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

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Our research group aims to develop a physics-based predictive simulation system for crustal activities in and around Japan. In the first three years of the project we completed a prototype of the simulation system, which consists of a quasi-static stress accumulation model, a dynamic rupture propagation model and seismic/geodetic data assimilation software, on a realistic 3-D structure model. In 2006, with the prototype simulation system, we carried out the combined simulations of quasi-static stress accumulation, dynamic rupture propagation and seismic wave radiation for the 1968 and 2003 Tokachi-oki earthquakes, and demonstrated that the future fault-slip motion is predictable through computer simulation if the past slip history and the present stress state are known. Then, in order to estimate the past slip history and the present stress state from observed geodetic and seismic data, we established a new inversion method that unifies the Jackson-Matsu'ura formula with direct prior information and the Yabuki-Matsu'ura formula with indirect prior information in a rational way. With the method of CMT data inversion we analyzed seismic events in the Hokkaido-Tohoku region, and found clear difference in stress patterns between the overriding North American plate and the descending Pacific plate.

Keywords: stress accumulation, dynamic rupture propagation, seismic wave radiation, combined simulation, inversion formula, CMT data inversion, seismogenic stress field

1. Introduction

Our research group aims to develop a physics-based predictive simulation system for crustal activities in and around Japan, where the four plates of Pacific, North American, Philippine Sea and Eurasian are interacting with each other in a complicated way. The total system consists of a quasi-static stress accumulation model, a dynamic rupture propagation model, and seismic/geodetic data assimilation software, developed on a realistic 3-D structure model called CAMP Standard Model [1]. In the first three years of this project we completed a prototype of the simulation system on the Earth Simulator [2]. With the prototype simulation system we can now perform the combined simulations of quasi-static stress accumulation, dynamic rupture propagation and seismic wave radiation for earthquake generation cycles at plate interfaces. Output data of the simulation are the crustal deformation, internal stress change and seismic wave radiation caused by seismic and/or aseismic slip at plate interfaces. Then, the next problem to be solved is how to assimilate massive observed data from nation-wide seismic/geodetic networks into predictive simulation. As the first step to address this problem we develop two inversion methods using Akaike's Bayesian Information Criterion (ABIC), one of which is the method to estimate the spatiotemporal variation of interplate coupling from geodetic data, and another is the method to estimate seismogenic stress fields from CMT data of seismic events [3].

2. Combined simulation of stress accumulation, dynamic rupture and seismic wave radiation

With the prototype simulation system for crustal activities in and around Japan, first, we carried out the combined simulation of quasi-static stress accumulation and subsequent dynamic rupture propagation in the source region of the 1968 Tokachi-oki earthquake (M8.1) [4]. On the basis of the inversion analysis of waveform data we set two strength asperities with different sizes on the North American-Pacific plate interface. The 3-D geometry of the plate interface is given by CAMP Standard Model. The frictional property at each point of the plate interface is specified by the three basic parameters (peak strength, characteristic weakening displacement, and characteristic healing time) of the slip- and time-dependent fault constitutive law [5]. The driving force of stress accumulation is the steady subduction of the Paccific plate beneath the North American plate. The simulation algorithm, based on a numerical boundary integral equation method, is essentially the same as that in the case of transcurrent plate boundaries [6]. A series of snapshots in Fig. 1 shows the gradual increase of shear stress with time in the source region of the 1968 Tokachi-oki earthquake. The shear stress reaches a critical state at 120 years after the preceding event. Then, we switch from the quasi-static simulation of stress accumulation to the dynamic simulation of rupture propagation. Initial stress distribution and fault constitutive relations for the dynamic simulation are given by the output of the quasi-static simulation at the critical state. In the dynamic rupture simulation we use the boundary integral equation method for triangular elements [7,8], which allows us to model non-planar fault geometry.

On the left of Fig. 2 we show the snapshots of dynamic rupture propagation started at 120 years after the preceding event. The snapshots on the right of Fig. 2 show the case of dynamic rupture forced to start at 60 years after the preceding event. From these simulation results we can see the following. When the stress state is close to the critical level, the started dynamic rupture is rapidly accelerated and develops into a large earthquake. When the stress state is much lower than the critical level, the started rupture is not accelerated and soon stops.

Next, we carried out the combined simulation of quasi-static stress accumulation, dynamic rupture propagation and seismic wave radiation for the 2003 Tokachi-oki earthquake (M8.0) in a similar way [9]. In the computation of seismic wave radiation and propagation we used the slip time functions obtained by the dynamic rupture simulation. The computation algorithm of seismic wave radiation and propaga-

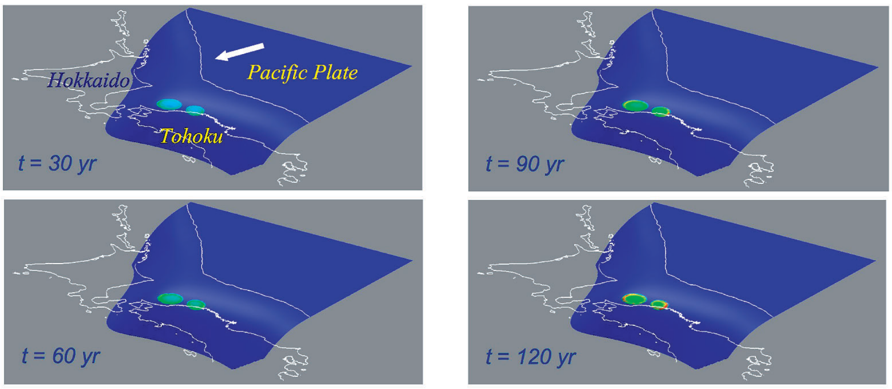

Fig. 1 Combined simulation of quasi-static stress accumulation and dynamic rupture propagation for the 1968 Tokachi-oki earthquake: Quasi-static stress accumulation [4]. The quasi-static stress accumulation in the source region is shown by a series of snapshots. The stress state becomes critical at 120 years after the preceding event.

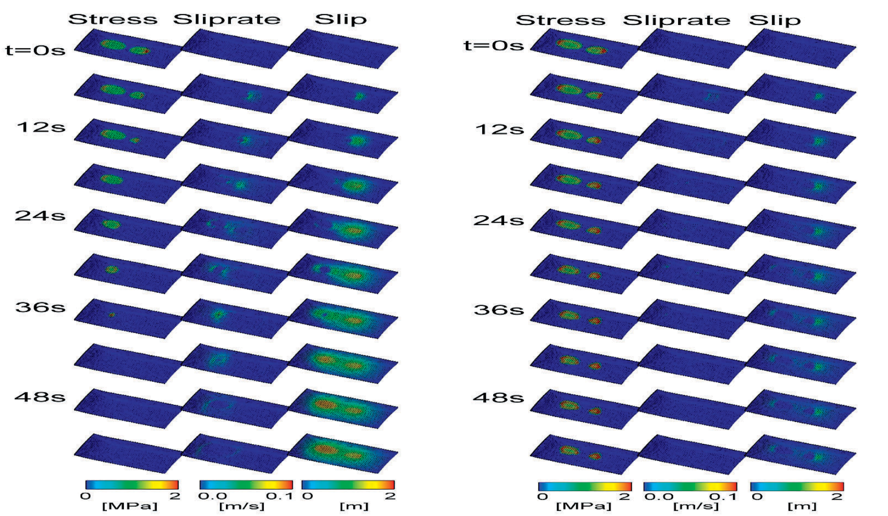

Fig. 2 Combined simulation of quasi-static stress accumulation and dynamic rupture propagation for the 1968 Tokachi-oki earthquake: Dynamic rupture propagation [4]. Left: The case of dynamic rupture started at 120 years after the preceding event. Right: The case of dynamic rupture forced to start at 60 years after the preceding event.

tion is based on the finite difference method for a 3-D heterogeneous medium [10]. In the upper half of Fig. 3 we show the source region of the 2003 Tokachi-oki earthquake (left), the initial stress distribution obtained by the quasi-statc simulation of stress accumulation (center), and the final fault slip distribution (right). In the lower half of Fig. 3 we show the snapshots of dynamic rupture propagation and seismic wave radiation.

As the result of the dynamic rupture simulation we obtain the spatio-temporal distribution of slip on the fault, which gives the input for the computation of seismic wave radiation and propagation. In the computation we used a realistic velocity structure model to take into account the propagation path and local site effects. In Fig. 4 we show the computed ground motions at the seismic stations along a coastline together with the observed ground motions. We can see good agreement between the predictions and the observations. Thus, we may conclude that if all the parameters in the simulation are correctly given, we can predict the ground motions that will be caused by future earthquakes. At present we do not have sufficient information about all the parameters, but this simulation is still quite useful as a tool for evaluating the scenario that will happen in future.

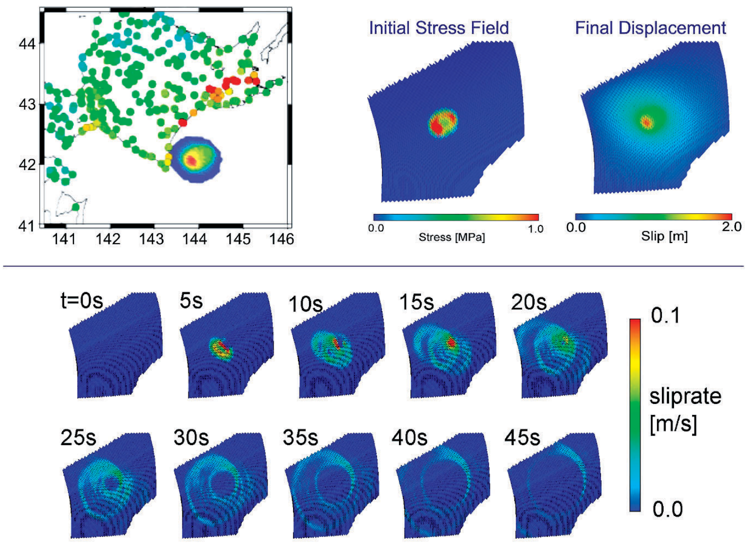

Fig. 3 Combined simulation of quasi-static stress accumulation, dynamic rupture propagation and seismic wave radiation for the 2003 Tokachi-oki earthquake [9]. Top: The source region (left), the initial stress distribution (center), and the final fault slip distribution (right). Bottom: Snapshots of dynamic rupture propagation and seismic wave radiation.

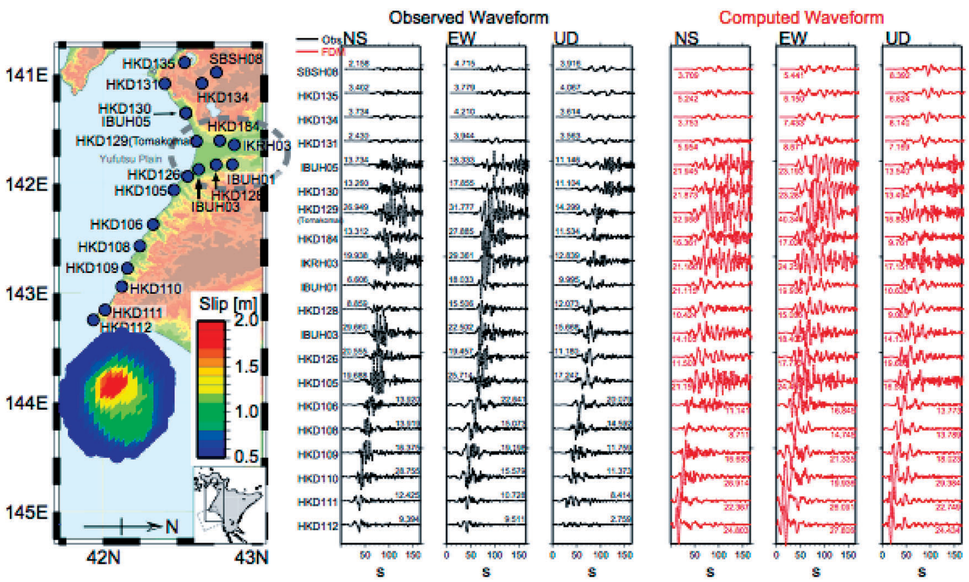

Fig. 4 Comparison of computed and observed ground motions for the 2003 Tokachi-oki earthquake [9]. Left: The location map showing the source region and the seismic stations. Center: Computed ground motions. Right: Observed ground motions.

3. Development of the inversion methods to estimate internal stress states

For geodetic data inversion, so far, two kinds of Bayesian methods have been widely used; one of which is the method based on the Jackson-Matsu'ura inversion formula with direct prior information about model parameters [11], and another is the method based on the Yabuki-Matsu'ura inversion formula with indirect prior constraint on the roughness of fault slip distribution [12]. Recently, incorporating both the direct and indirect prior information into observed data in a proper way, we succeeded in deriving a new inversion formula that unifies the Jackson-Matsu'ura formula and the Yabuki-Matsu'ura formula [13]. The unified inversion formula enables us to incorporate the postulate of plate tectonics into geodetic data inversion in a quantitative way. We examined the effectiveness of the unified inversion formula through the analysis of the surface displacement data associated with the 1923 Kanto earthquake.

With the method of CMT data inversion [14] we analyzed about 3000 seismic events with M3.5–5.0 in the Hokkaido-Tohoku region (NIED Seismic Moment Tensor Catalogue, 1997–2006), and obtained the 3-D pattern of the seismogenic stress field associated with the subduction of the Pacific plate beneath the North American plate [15]. On the left of Fig. 5 we show the epicenter distribution of the seismic events used in the CMT data inversion. On the right of Fig. 5 we show the pattern of the inverted stress field at 10 km in depth with the focal sphere representation. From this inversion result we can see the clear difference in stress patterns between the overriding North American plate and the descending Pacific plate.

4. Summary

We succeeded in the combined simulation of quasi-static stress accumulation, dynamic rupture propagation and seismic wave radiation for earthquake generation cycles at plate interfaces. This success demonstrates a predictablity for large interplate earthquakes on the condtion that we have sufficient information about all the parameters in computer simulation. At present we do not have sufficient information about all the parameters, but the combined simulation for earthquake generation is still quite useful as a tool for evaluating the scenario that will happen in future.

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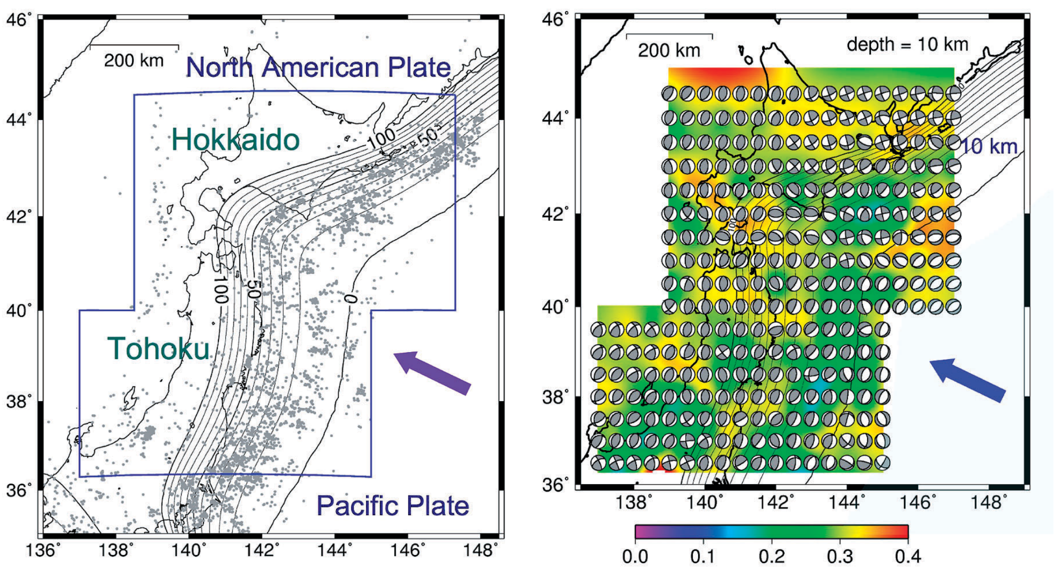

Fig. 5 The seismogenic stress field in the northeastern part of Japan estimated from CMT data inversion [15]. Left: The location map showing the epicenter distribution of seismic events and the iso-depth contours of the upper boundary of the descending Pacific plate. Right: The inverted seismogenic stress field with the focal sphere representation. The color scales show the degree of uncertainty.

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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 - IV

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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、日本列島域の現実的な3次元標準構造モデル(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18年度は、日本列島域の地殻活動シミュレーション・プロトタイプモデル(Matsu'ura, Hashimoto & Fukuyama, 4th ACES Workshop, 2004)を高度化し、1968年十勝沖地震及び2003年十勝沖地震を例とした地震発生サイクルシミュレーションを行うと同時に、広域地震／地殻変動データから地殻活動予測シミュレーションに有用な情報を抽出するインバージョン解析手法の定式化とソフトウェア開発並びに実際の観測データへの適用を行った。

地震発生ミュレーションに関しては、1968年十勝沖地震(M8.1)の震源域に大小二つの強度アスペリティーを設定して太平洋プレートの沈み込みに伴う震源域での準静的応力蓄積−動的破壊伝播の連成シミュレーションを行い、外部からの擾乱がトリガーになって開始した動的破壊が大地震にまで発展するか否は震源域の応力状態に強く依存することを定量的に示した(Hashimoto et al., 2006)。また、2003年十勝沖地震(M8.0)については、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い、理論的に予測された最大地動速度分布と実際に観測された最大地動速度分布が概ね一致することを示した(Fukuyama et al., 2006)。

地殻活動データ解析ソフトウェアに関しては、直接的先験情報を取り込んだ Jackson and Matsu'ura (1985)の逆化公式と間接的先験情報を取り込んだ Yabuki and Matsu'ura (1992)の逆化公式を自然な形で統合する一般的逆化公式を導出し、それに基づく地殻変動データ解析の新しいインバージョン手法を開発した(Matsu'ura et al., 2007)。また、前年度に開発したCMTデータインバージョンの手法を北海道—東北地域の地震データ(NIED, Seismic Moment Tensor Catalogue)に適用して同地域の3次元地震発生応力場を推定し、沈み込む太平洋プレート内の応力場と沈み込まれる北米プレート内の応力場のパターンの違いを明らかにした(Terakawa et al., 2006)。

キーワード：応力蓄積, 動的破壊, 地震波動伝播, 連成シミュレーション, 逆化公式, CMTデータインバージョン,
地震発生応力場