Global Elastic Response Simulation

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The targets of this project are; (1) to solve inverse problem, that is, to perform waveform inversion for three dimensional (3-D) shear wave velocity (Vs) structure inside the Earth using the Direct Solution Method and (2) to solve forward problem, that is, to calculate synthetic seismic waveform for fully 3-D Earth model. We have conducted waveform inversion for 3D shear wave velocity structure with much finer resolution than previously performed. We do not use ray theoretical approximation in computing synthetic waveforms, which enables us to treat rigorously the wave propagation effect due to lateral heterogeneity of the velocity structure. The 3D velocity model, we obtained, might indicate that we have two layered mantle convection and horizontal flow becomes predominant in the boundary layers in the lower mantle. We use the Spectral-Element Method for the forward modeling calculation and calculate synthetic seismic waveform for a 3-D Earth model, which includes a 3-D velocity and density structure, a 3-D crustal model, ellipticity as well as topography and bathymetry. We calculate snapshots of seismic wave propagation for 2004 great Sumatra earthquake and have confirmed that the fault slip model, which we used in this simulation, is accurate and the earthquake fault of this event really extends to more than 1000 km.

Keywords: Synthetic seismograms, 3-D velocity structure of the Earth, Direct Solution Method, Spectral Element Method

1. Waveform Inversion for 3-D global Earth structure

Inversion for detailed 3-D global Earth structure is important to constrain the dynamics of the Earth. Most of the previous 3-D Earth models were obtained primarily by inverting phase data extracted from seismic waveform data. There were a few studies to obtain Earth models by inverting seismic waveform data themselves. Such inversion method (called as waveform inversion) has a potential to improve the resolution of the Earth models because we can fully utilize the information included in the seismic waveform data. However, because waveform inversion requires huge computational resources in simulating global elastic responses, previous studies by other research groups incorporated approximations (optical ray approximations) to reduce the required CPU time, which degrades the resolution of the obtained models.

In this study we conducted full waveform inversion based on accurate global elastic response simulations. We did not use optical ray approximations, and rigorously computed the effect of lateral heterogeneity and the effect of finite wavelength. The required CPU time is huge, but we solved this problem by developing our efficient computational method (the Direct Solution Method; Takeuchi et al., 2000) and by using the Earth simulator.

Using the Earth simulator, we succeeded to increase the size of the data set and to improve the maximum resolution of the model. We previously presented a preliminary model by using the similar method as was used in this study (Takeuchi & Kobayashi, 2004). We used SR8000/MPP at the Information Technology Center, the University of Tokyo. The data set used was 1,161 waveform traces and the number of the model parameters was 1,014 (the maximum horizontal resolution of the model is degree-12). On the other hand, in this study, the data set used was 16,089 waveform traces, and the number of the model parameters was 3,610 (the maximum horizontal resolution is degree-18). We optimized the software for the Earth simulator, and we achieved 98.93% parallel efficiency for computations using 88 nodes (794 CPUs).

The obtained S wave velocity model in the lower mantle is shown in Figure 1. Because of the improvement of the inversion method, improvement of the resolution is expected especially beneath the oceanic regions where data sampling is poor. The obtained model is thus suitable to discuss the scale lengths of the lateral heterogeneity, which helps to understand the nature of the global mantle flow. The model in Figure 1 shows that the top and the bottom layers in the lower mantle show relatively red spectra, whereas the middle layer shows relatively white spectra. This result might indicate that we have two layered mantle convection and horizontal flow becomes predominant in the boundary layers in the lower mantle. Existence of stagnant slabs is one of the

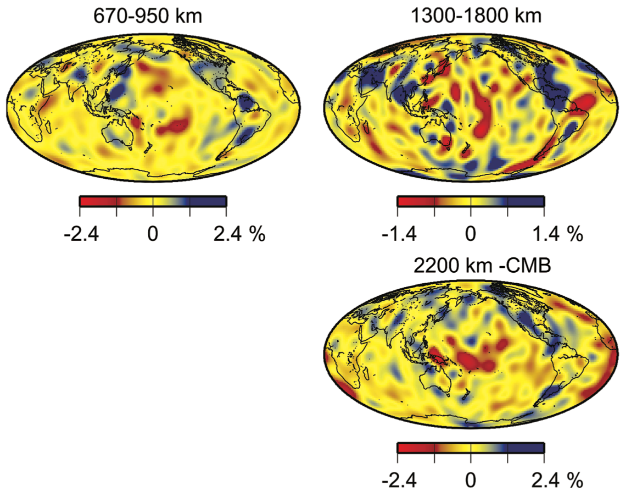

Fig. 1 S wave velocity model obtained by this study.

important evidences for two layered convection, but the spectra of seismological heterogeneity obtained in this study further provides evidence for this.

2. Synthetic seismograms for 2004 Sumatra earthquake

We calculate synthetic seismograms for fully 3-D Earth model using the Spectral-Element Method code and 243 nodes of the Earth Simulator for December 26, 2004 Great Sumatra earthquake (Mw 9.1) and create movie file that shows seismic wave propagation at the surface of the globe. Because this giant earthquake caused devastating disaster to countries surrounding Indian Ocean, the actual size of the earthquake fault, which generated seismic waves and tsunamis became a target of studies. We calculate synthetics for both Dec 26, 2004 and Mar. 28, 2005 events and compared with the observation. We use the Spectral-Element Method (SEM) developed by Komatitsch and Tromp (2002) to simulate global seismic wave propagation throughout a 3-D Earth model, which includes a 3-D seismic velocity and density structure, a 3-D crustal model, ellipticity as well as topography and bathymetry. The SEM first divides the Earth into six chunks. Each of the six chunks is divided into slices. Each slice is allocated to one CPU of the Earth Simulator. Communication between each CPU is done by MPI. We use 243 nodes of the Earth Simulator and divided the fully three-dimensional Earth model into 5.4 billion grid points. This should provide synthetic seismograms that are accurate up to 5 second and longer. We use finite source models by using a set of sub-events distributed along the fault surface, retrieved by inversion of body waves and long period surface waves (Tsuboi et al, 2005). The finite source models used in this simulation estimate Mw to be 9.1 for Dec 26 event and 8.7 for Mar 28 event. The fault length is 1200 km and 400 km respectively.

The comparison of the synthetic seismograms with the observation for Mar 28 event shows that synthetic P-waveforms model the observed seismogram quite well, reflecting that the finite source model is quite precise. This source model shows that the maximum slip occurs at depth of 30 km, which is consistent with the fact that the tsunami excitation was not significant compared with the devastating Dec 26 event. Because the agreement of the synthetics with the observation was satisfactory for Mar 28 event, the comparison of the synthetics for Dec 26 event using the fully three dimensional Earth model should also give implications on the complex source process of Dec 26 event.

The agreement of the synthetics for Dec 26 event is satisfactory for body wave phases, which confirms that the finite source model used in this simulation models the complex source rupture propagation of this event quite well. The total rupture duration of this model is about 550 sec. Combined with the fault length of about 1200 km for this model, we may conclude that it is not likely the rupture velocity becomes slower than 2.0 km/sec. However, the amplitude of surface waves for synthetic seismograms underestimates the observed amplitude especially at frequency range lower than 0.05 Hz, which may suggest that there exists extremely slow movement along the fault surface in the northern part of the fault segments near Andaman Islands.

Figure 2 illustrates an example of the snapshot prepared to create this movie file for Dec. 26, 2004 event. The snapshot indicates complex pattern of seismic wave propagation due to this extremely large earthquake fault.

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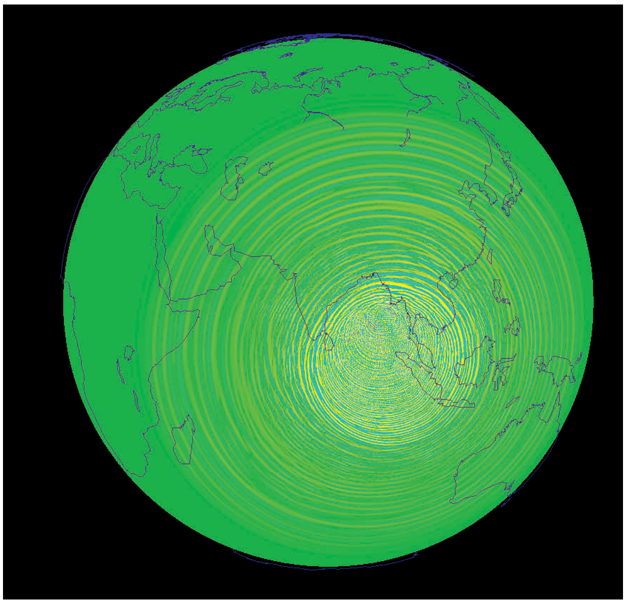

Fig. 2 Snapshot of the propagation of seismic waves in the Earth during the December 26, 2004 Sumatra Island earthquake.

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全地球弾性応答シミュレーション

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詳細な3次元不均質地球モデルのインバージョンは、地球のダイナミクスを理解する上で重要である。(地震波形データから抽出された)位相データではなく、波形データそのものを用いてインバージョンを行えば、地震波形データに含まれるすべての情報が活用できるので、解像度の改善が期待できる。膨大な計算時間を要することが問題であったが、我々は独自の効率的な計算手法(Direct Solution Method)と地球シミュレーターを活用することによりこれを解決した。以前に東京大学基盤センターのSR8000/MPPを用いた予備的な解析に比べ、データセットの大きさを約15倍、モデルパラメータ数を約3.5倍に増やすことに成功した。得られたモデルは特に(データサンプリングが乏しい)海洋域において解像度の改善がなされ、全地球的なマントル対流のパターンを制約することに有用であると期待される。実際に得られたS波速度構造を見ると、下部マントルの最上層と最下層では比較的長い水平波長の不均質構造が卓越しているのに対し、真ん中の層では比較的短い水平波長の不均質構造が卓越している。これはマントル対流が二層対流系をなし、最上層と最下層に境界層を形作っていることを示唆する。

我々はスペクトル要素法を地球シミュレータ上で用いることにより、周期5秒までの広帯域地震波形を現実的な3次元地球モデルに対して計算できることを示してきた。今年度は、2004年スマトラ地震に対して地震波動伝播の可視化を行い、観測波形との比較から震源断層の広がりについて議論した。震源過程はTsuboi et al (2003)と同様に、広帯域地震波形及び表面波のインバージョンで得られた複数の点震源を断層上に配置してモデル化した。この震源モデルを用いて理論地震波形を計算するために3次元地球モデルとしては、マントル3次元地震波速度構造にS20RTS、地殻構造モデルにCRUST2.0、地表及び海底の地形データにETOPO5を用いた。理論地震波形の計算には地球シミュレータの243ノード(1944CPU)を用い、3次元地球モデルを54億個の格子点に分割した。これにより地表における格子点の間隔は約2.9kmとなる。計算した理論地震波形記録と観測波形との一致は良く、用いた断層破壊モデルがほぼ現実の地震断層をモデル化していることを示している。この結果から、2004年スマトラ地震の断層は長さ1200kmで、震源における破壊は500秒以上にわたって継続したことが分かった。

キーワード: 理論地震波形記録, 地球内部3次元構造, Direct Solution Method, Spectral-Element Method