Development of a Predictive Simulation System for Crustal Activities in and around Japan - VII

Project Representative

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Our research group aims to develop a physics-based predictive simulation system for crustal activities in and around Japan, which consists of a combined simulation model for quasi-static stress accumulation and dynamic rupture propagation and the associated data assimilation software. In the first phase (2003-2005), we constructed a prototype of the combined simulation model on a realistic 3-D structure model. In the second phase (2006-2008), we tested the validity and applicability of the combined simulation model, and demonstrated that the physics-based computer simulation is useful for the quantitative evaluation of strong ground motions that will be produced by potential interplate earthquakes. We also developed the associated data assimilation software; that is, a GPS data inversion method to estimate interplate coupling rates, a CMT data inversion method to estimate crustal stress fields, and a GPS inversion method to estimate 3-D elastic/inelastic strain fields. In 2009, applying the GPS data inversion method to interseismic GPS data (1996-2000) in the southwestern part of Japan, we estimated the slip-deficit rate distribution on the Eurasian-Philippine Sea plate interface along the Nankai trough and the Ryukyu trench, and revealed that a high slip-deficit rate belt extends from the Suruga Bay to the Bungo Channel. On the basis of the inversion results, we computed stress accumulation rates in the seismogenic region, and performed a numerical simulation for the dynamic rupture of a potential Nankai-trough earthquake by using the boundary integral equation method.

Keywords: GPS data inversion, interplate coupling, stress accumulation, dynamic rupture propagation, combined simulation

1. Introduction

The occurrence of earthquakes can be regarded as the releases of tectonically accumulated elastic strain energy through dynamic fault ruptures. Given this, the entire earthquake generation process generally consists of tectonic loading, quasi-static rupture nucleation, dynamic rupture propagation, and fault strength recovery. We can now quantitatively describe the entire earthquake generation process with coupled nonlinear equations, consisting of a slip-response function, a fault constitutive law, and relative plate motion. The slip-response function, which relates fault slip to shear stress change, is a solution of the equation of motion in continuum mechanics. The fault constitutive law, which prescribes shear strength change with fault slip and contact time, is an energy balance equation in fracture zones. The relative plate motion is a driving force of the coupled nonlinear system. Thus, the essence of earthquake generation modeling is quite simple, but it is not easy to develop a predictive simulation model, because the actual world is complex in structure and also in material properties.

In the first phase (2003-2005) of the project, we constructed a realistic 3-D model of plate interface geometry in and around Japan, represented by the superposition of about 30,000 bi-cubic splines [1]. On this structure model we developed a quasi-static stress accumulation model and a dynamic rupture propagation model. Then, given the past fault-slip history, we performed the combined simulation of quasi-static stress accumulation and dynamic rupture propagation for the 1968 Tokachi-oki earthquake (M_w=8.2), and demonstrated that when the stress state is close to a critical level, dynamic rupture is rapidly accelerated and develops into a large earthquake, but when the stress state is much lower than the critical level, started rupture is not accelerated [2]. So, the problem is how to know the past fault-slip history and how to monitor the present stress state. In the case of Japan, fortunately, we have nation-wide dense geodetic and seismic observation networks such as GEONET operated by GIS (Geographical Survey Institute of Japan) and F-net operated by NIED (National Research Institute for Earth Science and Disaster Prevention).

In the second phase (2006-2008), we developed the associated data assimilation software; that is, a GPS data inversion method to estimate interplate coupling rates [3], a CMT data inversion method to estimate crustal stress fields [4], and a GPS data inversion method to estimate 3-D elastic/inelastic strain fields [5]. Applying the GPS data inversion method [3] to GEONET data (GSI) in the Hokkaido-Tohoku region for the interseismic calm period of 1996-2000, we estimated the slip-deficit rate distribution on the North American-Pacific plate interface, and revealed that the inverted five slip-deficit peaks almost completely coincide with the source regions of 10 large interplate earthquakes (M_w>7.5) occurred along the Kuril-Japan trench in the last century [6]. Based on the inversion results, we performed the combined simulation of quasi-static stress accumulation, dynamic rupture propagation and seismic wave propagation for the 2003 Tokachi-oki earthquake (M_w=8.1), and demonstrated that the physics-based computer simulation is useful for the quantitative evaluation of strong ground motions that will be produced by potential interplate earthquakes [7].

2. Interplate slip-deficit rate distribution along the Nankai trough inverted from GPS data

In 2009, applying the GPS data inversion method [3] to horizontal velocity data at GEONET stations in the southwestern part of Japan for the interseismic calm period of 1996-2000 (Fig. 1), we estimated precise slip-deficit rate distribution on the Eurasian-Philippine Sea plate interface along the Nankai trough and the Ryukyu trench. In the analysis, we took the changes in distance between adjacent GPS stations as data, instead of horizontal velocities, to remove the effect of block rotation. In practice, we composed a triangle network form 512 GPS stations with the Delaunay triangulation (the inset of Fig. 1), and used 1265 side-length change data for the inversion analysis.

In Fig. 2, we show the inverted slip-deficit rate distribution on the Eurasian-Philippine Sea plate interface together with the tsunami source regions of the 1944 Tonankai (M=7.9) and 1946 Nankai (M=8.0) earthquakes. From this figure we can see that a high slip-deficit rate belt in the depth range of 5-30 km extends along the Nankai trough from the Suruga Bay to the Bungo Channel. The 1944 Tonankai and 1946 Nankai earthquakes were shallow thrust-type submarine earthquakes accompanied by tsunamis. The tsunami source region of the 1946 event extends from the Kii peninsular to the west of the Tosa Bay, but not to the Bungo Channel, which agrees with the coseismic slip distribution estimated from the inversion analysis of triangulation and levelling data [8]. The discrepancy between

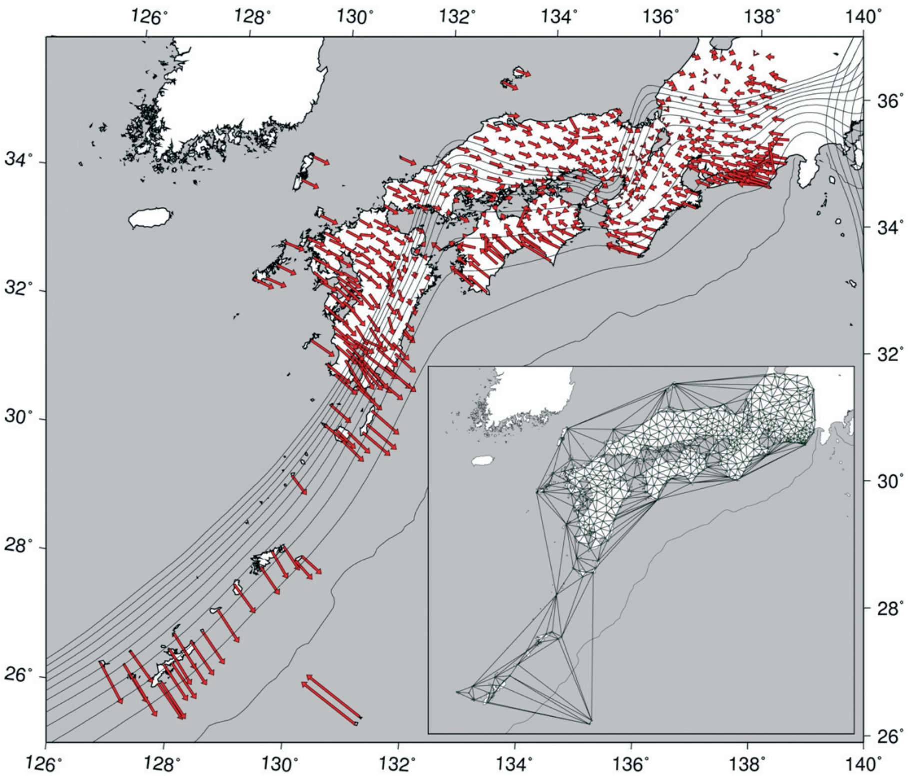

Fig. 1 Interseismic GPS velocity data in the southwestern part of Japan (Hashimoto, Sagiya & Matsu'ura, SSJ 2009 Fall Meeting). The red arrows indicate horizontal velocity vectors. The plate interface geometry is shown by the iso-depth contours at the interval of 10 km. The inset shows the triangle network composed of 512 GPS stations with the Delauney triangulation.

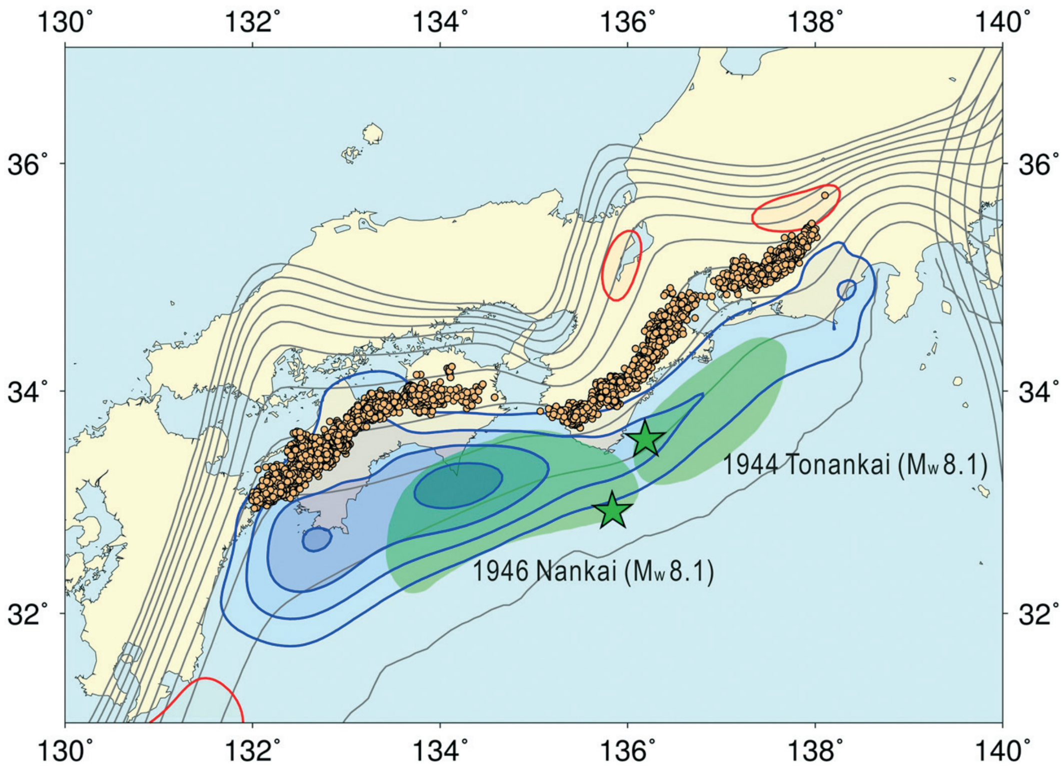

Fig. 2 The slip-deficit rate distribution inverted from GPS data (Hashimoto, Sagiya & Matsu'ura, SSJ 2009 Fall Meeting). The blue contours indicate the slip-deficit rate at the interval of 2 cm/yr. The green stars and green areas indicate the epicentres and tsunami source regions of the 1944 Tonankai and 1946 Nankai earthquakes. The small orange circles indicate the location of deep low-frequency tremors [9,10].

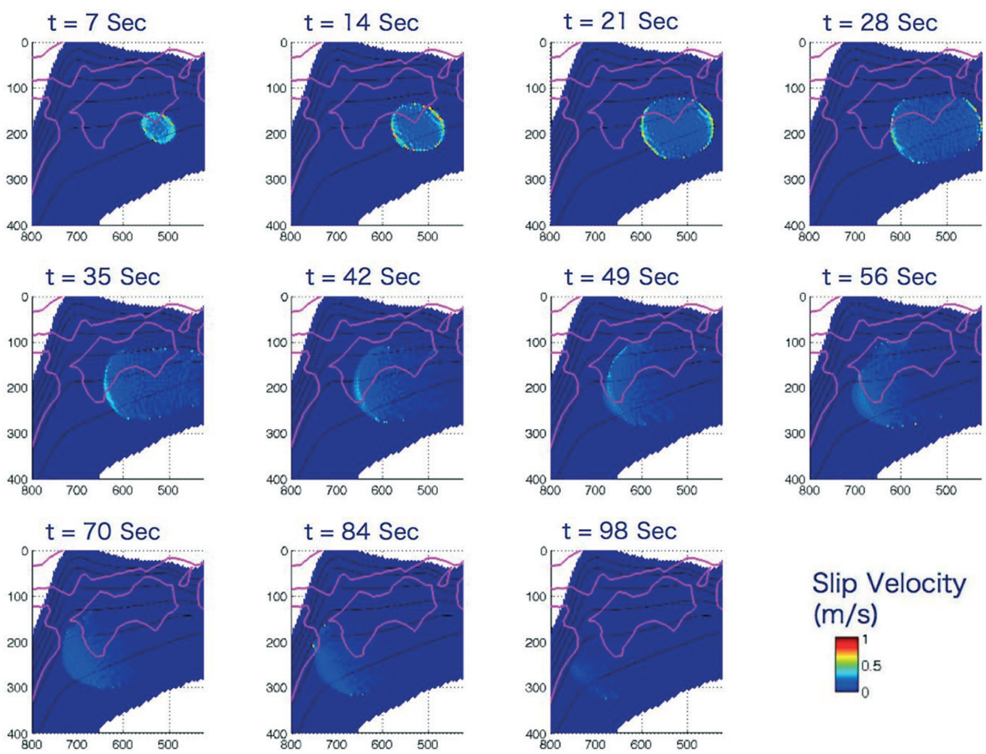

Fig. 3 Dynamic rupture simulation for a potential Nankai-trough earthquake (Hok, Fukuyama & Hashimoto, SSJ 2009 Fall Meeting). A series of snapshots shows slip velocity distribution at each time step. The dynamic rupture started near the Muroto promontory propagates westward and develops into a large earthquake that releases the tectonically accumulated stress completely.

the interseismic slip-deficit rate distribution and the coseismic slip distribution of the 1946 event suggests complexity in the past fault-slip history and the present stress state about the Bungo Channel.

3. Dynamic rupture simulation for a potential Nankai-trough earthquake

On the basis of the inversion results, we performed a numerical simulation for the dynamic rupture of a potential Nankai-trough earthquake by using the boundary integral equation method. In the numerical simulation, first, we computed the stress distribution on the plate interface just before the initiation of dynamic rupture by multiplying the inverted slip-deficit rates by an assumed interseismic period after the 1946 event. Then, we forced the dynamic rupture to start by giving small amount of stress drop. If we assume a uniform frictional property over the seismogenic region, the started dynamic rupture is accelerated and extends over the whole slip-deficit zone (Fig. 3). The dynamic rupture process is essentially controlled by the frictional property (peak strength and critical displacement) of faults as well as the initial stress state. The present numerical results shows that the started dynamic rupture extends to the Bungo Channel, which agrees with the case of the 1854 Ansei Nankai earthquake (M=8.4), but not with the case of the 1946 Showa Nankai earthquake. For the reliable prediction of potential interplate earthquakes along the Nankai trough, it is crucial to specify the spatial distributions of peak strength and critical displacement over the plate interface and reveal the background tectonic stress field around the plate interface through the integrated analysis of the past fault-slip history in the southwestern part of Japan.

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日本列島域の地殻活動予測シミュレーション・システムの開発 - Ⅶ

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本研究プロジェクトは、複雑なテクトニック環境の下にある日本列島及びその周辺域を一つのシステムとしてモデル化し、プレート運動に伴う長期的な地殻変形から大地震の発生まで、時間・空間スケールの著しく異なる地殻活動現象を統一的且つ定量的に予測する並列シミュレーション・システムを開発し、モデル計算と観測データを併合した日本列島域の地殻活動予測シミュレーションを行うことを目的としている。

地殻活動予測シミュレーション・システムは、日本列島域の 3 次元標準構造モデル（CAMP Standard Model; Hashimoto, Fukui & Matsu'ura, PAGEOPH, 2004）上に構築された、準静的応力蓄積モデル、動的破壊伝播モデル、及び地震 / 地殻変動データの解析・同化ソフトウェアから成る。平成 20 年度には、モデル計算と観測データの融合に向け、直接的及び間接的先験情報を考慮した GPS データの逆解析手法（Matsu'ura, Noda & Fukahata, GJI, 2007）を北海道－東北地域の地震間（1996-2000）の GPS 速度データに適用して北米－太平洋プレート境界の詳細なすべり遅れ分布を求め（Hashimoto, Noda, Sagiya & Matsu'ura, Nature Geoscience, 2009）、その結果に基づいて 2003 年十勝沖地震の準静的応力蓄積—動的破壊伝播—地震波動伝播の連成シミュレーションを行ない、将来的に発生が予想されるプレート境界地震による地震動を定量的に予測することが可能なことを示した（Fukuyama et al., BSSA, 2009）。平成 21 年度は、上記の GPS データ逆解析手法を西南日本域に適用してユーラシア－フィリピン海プレート境界の固着－すべり状態を推定し、駿河湾から豊後水道にかけて帯状に分布する東海・東南海・南海地震の震源域のすべり遅れレートの詳細な分布を明らかにした（Hashimoto, Sagiya & Matsu'ura, SSJ 2009 Fall Meeting）。また、GPS データから推定したプレート境界のすべり遅れレートに基づいて震源域の応力分布を計算し、境界積分方程式法による仮想南海地震の動的破壊伝播の予測シミュレーションを試みた（Hok, Fukuyama & Hashimoto, SSJ 2009 Fall Meeting）。一方、内陸地震発生メカニズムの解明に向けては、CMT データから地殻応力を推定する逆解析手法（Terakawa & Matsu'ura, GJI, 2008）を F-net の 15,000 の地震データに適用して日本列島全域の 3 次元地殻応力パターンを明らかにした（Terakawa & Matsu'ura, BSSJ, 2009）。また、GPS データから地殻内の 3 次元弾性 / 非弾性歪み速度場を推定する逆解析手法を確立し、新潟－神戸歪み集中帯の変形様式を明らかにした（Noda & Matsu'ura, GJI, 2010）。

キーワード : GPS データインバージョン , プレート間カップリング , 応力蓄積 , 動的破壊 , 連成シミュレーション