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

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Strong ground motions recorded in central Tokyo during the 1944 Tonankai Mw8.1 earthquake occurring in the Nankai Trough demonstrate significant developments of very large (>10 cm) and prolonged (>10 min) shaking of long-period (T>10–12 s) ground motions in the basin of Tokyo locating over 400 km from epicenter. In order to understand the process by which such long-period ground motions developed in central Tokyo and to mitigate possible future disasters arising from large earthquakes in the Nankai Trough, we conducted computer simulation of the Tonankai earthquake using the Earth Simulator. The result of compute simulation is compared with the observations of old seismograms recorded in Tokyo, demonstrated that such long-period ground motion is primarily developed as the wave propagating along the Nankai Trough due to the amplification and directional guidance of long-period surface waves within a thick sedimentary layer overlaid upon the shallowly descending Philippine Sea Plate below Japanese island.

Such development of the long-period ground motions during the subduction zone earthquakes indicating large tsunami will be developed due to vertical deformation of seafloors above the subduction zone. We therefore conducted tsunami simulation for the earthquake using the simulation results of seismic wave as the source of tsunami. The results of tsunami simulation demonstrating very high (h>5m) tsunami developing due to the shallow slip of the Tonankai earthquake and propagating very long distances in Nankai trough to approach to Kanto area after 60 s from the earthquake inciate. The coupled simulation of seismic wave propagation and tsunami generation/propagation simulation using detail earthquake source and subdurface structural model is very important to mitigate strong ground motion including long-period ground motions and tsunami disasters expecting for future earthquake scenario.

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

1. Introduction

Large M8 earthquakes have occurred repeatedly within the Nankai Trough at a recurrence period of about 90–110 years. The 1944 Tonankai (Mw8.1) earthquake resulted in more than 1250 deaths along the Pacific-facing southern coast of Japan. Tokyo, the largest population center in Japan, is located about 400 km from the hypocenter, and recorded a maximum intensity of 3–4 on the JMA scale. No significant damage was reported in Tokyo during the large but distant earthquake; however, ground motions recorded in Tokyo demonstrate the development of very large (>10 cm) and prolonged (>10 min) shaking associated with long-period (T0 = 10–13 s) ground shakings generated by the earthquake (Furumura and Nakamura, 2006).

These observations warn of the potential vulnerability of modern large-scale constructions to large, nearby earthquakes. Thus, it is an urgent matter to investigate the processes by which long-period ground motions within the Kanto Plain originate and evolve. This will aid in the mitigation of future seismic-related disasters predicted to result from earthquakes within the Nankai Trough.

Although the strong motions generated during the 1944 Tonankai earthquake were almost clipped in near-field stations by intense ground shaking, few distant stations such as installed in Tokyo were clearly recorded long-period ground motions that developed in Kanto basin (Fig. 1).

We curried out large-scale computer simulations of seismic waves propagation the 1944 Tonankai earthquake by employing the Earth Simulator supercomputer with a high-resolution subsurface structure model of central Japan which has been developed recently by analyzing a large number of reflection and refraction experiments and the physical parameters such as P- and S-wave velocity, density, and anelastic attenuation (Q) properties has been modified extensively by matching the simulated waveform and observed seismograms of recent large earthquakes.

Strong motion waveforms derived from the simulation shows good correlation between main feature of the

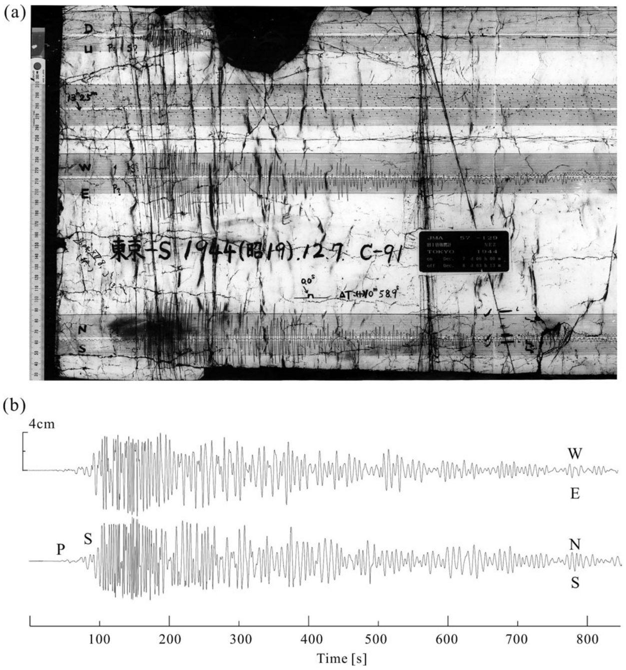

Fig. 1 (a) Example of a smoked-paper seismogram from a Central Meteorological Agency strong-motion instrument housed at Yokohama during the 1944 Tonankai Earthquake. (b) Digitized waveform data of the WE and NS components of displacement motions. Instrumental corrections were not applied to the digitized seismograms.

observed ground motions during the earthquake, demonstrating that the model is already be in a suitable level to simulate ground motions from large earthquakes occurring in the Nankai Trough. Snapshots of seismic wave propagation derived from the simulation provide for a detailed understanding of the nature of the seismic wavefield and the development of intense and prolonged long-period ground motions within central Tokyo during the 1944 Tonankai earthquake.

Large, shallow subduction zone earthquakes also produce large tsunami due to the vertical deformation of seafloors caused by the earthquakes. This crustal deformation effect should be very significant when the earthquake occurs in heterogeneous structure with thick cover of soft sedimentary layers above rigid subducting plate. We thus conduct tsunami generation and propagation simulation using the results of FDM simulation of seismic wave propagations, and the final vertical deformation of seafloor is used as the initial tsunami. The tsunami propagation is calculated by solving mass constitutive equations and linearlized tsunami equations by FDM.

2. Parallel Simulation of the 1944 Tonankai earthquake

We firstly evaluated strong motions arising from the 1944 Tonankai earthquake using a source-slip model that was developed by inversion from the strong-motion record (Fig. 2). The size of the inferred fault is 180 × 90 km, which was re-sampled into 2 × 2 km subfaults using a linear interpolation function. A triangular slip-velocity function with a pulse width of 2 s was assigned to each subfault. As the inferred interpolated source slip model might be too smooth to introduce a strong rupture-directivity effect along the direction of fault rupture propagation, we introduced a random fluctuation in the fault rupture speed at each point on the subfault. This random fluctuation is represented by a Gaussian function with a standard deviation of 5%, and the random fluctuation of rupture velocity is embedding over an average rupture speed of Vr = 2.95 km/s.

Snapshots of simulated horizontal ground velocity motions

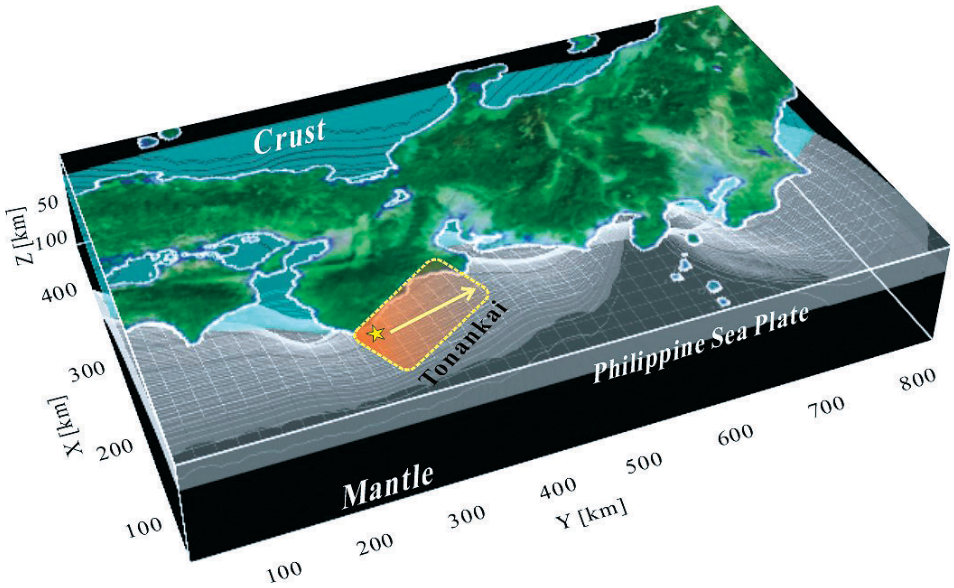

Fig. 2 Source (orange area) model of the 1944 Tonankai (Mw8.1) earthquake and 3D structural model of Nankai Trough subduction zone used for 3D simulation of seismic wave propagation and tsunami propagation simulation.

during the 1944 Tonankai earthquake are shown in Fig. 3. Each snapshot clearly demonstrates the radiation of S-waves from the M8 source and the development of long-period ground motions via interaction with sedimentary structures within the Nankai Trough. The effect of the low-wavespeed sedimentary wedge in terms of guiding long-period surface waves to the east is clearly evident in the middle frames (T = 90 s). The snapshots capture the significant amplification of ground motions within large sedimentary basins such as those beneath Osaka, Nagoya, and Tokyo. Central Tokyo is affected by prolonged ground shaking for several minutes leading up to the propagation of the S-wave front across the Kanto Basin to the north (T = 120 s). As the enhanced ground motions within the sedimentary basin are several times larger than those in surrounding area.

Figure 4 shows a comparison of the simulated waveforms of NS-component ground velocity motions and the velocity response spectra assuming 5% damping constant (h = 0.05)

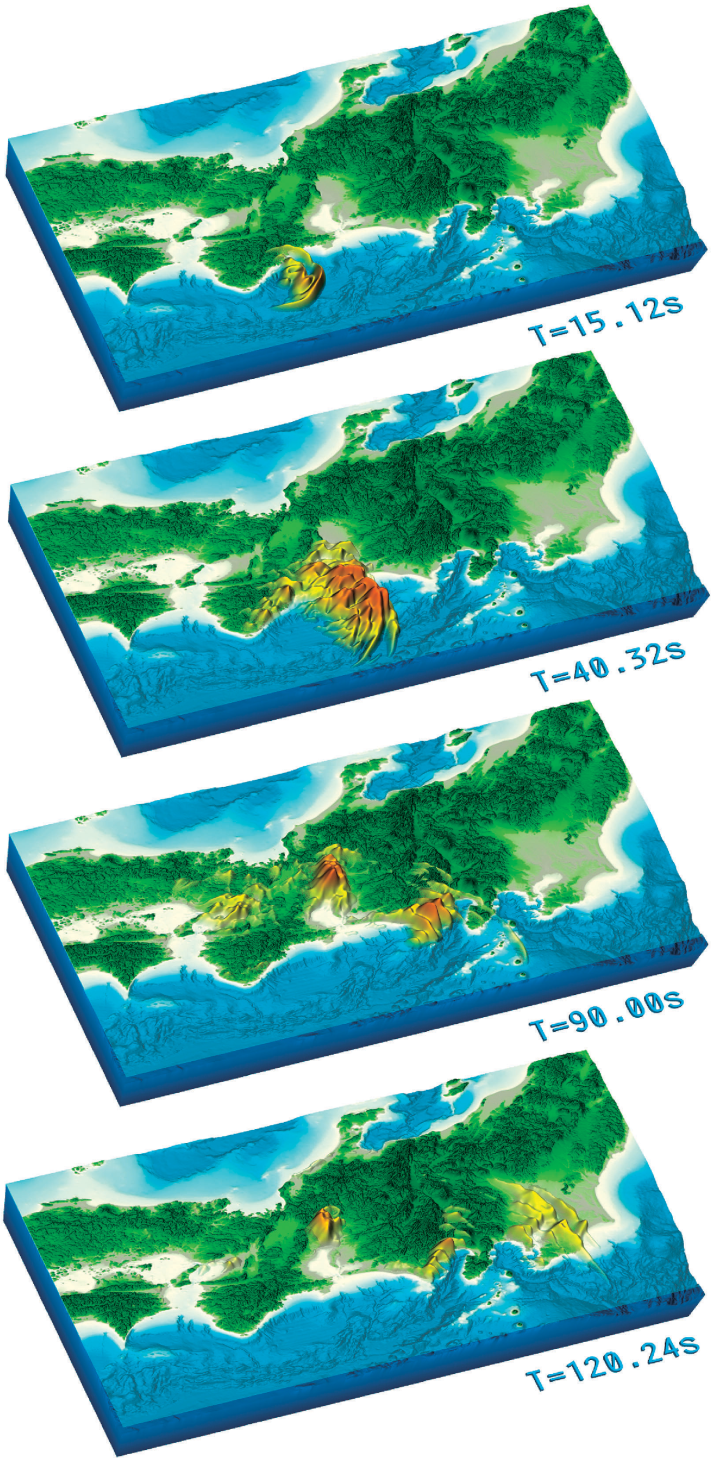

Fig. 3 Snapshots the propagation of simulated seismic waves arising from the 1944 Tonankai earthquake for T = 15, 40, 90, and 120 s from source rupture.

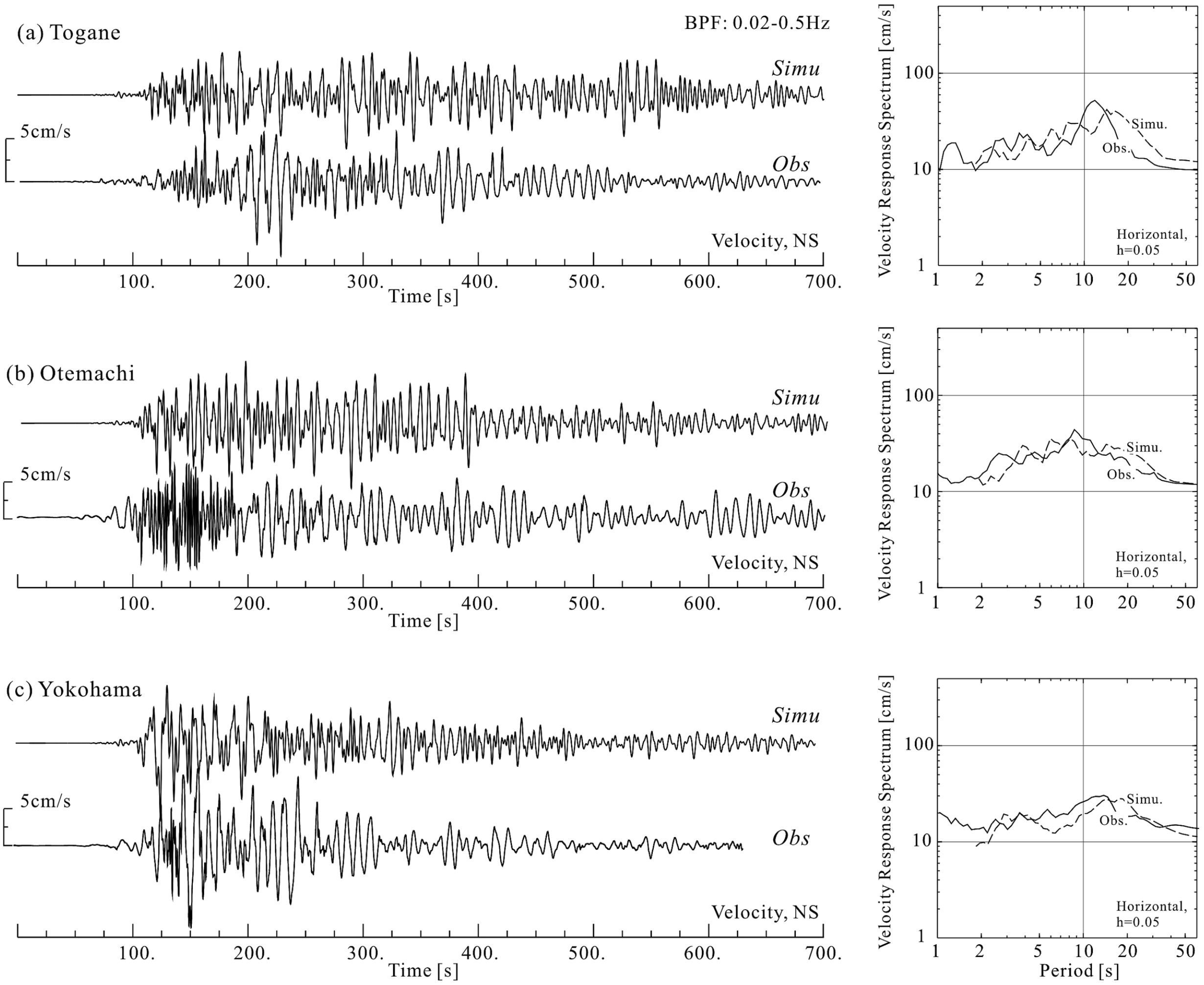

Fig. 4 Comparison between the simulation (top) and observational data (bottom) in terms of the waveform of NS-component ground velocity motions and velocity response spectra recorded at (a) Togane, (b) Otemachi, and (c) Yokohama for the 1944 Tonankai earthquake.

with observational data recorded at Togane, Otemachi, and Yokohama, in Kanto Basin. A low-pass filter with a band-pass frequency of 0.02–0.5 Hz was applied to the simulated and observed seismograms. The simulation results demonstrate the major features of observed ground motions such as the dominant period of the surface waves and the shape of the coda.

The level of the velocity response spectra of observed and simulated ground motions are in good agreement, but some differences in the dominant period of peak ground motion are recorded for Togane and Yokohama, probably due to limitations in the source model and sedimentary structure model used in the simulation. However, as the major features of the long-period ground motions developed within the Kanto Plain are well simulated by the model, we believe that the present model has largely attained the level of accuracy required to estimate the strength of long-period ground motions expected in central Tokyo during future earthquakes within the Nankai Trough.

The result of the computer simulation of the 1944 Tonankai earthquake also depicts strong ground motions within areas for which observational data were not available at the time due to a lack of seismic instruments or the fact that the seismometer was completely clipped due to intense ground shaking (as occurred in near-field such as in Osaka and Nagoya).

3. Tsunami Simulation of the 1944 Tonankai earthquake

We developed an integrated simulation model for tsunami and seismic wave propagation generated by large subduction zone earthquakes (Staito and Furumura, 2006). The spatial and temporal deformation of sea floor is already solved by a 3-D simulation of seismic wave. Thus, we used the vertical component of the sea floor deformation derived by the earthquake as the source of tsunami. Unlike the current conventional simulation models that use static deformation of sea floor as tsunami source, our integrated model can evaluate the effect of dynamic deformation process of sea floor caused by complex fault rupture in 3-D heterogeneous subsurface structure at subduction zone.

The simulated ground motion shows large deformation of the seafloor in localized region as compared with that derived from a conventional model assuming homogeneous half-space structure. This is because the seismic strain is accumulated in small elasticity portion in inhomogeneous subsurface structure. As a result, tsunami wave of our simulation has larger maximum amplitude than that calculated with homogeneous half-space medium. The snapshots of tsunami propagation at time $T = 5, 10, 25, 50$ minutes from the earthquake origin time are shown in Fig. 5. The deformation of sea floor associated by the propagation of Rayleigh wave on sea floor also excites weak tsunami in the direction of fault rupture propagation as a forerunner of major tsunami signals, which is clearly demonstrating in our simulation.

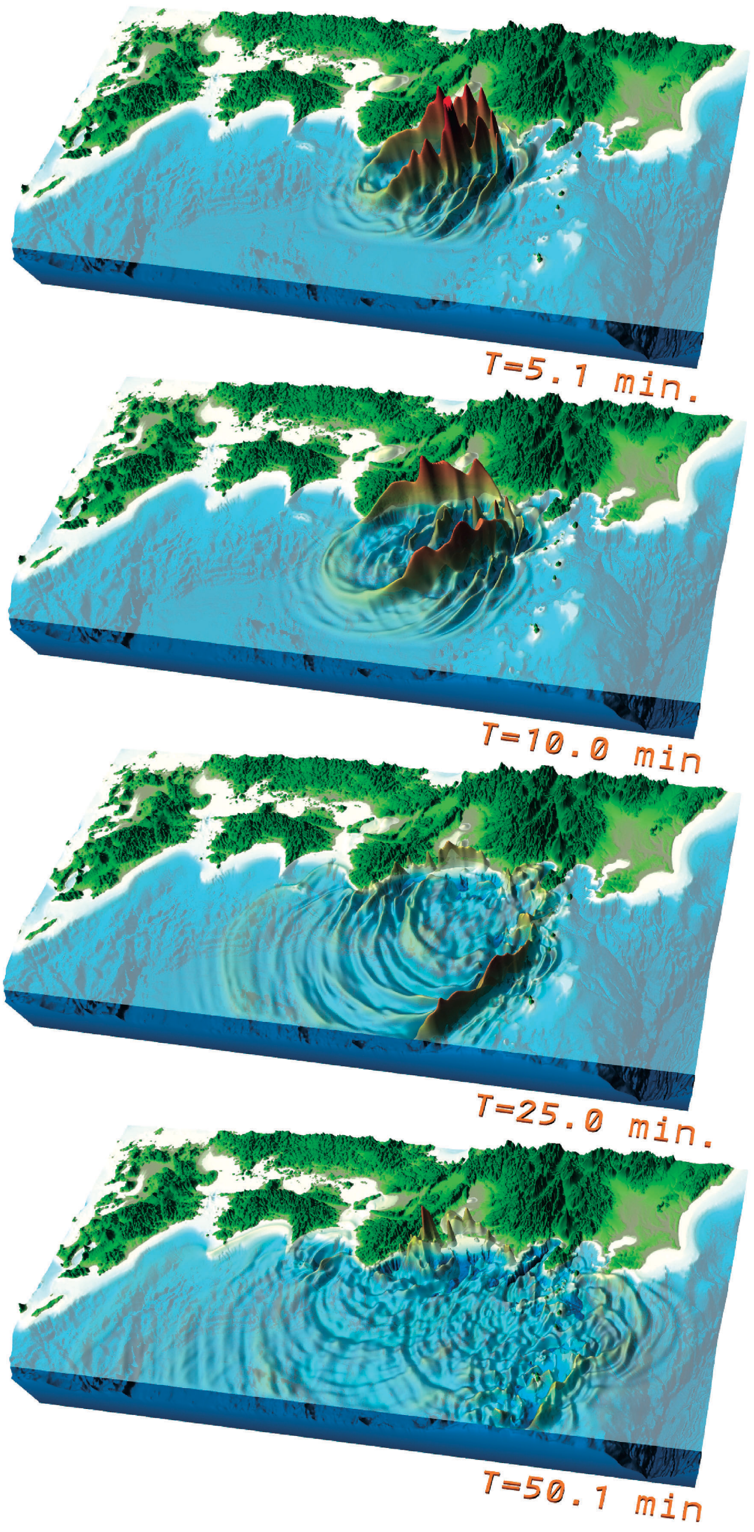

Fig. 5 Snapshots of tsunami propagation during the 1944 Tonankai earthquake, after 5, 10, 25, and 50 min from the earthquake starts.

4. Conclusion

The development of long-period ground motions with a predominant period of about 6–12 s within the thick cover of sedimentary layers beneath Tokyo is a common characteristic of all large earthquakes, but the earthquakes within the Nankai Trough are expected to be the most disastrous in terms of producing extremely large and lengthy long-period ground shaking.

The strong motion record of the 1944 Tonankai Mw8.1 earthquake and computer simulations demonstrates intense and prolonged shaking in central Tokyo associated with long-period ground motions with a dominant period of about 12–14 s (Furumura and Nakamura, 2006; Furumura et al., 2006). This finding highlights the potential vulnerability of modern large-scale constructions to future earthquakes within the Nankai Trough.

The Tonankai earthquake also caused large tsunami killing over 1500 persons in the coastal area. Thus the occurrence of the next Tonankai earthquake warn severe tsunami disaster as well as the strong motions. In the present simulation we solved traditional simplified tsunami equations based on a linear long-wave theory, so that dispersion effect of tsunami as propagating longer distances in deep sea water is not taking accounted in the model. Such assumption often cause serious problem of overestimating tsunami height when the earthquake occur deep sea. Thus we will improve out simulation model of tsunami by solving 3-D Navier-stokes equations using large number of processor of the Earth Simulator. We also need to incorporate very soft sedimentary layers overlying subducting plate, since such soft layer sometimes cause extremely large tsunami such as during the great Sanriku Tsunami earthquake in 1896. The magnitude scale of this event is less than 8.5 but huge tsunami killed of more than 20,000 persons.

One of the important goals of strong-motion seismology is to predict the ground motions and relating tsunami likely to occur in future subduction zone earthquakes scenarios and to assist in the development of appropriate building codes and seawalls for different areas within sedimentary basins. In terms of achieving this goal, the improvements in the simulation model, especially the sedimentary structure beneath the Kanto Basin and subduction zone, is highly desired.

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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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南海トラフの地下構造モデルの高精度化を進め、最新の震源モデルを用いて1944年東南海地震のシミュレーションの再計算を実施した。関東平野で生成した長周期地震動（T=8−12s）の特性を調査するために、大手町、横浜、東金（千葉県）で記録された古い地震計記録を復元し、計算結果と比較することによりシミュレーションモデルの精度を検証した。計算結果は、観測された地動の特性（震幅、継続時間、周期特性）を十分な精度で説明することが確認でき、現在のシミュレーションモデルを用いて将来発生のおそれのある南海トラフ地震の計算を高精度に進める目処を得た。海域の大地震により生成された海底地殻変動は津波を引き起こす。大地震による被害軽減を目的に、地震動シミュレーションと津波発生・伝播シミュレーションモデルを結合した、新しい地震-津波モデルを開発した。従来の津波伝播シミュレーションでは、均質な媒質における海底地殻変動を解析的に求め、これを津波波源として計算を進めるのが一般的であったが、本シミュレーションでは、3次元不均質地下構造と断層破壊の動的特性を正しく評価することができる。この計算手法では、沈み込み帯の柔らかい堆積物により発生する地震津波の予測に特に有効である。

キーワード：東南海地震, 長周期地震動, 津波, 連成シミュレーション