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

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We developed a procedure for integrated simulation of seismic wave and tsunami for mitigation of earthquake and tsunami disasters associated with large subduction-zone earthquakes occurring in the Nankai Trough. We firstly calculate ground motion due to the earthquake by solving equation of motions with heterogeneous source-rupture model and 3-D heterogeneous subsurface structural model. We then calculate tsunami generation and propagation in heterogeneous bathymetry by solving the 3-D Navier-Stokes equation. Ground motion and tsunami simulations are combined through an appropriate dynamic boundary condition at the sea floor. Thanks to the Earth Simulator supercomputer, we have been able to reproducing strong ground motion and tsunamis caused by the M8.0 Tonankai earthquake in 1944.

Keywords: Earthquake, 1944 Tonankai earthquake, Long Period Ground motions, Strong Ground Motions, Tsunami

1. Introduction

Large magnitude (M) >8 earthquakes have repeatedly occurred in the Nankai Trough every 100-200 years. Strong ground motion and tsunamis due to the 1944 M8.0 Tonankai and the 1946 M8.0 Nankai earthquakes seriously damaged areas from Kyushu to Tokai, killing over 2,500 persons in total. Over 60 years have been passed since these events, so the next Nankai Trough earthquake is predicted to occur within the next 30 years.

To better understand and mitigate earthquake and tsunami disasters from such earthquakes, we must be able to realistically simulate these phenomena by employing supercomputers to calculate equation of motion that describe seismic wave propagation and the Navier-Stokes (N-S) equation that describe water flow with detailed source-rupture models, high-density three-dimensional (3-D) subsurface structural models, and high-resolution bathymetry data.

The dynamic seafloor displacement due to the earthquake causes an initial tsunami on the sea surface above the source area. However, ground-motion and tsunami simulations are usually conducted independently using different source and structural models even though they are relating very closely. Current tsunami simulations are often based on approximation equations such as linear long-wave theory (LLW) rather than directly solving N-S equations. For these reasons, understanding of strong ground motion and tsunamis associated with the Nankai-Trough earthquakes remains insufficient.

Therefore, we have developed an integration simulation model combining ground motion and tsunami simulation that accurately represents strong ground motion and tsunamis caused by the Nankai Trough earthquakes. In this integrated simulation, the ground motion and tsunami due to heterogeneous source-rupture process and propagating in 3-D subsurface structure can be simulated consistently. Such coupled ground motion and tsunami simulation was developed and first applied to the 1993 M7.8 Hokkaido-Nansei Oki earthquake simulation by Ohmachi et al. (2001) [1], who used the boundary element method (BEM) for calculating dynamic seabed displacement caused by complex fault-rupture in a homogeneous half-space subsurface structure, then tsunami simulation was conducted by solving the N-S equation in 3-D based on the finite-difference method (FDM). Following this pioneering study, we developed an alternative integrated simulation model using a realistic 3-D heterogeneous subsurface structure model and high-resolution bathymetric data by efficient large-scale parallel simulation using supercomputers. We calculate dynamic ground displacement and coseismic seafloor deformation by FDM simulation of equations of motion in 3-D. Then, the results of seafloor ground motion are used for tsunami generation and propagation simulation as an input in the FDM simulation of 3-D N-S equations.

2. Ground Motion and Tsunami Simulations of the 1944 Tonankai earthquake

2.1 Ground Motion Simulation

Seismic wave propagation and strong ground motions can be solve by parallel 3-D FDM simulation of equation of motions (Furumura and Chen, 2004, [2]) based on a domain-partitioned procedure. The simulation model covers 496 x 800 km and extends 141 km deep, which has been discretized using a uniform mesh of 0.4 x 0.4 x 0.2 km. A structural model of the Earth's crust and upper-mantle beneath central Japan is constructed based on the model of sedimentary structures and the shape of the subducting Philippine-Sea Plate. Both are constructed by based on reflection and refraction experiments, deep land drilling, and gravity data. The source-slip model for the 1944 Tonankai earthquake is derived by an inversion using a near-field strong motion waveform. The inferred fault model is 180 x 90 km, and maximum slip of 4 m radiates seismic waves with a total seismic moment of $Mo=1.0*10^{21}$ Nm (Mw=8.0; Fig. 1).

The results of the FDM simulation for the seismic wave propagation from the 1944 Tonankai earthquake demonstrate the strength of horizontal velocity ground motion at time T=15s, 40s, 90s, and 120s from when the earthquake begins (Fig. 3). A sequence of snapshots clearly shows the spread of seismic waves from the source fault where the fault ruptures spreading from southwest to northeast at a speed slightly less than S-wave speed.

The development of the long-period ground motion at a period of T=3-6 s is clear developed at the rupture front due to the directivity of the rupturing fault. Later time frames (T=90s and 120s) capturing significant amplification of long-period ground motion in large sedimentary basins such as those beneath Osaka, Nagoya, and Tokyo, where thick sedimentary rocks of over h=3000 m cover rigid bedrock (Fig. 3).

2.2 Tsunami Simulation

We then using ground motion simulations results in dynamic seafloor movement caused by the 1944 Tonankai earthquake in tsunami generation and propagation simulation which is described by 3-D Navier-Stokes equations for incompressible flow. Our simulation treats offshore tsunamis because the boundary condition on the sea surface cannot account for tsunami wavefront breaking and tsunami run-up. In order to solve the Navier-Stokes equations, we use the conventional SOLA technique developed by Hirt et al. (1975) [3], which has been widely used for simulating flow of fluid in 3-D. In simulation, velocities and pressure components in cells on the staggered-grid are updated iteratively at each time step to satisfy the following continuity conditions for incompressible fluid at a satisfactory level.

The dynamic vertical seafloor movement on the sea floor derived by the simulation of ground motion is introduced into the tsunami simulation, with the velocity boundary condition at the seafloor during source rupture time. The vertical flow of water due to seafloor movement above the source region lifts the sea surface, which is the initial tsunami developed by the earthquake. The developed initial tsunami distribution at the sea surface is usually smoother than the shape of coseismic seafloor deformation caused by the earthquake because a thick cover of seawater and finite source-duration time works as a sort of high-cut filter to remove large-wave number components from the shape of initial tsunami developed at sea surface (Kajiura,

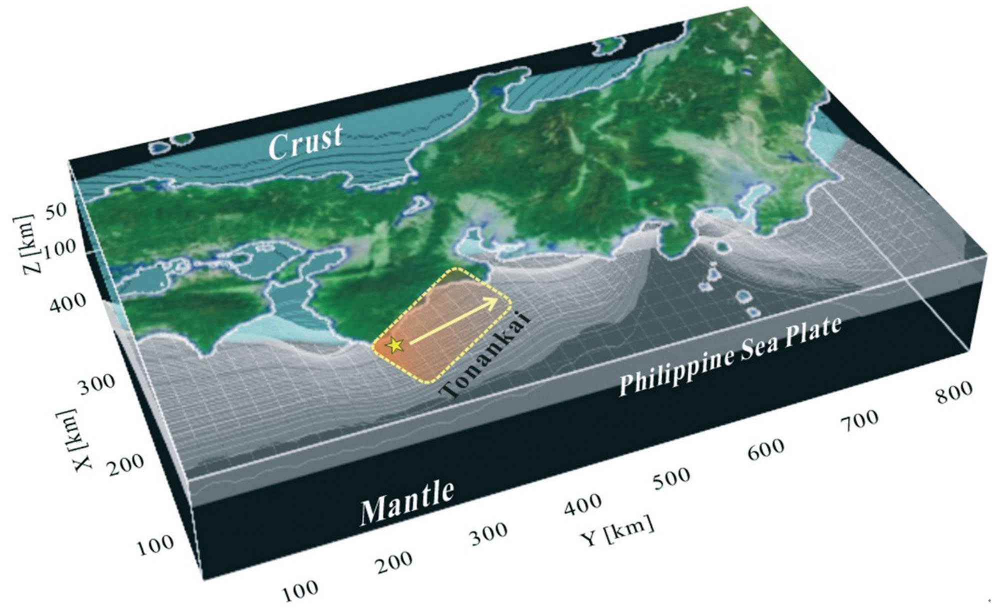

Fig. 1 Source (orange area) model of the 1944 Tonankai (Mw8.1) earthquake and 3D structural model of Nankai Trough subduction zone used for 3D simulation of seismic wave propagation and tsunami propagation simulation.

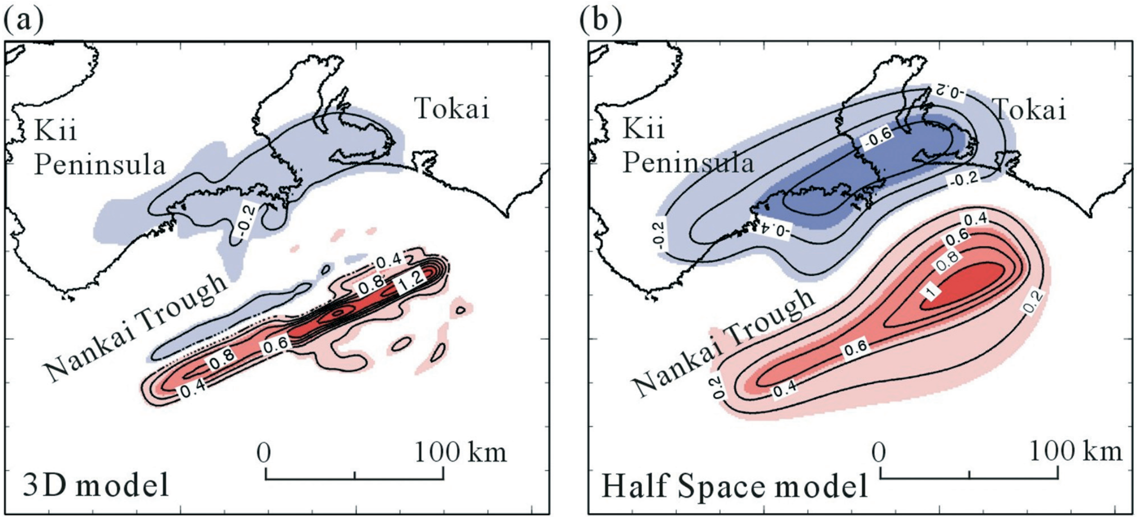

Fig.2 Coseismic deformation of seafloor with uplift (red) and subsidence (blue) of seafloor derived in 3-D simulation of seismic wave propagation using (a) a 3-D heterogeneous structural model and (b) a homogeneous half-space model.

1963, [4]; Saito and Furumura, 2009, [5]). Our 3-D N-S tsunami simulation simulates such all effects naturally and accurately.

The most consuming FDM simulation calculation of the 3-D N-S equation based on the SOLA algorithm is for updating velocity and pressure components at individual cells together with surrounding cells iteratively at each time step. Such an iteration calculation sequence is, however, inefficient in extracting the power of the vector computing hardware such as employed in the Earth Simulator. Thus, it is still necessary to modify present tsunami simulation code suitable for vector computing. For parallel simulations we here used a single-level flat MPI model in which single-threaded MPI processes are executed on each processor core.

Model of the 3-D tsunami simulation was 500 x 1200 km and 10 km deep, discretized into 1000 * 2400 * 100 grid points with a grid of 500 m horizontally and 100 m deep. We also used digital bathymetric data of J-EGG 500, provided by the Japan Oceanographic Data Center, in the tsunami simulation.

Figure 2 illustrates coseismic seafloor displacement distribution derived by ground motion simulation for the 1944 Tonankai earthquake using the 3-D heterogeneous subsurface structure model for the Nankai-Trough subduction zone (Fig. 1) and that derived by using a homogeneous half-space model assuming rigid bedrock (Vp=8 km/s, Vs=4.6 km/s). Note that

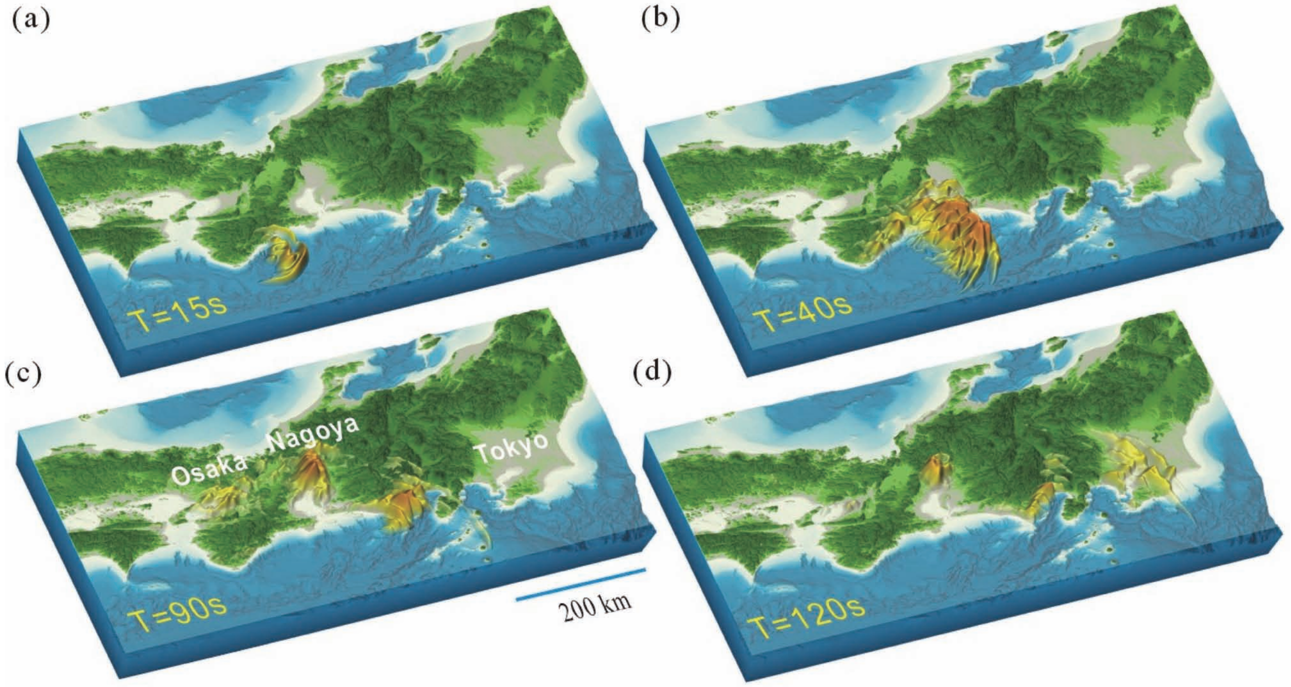

Fig.3 Snapshot of ground motion for the 1944 Tonankai Earthquake derived by 3D FDM simulation of seismic wave propagation.

present tsunami simulation usually assumes such static seafloor elevation in a homogeneous half-space structure using a conventional computer code such as developed by Okada (1985) [6], rather than considering complex seafloor movement due to the actual 3-D heterogeneous structure.

Sea floor elevation results due to low-angle thrust faulting at the top of the shallowly dipping Philippine-Sea Plate show large uplift in the seafloor along the trench of the Nankai Trough and subsidence of ground surface at the eastern coast of the Kii Peninsula. Such coseismic displacement distribution pattern derived by the 3-D model shows a large seafloor elevation in a relatively narrow zone about 20 km wide and 180 km long (Fig. 2a). On the other hand the coseismic displacement pattern derived by simulation using the half-space model is spreading to the wider area of about 80 km and 200 km (Fig. 2b). Maximum seafloor elevation derived by the 3-D and homogeneous half-space subsurface models is almost same at 1.2 m and 1.0 m, respectively.

The tsunami derived by the simulation for the 1944 Tonankai earthquake at time T = 10, 20, 30, and 40 minutes after when the earthquake began had a tsunami wavefield for sea surface uplift and subsidence (Fig. 4). The large slip at the northeastern part of the fault plane and fault rupture propagation from southwest to northeast produced large tsunamis eastward of the source region of the Tonankai earthquake. Some 10 minutes after the earthquake, a large tsunami arrived at the eastern Kii Peninsula and Tokai coast. As the tsunami propagated coastally, the tsunami height increases dramatically. Tsunamis over 2 m high hit the Pacific Ocean coast 10-20 min after the earthquake. Some 20 min after the earthquake the head of the tsunami had spread to the Izu Islands 300 km east of the hypocenter and to Cape Muroto in Shikoku, and by 40 min the tsunami propagated to the Boso Peninsula and Cape Shiono. As time passed, scattering of tsunami due to multiple reflections in heterogeneous bathymetry and around the islands modified the tsunami waveform very dramatically, leading to complex and long-term sea surface disturbances.

We compared tsunami simulation results for the 3-D N-S model to those from conventional tsunami simulation based on 2-D linear long-wave (LLW) theory. The LLW model effectively treats tsunamis in shallow seas with depth (H) less than the tsunami wavelength (L) ($H < 10\text{-}20\times L$). In our tsunami simulation for the LLW model, the initial tsunami for the sea surface elevation distribution is assumed to be identical to that of sea bottom elevation, which is also reasonable for considering tsunami generation in shallow seas with sea depth H less than 10 times of the sea bottom deformation area Sa ($H < 10\times Sa$; Saito and Furumura, 2010, [5]). Note that the linear theory (Kajiura, 1963. [4]) can also be used for more accurate estimation of initial tsunami distribution on the sea surface caused by the sea floor deformation in deep sea.

Simulated tsunami waveforms at Mera, Uchiura, Matsuzaka, and Tosa Shimizu stations are shown in Fig. 5 which have been applied a high-cut filter with a cut-off frequency of fc=0.0167 Hz (cut-off period of Tc=1 min) to remove high-frequency signals. The tsunami waveform derived by the half-space subsurface structure model shows a smooth, longer-wavelength tsunami compared to that from the heterogeneous 3-D structural model as is easily expected from the seafloor displacement distribution pattern shown in Fig. 2. On the other hand the

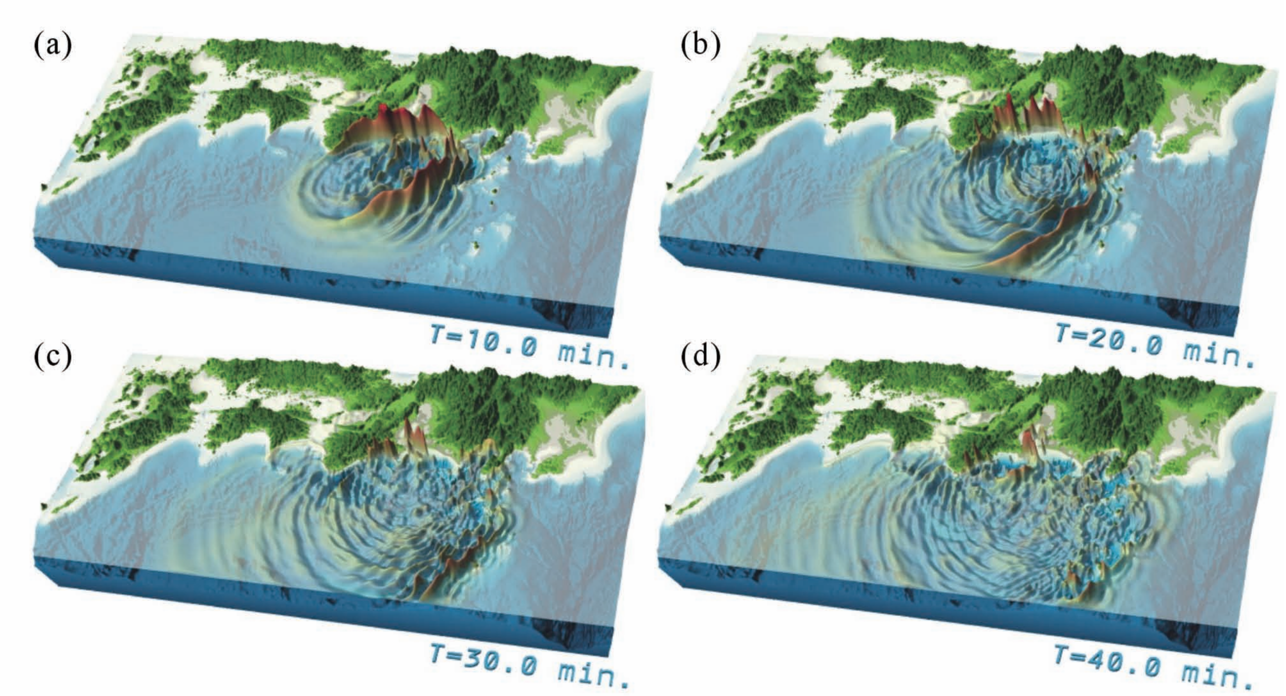

Fig.4 Snapshots of tsunami from the 1944 Tonankai Earthquake derived by the 3D Navier-Stokes equation simulation.

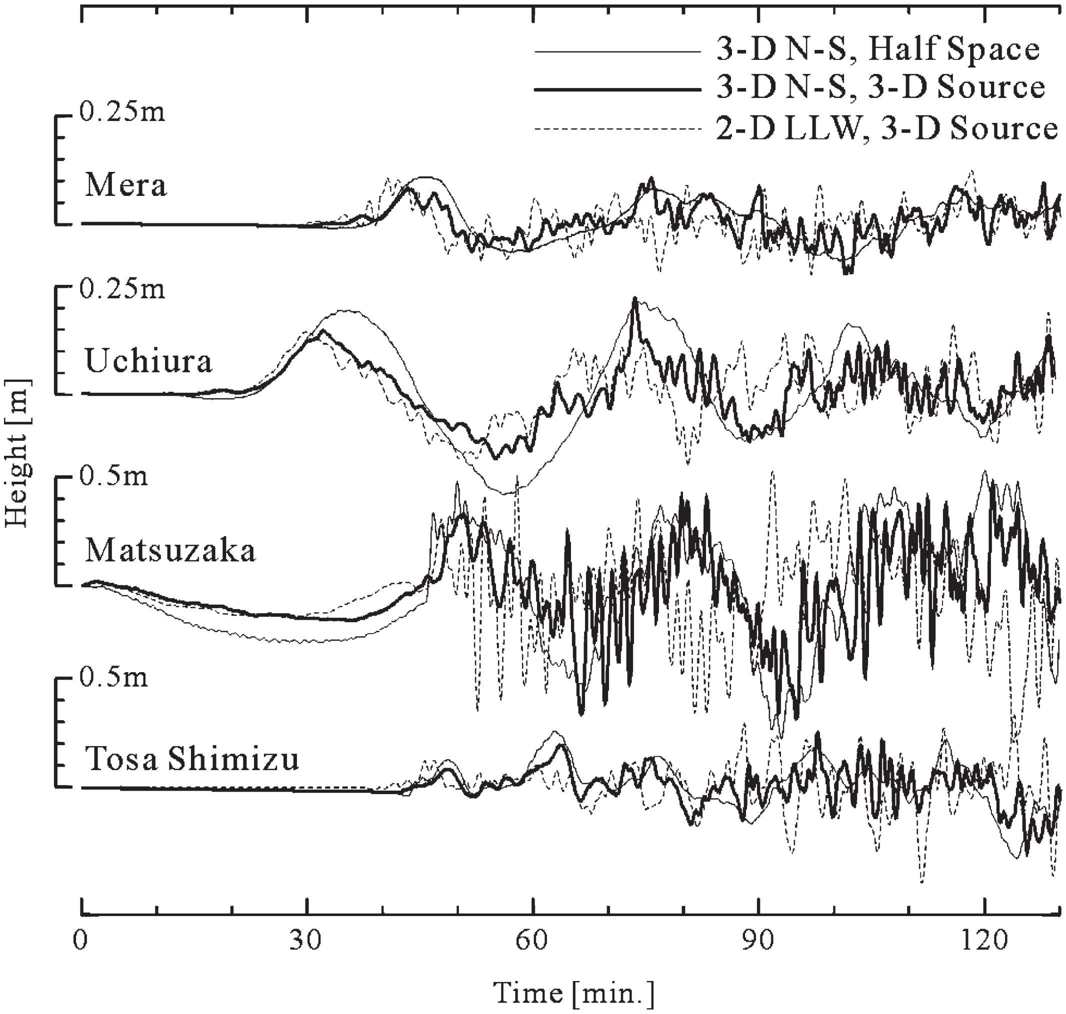

Fig.5 Simulated tsunami waveform at Mera, Uchiura, Matsuzaka, and Tosa Shimizu (stations in Fig. 5) derived by simulation using 3-D N-S and source models assuming a 3-D heterogeneous structure (thick lines) (Fig. 2a) and a homogeneous half-space model (thin lines) (Fig. 2b) and 2-D LLW model (dashed lines).

tsunami waveform derived by the simulation from the 3-D N-S model shows a somewhat smoother wave shape than that for the 2-D LLW model because the cover of thick sea water above the source acts high-wavenumber cut filter. A finite source-rupture time for the earthquake also removes large wave number components from the initial tsunami distribution on the sea surface. Some delay in tsunami arrival of 3-5 min in the 3-D N-S simulation in the tsunami record of distant Mera and Tosa Shimizu stations is due to the dispersion of tsunami propagating in deep Nankai Trough. Such effects are not accounted for in the 2-D LLW model.

3. Conclusion

Large (M > 8) earthquakes occurring in the Nankai Trough might be causing significant disasters from Kyushu to Tokai along Japan's Pacific Ocean coast due to large, long-term ground shaking of long-period ground motions in sedimentary basins and tsunamis along the coastal zone. Coseismic vertical movements associated with large earthquakes also have caused rise and subsidence in coastlines near the source area. Downtown Kochi, Shikoku, sank after the 1946 Nankai earthquake due to coastal subsidence - exceeding 0.5 m. Such coseismic displacement is expected to cause additional coastal disasters with enhanced tsunami inundation and tidal wave effects.

To mitigate such earthquake-related disasters anticipated in future Nankai-Trough earthquakes, integrated ground motion and tsunami simulation using high-performance computers and reliable simulation models is indispensable.

By using present ES supercomputers, we have reproduced long-period ground motion, coseismic deformation, and tsunamis during the 1944 Tonankai earthquake very efficiently. Simulation and observation results agreed well for long-period ground motion developing in central Tokyo, indicating the effectiveness of the present simulation model for modeling long-period (T > 2 s) ground motion for the past and future earthquakes.

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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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南海トラフ巨大地震による強震動と津波を高精度に評価し、災害の予測と軽減に資することを目的に、地震と津波の連成シミュレーションコードを開発した。本シミュレーションでは、まず震源モデルと地下構造モデルを用いて地震動と地震地殻変動を運動方程式の 3 次元差分法計算により評価する。次に、求められた海底面及び陸の地殻変動を入力として、津波の発生と伝播を 3 次元ナビエストークス式の差分法計算により行う。地震と津波の連成シミュレーションにより、不均質な地下構造で発生する地震が作り出す地殻変動を正しく評価することができ、そして地震から津波にいたる海溝型巨大地震の災害を時間を追って考えることができるようになる。従来の津波評価では地殻変動は均一な地下構造を用いた評価が一般的であり、また津波伝播計算には線形長波モデルが用いられることが多かった。本シミュレーションにより、3 次元的に不均質の強い海底下での特異な地殻変動と、深い海を伝わる津波の分散波の特徴を表現することができるようになり、南海トラフ地震による津波の継続時間を含めた津波波形の評価に威力を発揮するものと期待される。ナビエストークス式計算のベクトル化効率が悪く、コードチューニング等による改善が課題として残される。