、実際の南海トラフ巨大地震発生サイクルに見られる、断層面のセグメント化やセグメント間の連動現象を再現することに成功した。このように、摩擦特性の不均質は、南海トラフにおける複雑な地震サイクルを再現する上で重要な意味をもつことが分かった。

また、より現実的な3次元粘弾性媒質における、すべり応答関数を計算するため、メッシュ作成ソフトウェアCHIKAKU（原研・理研）を用いて、西南日本粘弾性不均質GeoFEMモデルを再構築した。

キーワード：準静的地震サイクル，アスペリティー，セグメント化，フィリピン海プレート，南海トラフン