Computer Simulation of Long-Period Ground Motions from the 23 October 2004 Mw6.6 Niigata-ken Chuetsu Earthquake, Japan

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Unusually large and long-time shaking of long-period ground motions of duration ~7 s resulted in severe shaking of high-rise buildings in central Tokyo during the 2004 Mw6.6 Niigata-ken Chuetsu earthquake. The seismic wavefield reconstructed from a dense array of seismic recordings and a corresponding computer simulation using the Earth Simulator supercomputer demonstrates that the mortar-like shape of the Kanto basin and the thick cover of overlying sediments below Tokyo Bay are the main causes of the anomalously prolonged ground shaking resulting from the multipathing and focusing of seismic waves toward central Tokyo.

Keywords: Earthquake, Seismic Waves, Strong Ground Motions

Introduction

A large (Mw6.6) inland earthquake occurred at Chuetsu, Niigata, Japan on 23 Oct. 2004, about 200 km northwest of Tokyo. Although the maximum intensity recorded in Tokyo from this earthquake was just 3 on the Japan Meteorological Agency's 7-point scale, Tokyo was subject to more than five minutes of intense (>3 cm) ground shaking. The dominant period of ground motions recorded was relatively long, about 7 s, and caused significant resonance within high-rise buildings of approximately 70 floors in height. All elevators in these buildings, including those in the Tokyo Metropolitan Government Office, were stopped and many people in the buildings suffered motion sickness.

The duration of the long-period ground motions brings to mind the severe damage caused in Mexico City during the 1855 Michoacan (Mw8.0) earthquake, which resulted in more than 20,000 fatalities following the distant earthquake 400 km away. Fortunately no fatalities resulted in Tokyo from the Mw6.6 Chuetsu earthquake, but the intense and prolonged ground shaking that struck Tokyo provides a warning of the destruction that might accompany the future M8 earthquakes. The Tokai earthquake, occurring at the Suruga Trough about 150 km away from Tokyo, is one of such hypothesis earthquake that is predicted to occur in the near future. Thus, the high risks posed by the large earthquakes make it an urgent matter to explore the origin of the long-period ground motions, and to relate the ground motions to the complex subsurface structure of the Kanto basin.

Observation of Ground Motions

Ground motions resulting from the Chuetsu earthquake were well recorded by the nation-wide K-NET and KiK-net strong motion networks of the National Research Institute of Earth Science and Disaster Prevention (Fig. 1). These networks recorded the spatial and temporal distribution of ground velocity motions following the earthquake. Each of the 4 snapshots show in Fig. 1 is derived from interpolation of seismograms from 513 stations after application of a low pass filter (f < 0.5 Hz) to reduce the spatial aliasing effect. In the T = 20 s snapshot, a large ground motion results from an almost isotropic radiation of S-waves from the hypocenter upon the reverse-fault. As the waves spread from the source region, the effect of near-surface heterogeneity becomes apparent (60 s). Significant amplification of ground motions within sedimentary rocks of the Kanto basin is clearly captured in the following two frames at 120 s and 180 s, and the peak ground velocity recorded in central Tokyo is at least 10 times greater than that measured in surrounding areas. Intense and prolonged ground motions within the basin continue for several minutes, providing a clear outline of the basin margins.

As the K-NET and KiK-net stations rely on triggering to initiate the recording of data, not all stations recorded data once the acceleration levels dropped; however, recordings within central Tokyo (station TKY015 at Sumida-ku, central Tokyo) were sufficiently continuous to enable an analysis of the response of individual buildings to the ground motions.

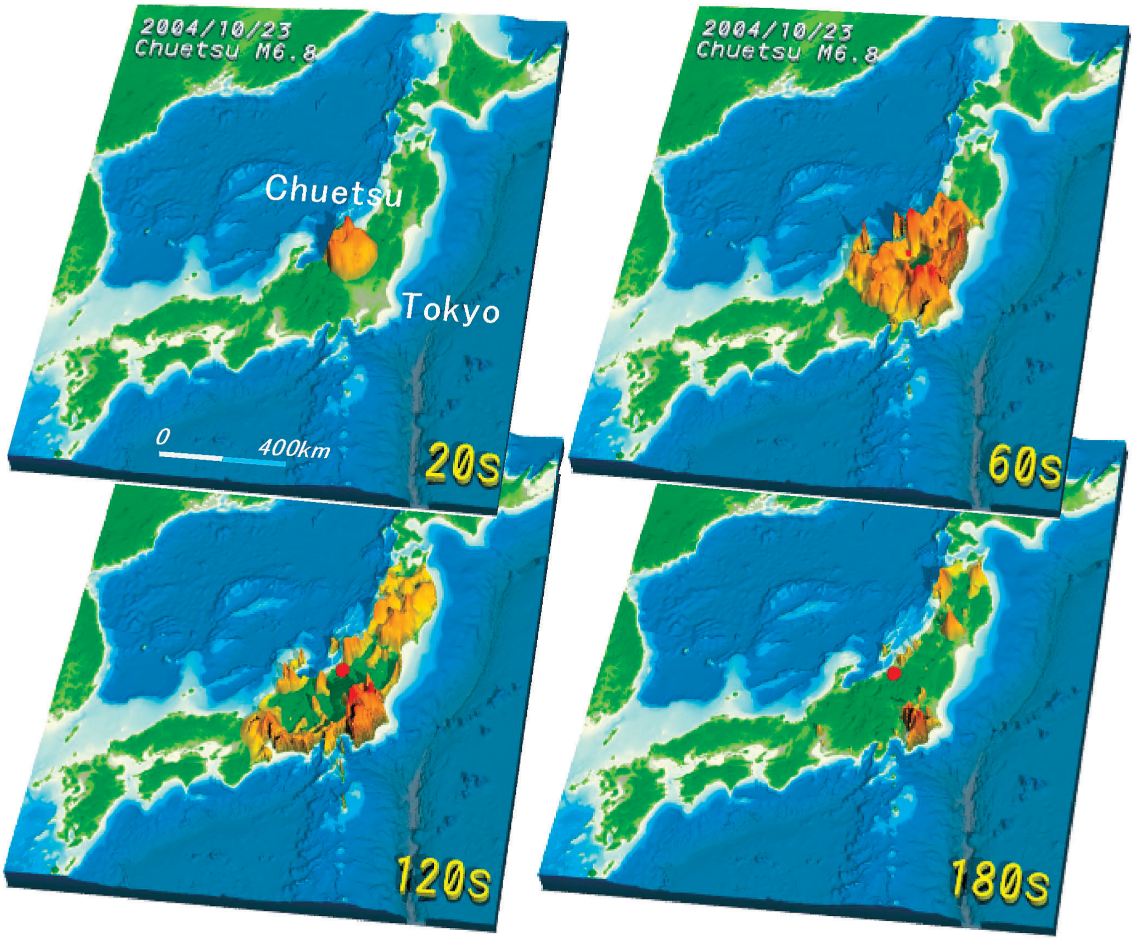

Fig. 1 Distribution of ground motion following the Niigata-ken Chuetsu earthquake, Japan. The amplitude of ground velocity motions derived by interpolation of dense seismic array recording is displayed in each sequence of snapshot at T = 20, 60, 120, and 180 s after rupture.

The resultant response spectrum demonstrates that the arrival of the surface waves produced a maximum response of about 10–20 cm in tall buildings of about 70 floors in height; this corresponds to a natural period of about 7 s. The large and sharp peak at this period decreases abruptly at longer and shorter periods. This pattern indicates that the energy of the long-period ground motion is most damaging for large-scale constructions such as high-rise buildings, large oil reservation tanks, and long bridges, and is less damaging for buildings of less than about 30 floors in height.

The density spacing of K-NET and KiK-net stations is about 20–25 km, which is too coarse to investigate the complex seismic wave behavior during interaction with the 3D structure of the Kanto basin, and thus the K-NET and KiK-net data cannot be used to explore the origin of the prolonged ground shaking recorded in central Tokyo. Recordings from intensity meters located in the Tokyo metropolitan area are therefore used to understand surface wave propagation in the Kanto basin, as the station intervals are about 2–10 km.

Propagation of the surface wave is illustrated in Fig. 2 as the particle motion of horizontal ground motions for the 7 s time window. The particle motions in the first frame (Fig. 2; 85 s) show the development of surface waves near the boundary of Gunma and Saitama prefectures, and large ground motions propagating directly toward Tokyo at a wave speed of about 1 km/s. Particle motion is almost polarized along the radial direction of the wave propagation, and this confirms that Rayleigh waveforms are the dominant component of the large ground motion. The contribution of the Love wave is only minor, as radiation of the horizontally polarized S-wave from the earthquake hypocenter is minimal. Amplification and elongation of ground motion is clearly seen as the wave approaches Tokyo. In the middle frame (95 s) a family of large surface waves that is propagating along the western margin of the Kanto basin toward Kanagawa suddenly turns toward the east, and heads toward central Tokyo. In the final frame (150 s), the two surface waves converge in central Tokyo, resulting in intense and prolonged ground shaking for more than several minutes.

Our data clearly demonstrate the anomalous propagation of surface waves along the margin of the Kanto basin, and focusing of seismic energy into the deepest part of the sedimentary basin. Such rerouting of surface waves along the

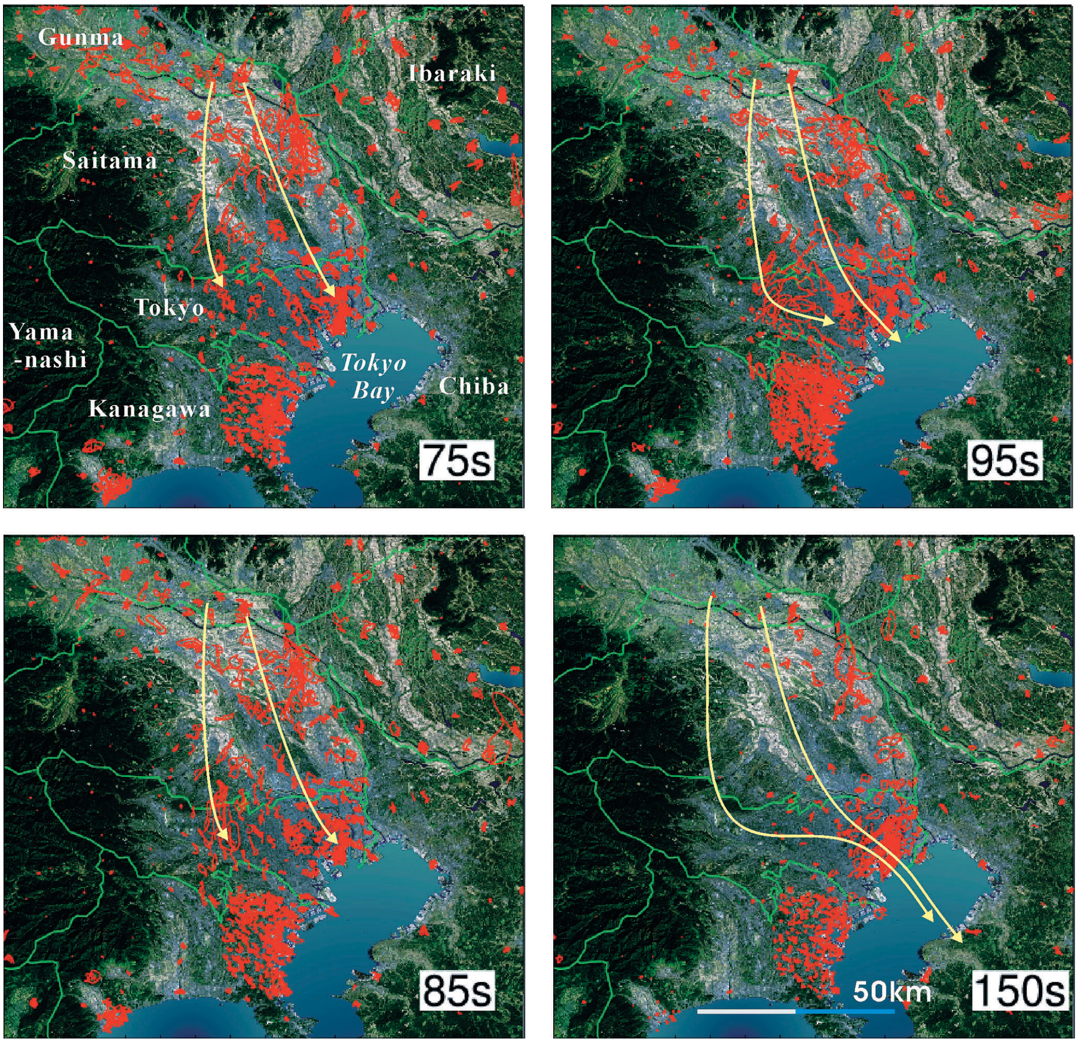

Fig. 2 Particle motion of horizontal ground motions recorded by 459 intensity meters stationed in the Kanto basin and at 268 K-NET and KiK-net stations. The two yellow arrows indicate the estimated major wave propagation paths of the surface waves that affected central Tokyo. The time from earthquake rupture is shown in the bottom right corner.

mountainous margin of the Kanto basin has also been documented following shallow earthquakes near Izu peninsula, southwest of Tokyo [1], [2], [3], and appears to be a characteristic feature of earthquakes close to the Kanto region.

Computer Simulation of the Chuetsu Earthquake

The observation of ground motions has thus far been restricted to land-based instrumentation, as there are no seismic stations located within Tokyo Bay; however, the seismic behavior of the aggregated surface wave below Tokyo Bay is an important factor in understanding strong motion damage in the bay area and surrounding coastal regions.

Simulation Model

Computer simulation of seismic wave propagation was therefore conducted using the Earth Simulator supercomputer with a detailed subsurface structure of the Kanto basin [4] to central Japan [5], and an appropriate source slip model for the Chuetsu earthquake [6]. The simulation model covers a surface area of 440 km by 250 km to a depth of 160 km, and is discritized by a small mesh of 0.2 km by 0.2 km by 0.1 km for layers less than 10 km in depth and a double-sized grid for layers at depths of 10–140 km. Seismic wave propagation at each grid point was calculated by solving the equation of motion using a 16th order staggered multi-grid FDM [7].

The 3D structure model is constructed by six sedimentary layers overly basement which has been constructed based on the refraction and reflection experiments and deep borehole data. The fault rupture model is derived from an inversion using strong motion records and teleseismic waveforms. The inferred fault segment records a large slip of ~2 m upon the shallower parts of the fault plane at about 9 km depth, and fault rupture runs bilaterally to the northeast and southwest at an average rupture velocity of 2.8 km/s.

A minimum S-wave velocity of Vs = 0.5 km/s is assigned to the uppermost sedimentary layer, and the simulation can accurately reproduce seismic wave propagation for period of > 1 s. The parallel FDM simulation used 0.25 TB of computer memory and a wall-clock time of 40 minutes while using 320 processors of the Earth Simulator.

Simulation Results

The results of the simulation are summarized in Fig. 3 as a series of three snapshots of particle motions at uniformly aligned locations representing seismic stations at 8 km intervals in Kanto basin; these simulation results can be compared with equivalent observed ground motions shown in Fig. 2. Simulated and observed waveforms of NS ground motions at four stations are also compared. Features of the observed ground motions, including the arrival of P- and S-waves and the elongation of long-period surface waves, are accurately reproduced by the simulation, although the simulation does not accommodate short-period signals of < 1 s and this results in an underestimation of P- and S-wave amplitude.

The simulation snapshot at 85 s (Fig. 3a) illustrates the generation of surface waves at the northwestern edge of the Kanto basin and significant amplification of ground motions in the soft sediments overlying the rigid bedrock. The simulation results at 95 s (Fig. 3b) show rerouting of surface waves along the margin of the basin and subsequent focusing toward the center of Tokyo Bay via a saddle in the basement topography. The surface waves travel across Tokyo Bay to Chiba via the deepest part of the basement (Fig. 3c; 150 s), and then turning back toward Tokyo via the same route. The last snapshot (150 s) demonstrates the stagnation of surface waves in the deepest part of the basin.

The result of the high-resolution computer simulation indicate that the mortar-like shape of the Kanto basin and the thick cover of overlying sediments below Tokyo Bay are the main causes of the multi-pathing, focusing of surface waves, and prolonged ground shaking that affects central Tokyo during large earthquakes.

Conclusion and Further Research

Long-period ground motions from the Chuetsu earthquake had a strong impact upon the densely populated area of central Tokyo, especially for high-rise buildings. The anomalous propagation of surface waves in relation to the 3D subsurface structure beneath Tokyo generates very large and prolonged surface wave trains of periods of ~7 s. It is unfortunate that surface waves with a dominant period of about 7 s cause significant resonance and potential instability in buildings of ~70 stories in height, of which there are many in Tokyo. Such long-period signals do not result from small earthquake faults of Mw <6.5, and the most recent large earthquake in the vicinity of Tokyo was the Mw6.8 Naganoken Seibu earthquake that occurred more than 20 years ago in 1984. Thus, observations from the Chuetsu earthquake are

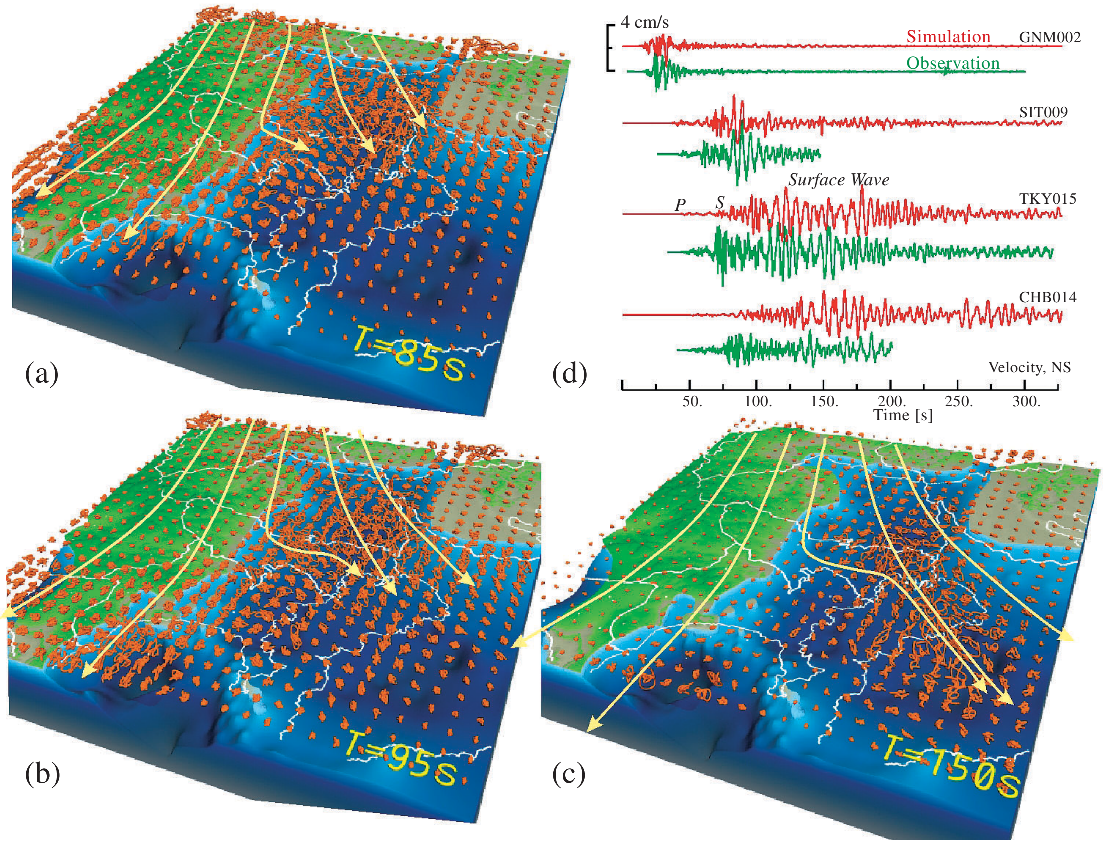

Fig. 3 (a-c) 3D view of simulated particle motions and ray path of derived surface waves. Time from origin is shown in the bottom right corner of each figure. (d) Comparison of simulation waveforms (orange) and observed waveforms (green) of ground velocity motions.

the first to reveal the potential weaknesses of modern large-scale constructions such in Tokyo.

A potentially damaging future earthquake may be the Tokai earthquake occurring at the Suruga Trough, about 150 km south west of Tokyo, where M8 earthquakes have historically occurred at intervals of ~100 years. The most recent M8.4 Ansei Tokai earthquake occurred in 1854 more than 150 years ago. The expected long-period ground motion in Tokyo resulting from the future M8 Tokai earthquake is at least 10 times greater than ground motions associated with the Chuetsu earthquake.

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2004年10月23日新潟県中越地震（Mw6.6）による長周期地震動のコンピュータシミュレーション

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概要

新潟県中越地震では、震源から200kmも離れた関東平野において、周期が7秒にもなる長周期の地震動が強く生成し、その大きく長い揺れによっておよそ70階建ての超高層ビルが強い共振を起こし、大きく揺れたことが問題となった。そこで、関東平野での長周期地震動の生成メカニズムを探るために、平野に高密度に展開されている強震計、自治体震度計データを解析するとともに、地球シミュレータを用いた中越地震のコンピュータシミュレーションから地震波の伝播と表面波の励起の特性を詳しく評価した。

シミュレーション結果を可視化し、観測データと合わせた波動伝播の解釈を進めた。そして、中越地震で起きた大きな長周期地震動は、関東平野下の洗面器状の堆積層構造において、地震波が都心部に向かって回り込むように集まってきたことが原因であることを確認した。計算結果が観測データを良く説明することから、シミュレーションモデルの有効性が示されるとともに、将来発生が危惧される大地震の揺れの予測にモデルが適用できることが確認できた。

キーワード：地震，地震波，強震動