Numerical Simulation of Seismic Wave Propagation and Strong Motions in 3D Heterogeneous Structure

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An attractive parallel code for large-scale 3D simulation of seismic wave propagation and strong motions for 3D heterogeneous media was developed and implemented to the Earth Simulator. The parallelism of the FDM simulation is based on the domain partition method. The seismic wavedield is calculated by using the 16th-order staggered-grid FDM in horizontal directions, and 4th-order FDM is used in vertical direction. We adopted an automatic parallelism inside the node, and MPI is used for the inter-node computing. We applied the method for large scale 3D simulation of strong motions for the 2000 Tottori-ken Seibu (Mj7.3) earthquake, 1993 Kushiro-oki (M7.8) earthquake, and Nankai-Trough scenario earthquake. The simulation results agree to the observed ground motions at dense seismic array fairly well, so it is indicating the efficiency in the simulation model.

Keywords: FDM, Earthquake, Nankai Earthquake, Seismology, Parallel Computing

Introduction

Over the past few years very dense arrays of high-resolution strong ground motion instruments have been deployed across Japan by NIED, and the combination of the K-NET and the KiK-net provides more than 1600 strong motion instruments at a nearly uniform station interval of 10 to 20 km. The development of such a dense array of instruments means that it is now feasible to visualize the behavior of the seismic wave propagation from the large earthquakes.

The recent developments of high-performance vector parallel computer, the Earth Simulator, promises large-scale parallel 3D simulation of seismic wave propagation at reasonably higher frequencies to a several hundred kilometers from the source.

In this report we will combine the seismic observations by dense seismic array and the corresponding large-scale 3D simulations to cross-check the effect of source and structures on the regional seismic wavefield.

Adaptability to Vector Computing: Higher-order FDM vs. PSM

We implemented the parallel PSM/FDM code (Furumura et al., 2002ab) to the Earth Simulator, and examined the applicability of the PSM and the FDM calculations on such a vector machine. To confirm the effectiveness of the vector computing, we also compare the speed with that for scalar computing by turning off the vector unit using a proper compiler options. Figure 1(a) illustrates the computation time of the FDM calculation using a different order of approximations (2nd, 4th,...,128th) and that for the PSM using the 1-D FFT for a real-valued data. It is clear on both scalar and vector computing that the computation time of the FDM simulation increase linearly with the length of FDM operator increase. Whilest the PSM runs almost similar speed on a scalar machine as the 16th-order FDM. It is also clear that the FDM simulation accelerates significantly (over 20 times or more) by vector computing, but the PSM keeps almost same speed as the scalar computing. This may because that the butterfly operation used in the FFT is too complicated to match to the vector operation. It has been recognized that the PSM is more efficient than the FDM on scalar computers such as e.g. PC clusters (Furumura et al., 2003), but it is not applied to the vector computers. We therefore use higher-order FDM rather than PSM for the simulation of seismic wave propagations.

Parallel performance of the FDM simulation

The parallel performance of the FDM simulation is roughly estimated by the ratio of data transmission rates (Vc) to the calculation speed (Vd) on a given processor by

$$R\,(Np)=Np/(1+Np^{*}\,M/Np\,^{*}\,6\,^{*}Vd/Vc),$$

where R is the expected speed-up rate using Np processors, and M is the order of FDM (M=2,4,8,..) used in vertical direction (see Furumura et al. 2002a in detail). We obtained

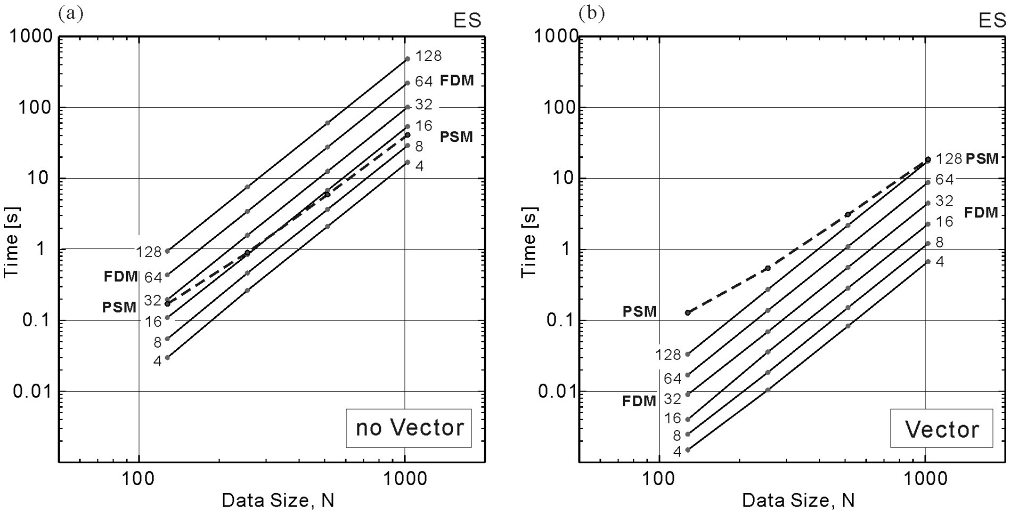

Fig. 1 Computation time of the FDM and the PSM modeling on the Earth Simulator (a) without vector computing, and (b) using vector unit.

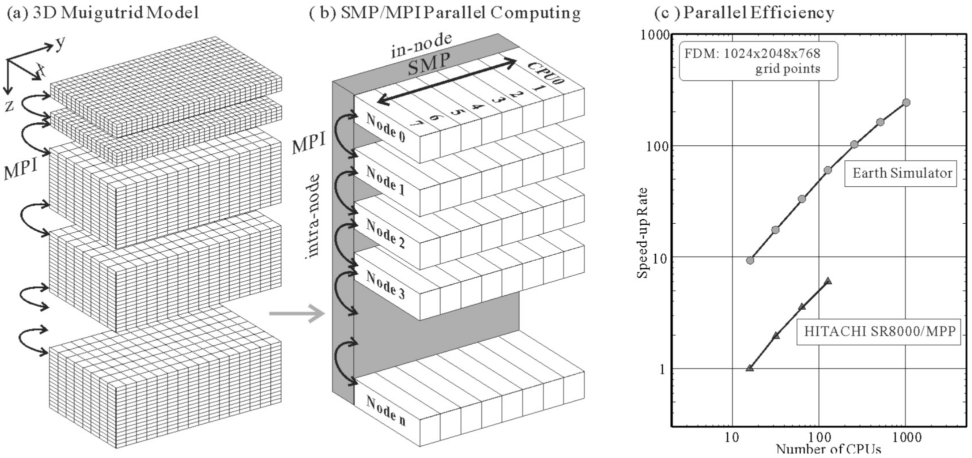

Fig. 2 (a) Multigrid FDM simulation model, (b) hybrid SMP/MPI parallel model, and (c) Speed-up rate of the parallel computing using large number of processors of the Earth Simulator and the SR8000/MPP.

Vc=855,200Kbyte/s and Vd=78,910Kbyte/s for the Earth Simulator using a simple benchmark test and a 3D model (1024^3 grid model and 4th-order FDM). Figure2c illustrates the speed-up rate of the parallel computing using 16 to 1024 processors on the Earth Simulator, demonstrating a fairly good speed-up with large number of processors. It is also found that the Earth Simulator is roughly ten times faster than HITACHI SR8000/MPP with same number of processors.

Strong ground motion from the 2000 Tottori-ken Seibu earthquake

Large inland (Mw6.6) earthquake occurred at Tottori, Japan, on 6 Oct. 2000. The ground motion from the earthquake was well recorded at 521 stations of K-NET and KiK-net, so we can visualized the seismic wave field by an interpolation of seismograms in space and time (Furumura et al., 2003; Fig. 3a).

We conduct a numerical simulation of seismic wave propagations using a subsurface structural model of western Japan and a source model for the earthquake. The simulation model is 820km by 410km by 128km, which is dicritized by a grid size of 0.8km in horizontal directions and 0.4km in vertical. We used a 16-th order staggered-grid FDM in horizontal directions and 4-th order FDM in vertical direction. The 3D simulation took a memory of 96GByte and CPU time of about 35 minutes using 16 node (128CPUs) of the Earth Simulator.

There are good match between the computer simulation (Fig.3b) and observations, though the simulated surface waves are slightly underestimated in the amplitude from these models. The site amplification effect in the sedimentary basins are clearly found, which cause large and long ground motions (120s). Note that such an amplification and prolong effect in localized heterogeneities were never reproduced in the previous experiment using a low-resolution model (Furumura et al., 2003).

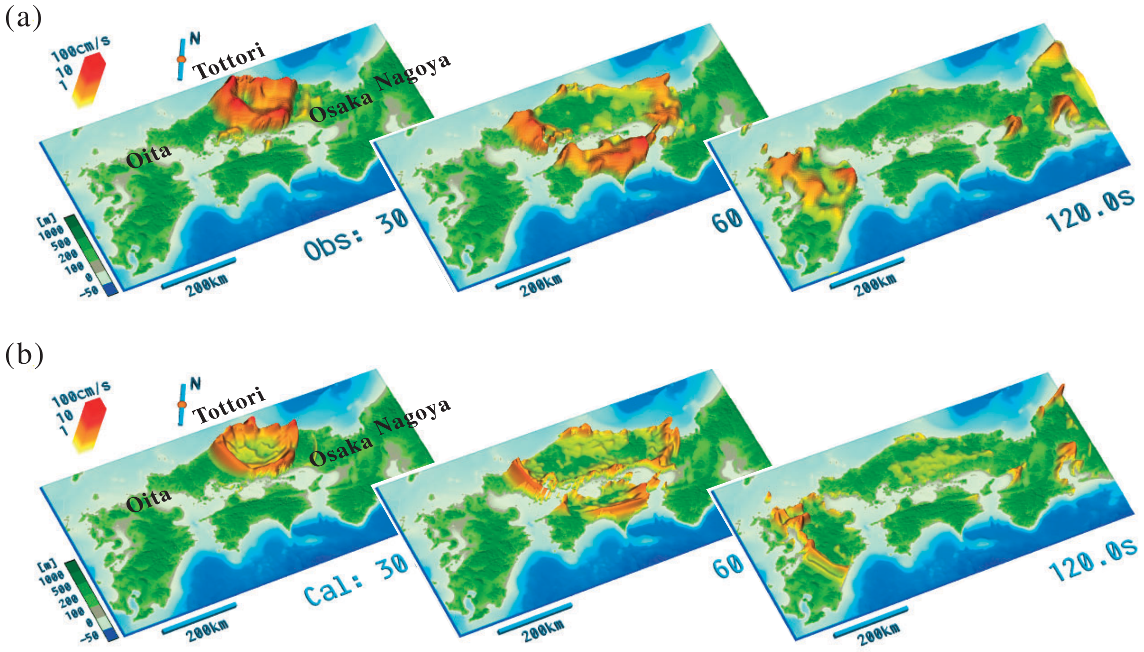

Fig. 3 Snapshots of ground motion for the 2000 Tottori-ken Seibu earthquake, (a) Observation from dense array, and (b) Computer simulations using the Earth Simulator.

Expected ground motions from the Nankai-trough earthquakes

Long historical documents indicate that huge (M~8) earthquakes has repeatedly been occurred at the Nankai trough at an interval of about 90 to 140 years over the thrust faulting of the Philippine-Sea Plate. The previous events at Tonankai (Mw7.9) in 1994 and at Nankai (Mw8.1) in 1946 caused severe damage of over 2,500 causalities in western Japan. So we evaluated the possible scenarios of strong ground motions expecting for future Nankai earthquakes.

Figure 4a displays the snapshot of strong ground motions for a expecting Nankai scenario earthquake, assuming that the fault ruptures occur at Tonankai and Nankai area, simultaneously, like the 1707 Houei Nankai Earthquake. We used the same fault rupture model for the 1944 and the 1946 events for this simulation. Figure 4b shows the potential impact of this earthquake in terms of the intensity of the Japan Meteorological Agency (JMA) point 7 scale.

Conclusion

Although it has long been recognized that the numerical 3D simulation of seismic waves is too expensive to apply practically, the recent powerful parallel computers enable realistic simulation of ground motions in large scale models to several hundred kilometers and at relatively higher-frequencies over 1Hz. This is shown clearly in examples of shown above.

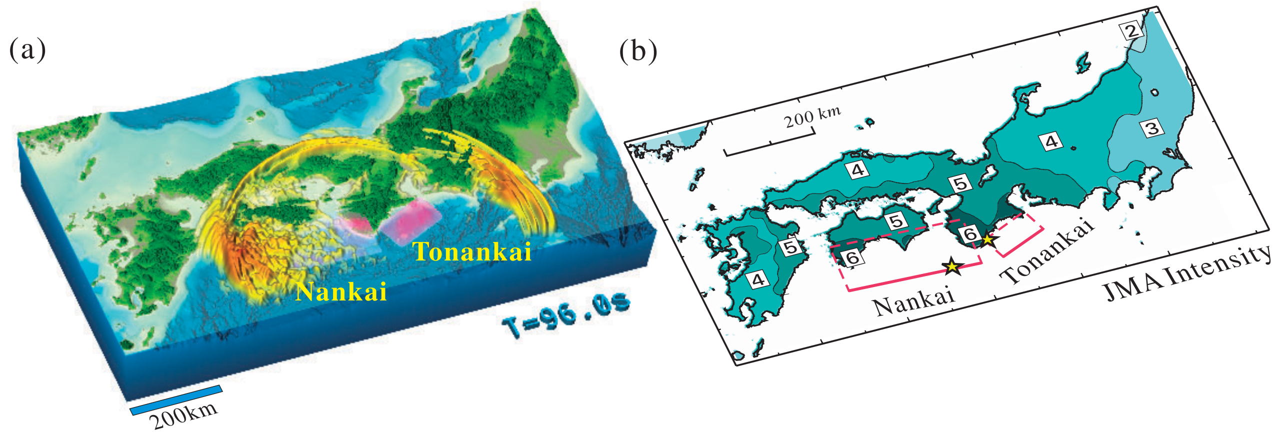

Fig. 4 Expected ground motions for a Nankai earthquake scenario. (a) Snapshot of ground motion during the earthquake, and (b) potential impact in terms of JMA seismic intensities.

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References

Furumura, T., K. Koketsu, and K.-L. Wen (2002a): "Parallel PSM/FDM hybrid simulation of ground motions from the 1999 Chi-Chi, Taiwan, Earthquake", Pure Appl. Geophys, Vol.159, pp. 2133-2146.

Furumura, T. (2002b): "Numerical simulation of seismic wave propagation using the multigrid, parallel PSM/FDM code", Proc. 107th Soc. Expl. Geophys. Japan Conference, Vol. 107, pp. 9-12.

Furumura, T., B.L.N. Kennett, and K. Koketsu (2003): "Visualization of 3D wave propagation from the 2000 Tottori-ken Seibu, Japan, earthquake: observation and numerical simulation", Bull. Seism. Soc. Am., Vol.93, pp870-881.

3次元不均質場での波動伝播と強震動シミュレーション

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3次元不均質場での波動伝播と強震動の評価のために、3次元波動伝播シミュレーションコードの地球シミュレータ上への移植と、これを用いた大規模並列計算を行った。3次元シミュレーションは領域分割法に基づく。波動伝播の計算は、水平方向には16次精度のStaggered格子FDMを、そして鉛直方向には4次精度のFDMを用いて行う。ノード内は自動並列によりベクトル・並列計算が行われ、ノード間にはMPI通信が用いられている。本計算コードを用いて2000年鳥取県西部地震（Mj7.3）、1983年釧路沖地震（M7.8）、そして想定南海トラフ地震の強震動シミュレーションを実施した。計算結果は高密度強震観測網で記録された地震動の性質をよく説明する。これにより、地震波動伝播・強震動シミュレーションモデルとその大規模並列計算の有効性が示された。

キーワード：FDM、地震、南海地震、並列計算