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

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Large-scale parallel FDM simulations of seismic wave propagation have been conducted using the Earth Simulator in order to clarify the complex seismic wavefield resulting from heterogeneities in structures and the source rupture process during the Hyogo-ken Nanbu (Kobe) earthquake (Mj7.2) in 1995. High-resolution simulation using 240 nodes (1920 processing elements) of the Earth Simulator for seismic waves from the Kobe earthquake provided a very good reproduction of strong ground motions and a narrow zone of larger intensity (damage belt) appearing in the Awaji Island and Kobe-Hanshin region. Thus, the current simulation model is considered to be suitable for application in predicting strong ground motions for possible future earthquakes, such as the occurrence of a large earthquake in Tokyo. The Tokyo metropolitan area is located over a tectonically complicated region, in which M7 inland earthquakes and M8 plate earthquakes have frequently occurred. simulation results for a hypothetical earthquake in Tokyo indicate that most population centers would be affected by significant ground shaking of Japan Meteorological Agency (JMA) intensity greater than 6 due to the strong amplification of ground motions in the thick sediments below Tokyo. Large earthquakes also produce strong shaking for relatively longer periods of approximately 6 to 8 s due to the resonance of seismic waves in the thick sedimentary basin. Such long-period ground motions would be most damaging to large-scale man -made structures, such as high-rise buildings, long bridges, and large oil reserve tanks, which were constructed in Tokyo after the 1923 Kanto earthquake.

Keywords: Earthquake, 1995 Kobe Earthquake, Seismic Waves, Strong Ground Motions

Introduction

An important goal of strong-motion seismology is the prediction of strong-motion damage in future earthquake scenarios. Computer simulation of seismic wave propagation is indispensable in gaining a good understanding of complex seismic behavior resulting from heterogeneities in structures along the propagation path and the source rupture process adopted in the model.

In the present project, a parallel finite-difference method (FDM) simulation for seismic wave propagation is introduced, and the efficiency of the Earth Simulator for simulating strong ground motions is presented through simulation examples for the 1995 Kobe earthquake (Mw 7.2) and a hypothetical Tokyo earthquake scenario.

Parallel Simulation of the 1995 Kobe earthquake

The Hyogo-ken Nanbu (Kobe) earthquake of January 17, 1995 (Mw 6.9) was the most damaging in modern Japanese history, killing over 6,700 people in Kobe and the Hanshin region. A notable feature of this earthquake was that most of the damage of the JMA intensity scale 7 occurred within a narrow zone, which came to be known as the "damage belt" due to the bending and amplification effect of seismic wave in the 3D structure below Kobe.

We have long attempted to simulate the strong ground motions that occurred during the Kobe earthquake, but, the patterns of the intensity distribution derived in these simulations were not clear enough to reproduce the sharp contrast of the narrow and long damage, due to insufficient resolution of the structural model and the high-frequency signals employed in simulations [1].

Ten years after the destructive Kobe earthquake, improvements in computing power have made it possible for large-scale simulation of strong ground motions with relatively higher-frequencies of over 1 Hz. In addition, a high-resolution structural model of Kobe with a resolution of 100 m in the horizontal direction and 50 m in the vertical direction has been constructed by the Geological Survey of Japan based on a large number of reflection and refraction experiments conducted in the Osaka basin ([2]; Fig. 4). Therefore, we conducted a high-resolution computer simulation of seismic wave propagation using the Earth Simulator and the latest high-resolution subsurface structural model in order to try to reproduce the narrow damage belt. The present simulation

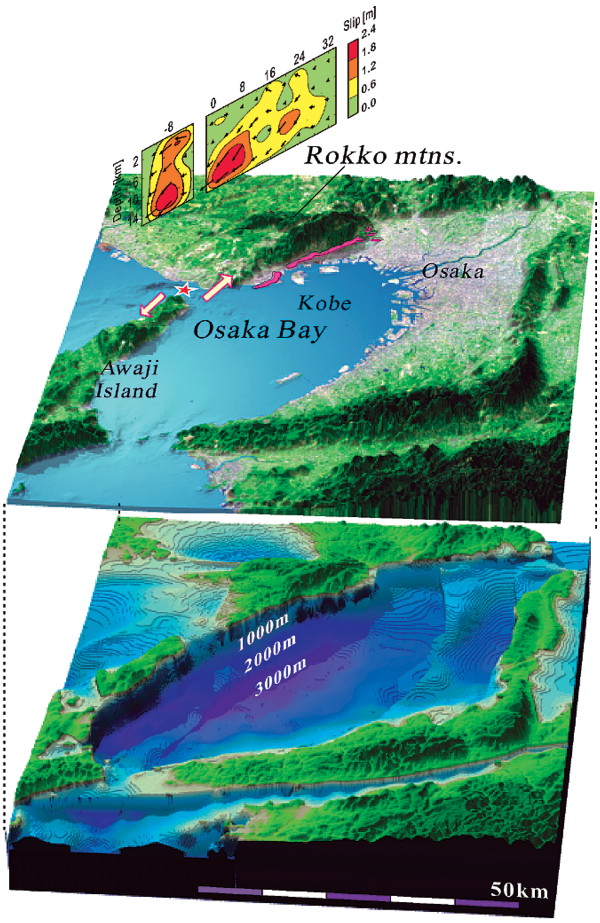

Fig. 1 Topography of Kobe-Hanshin area, and the subsurface structure of the bedrock/sediment interface. The source-slip model for the 1995 Kobe earthquake is shown in the top.

model covers a zone of 90 km × 85 km × 40 km which has been discretized by a small grid spacing of 0.05 km × 0.05 km × 0.025 km (Fig. 1). The mesh size of the present simulation is four times smaller and the target area is larger than those of the previous simulation [1]. Then the present simulation requires 62.6 billion grid points, which is approximately 1,500 times larger than that of the previous experiment.

Simulation results are shown in Fig. 2. In the first frame (T = 5.25 s), the seismic wave begins to appear at the surface near the Akashi Strait, and at T = 7.5 s, a directivity pulse generated from the rupturing fault is very clearly approaching Kobe. The directivity pulses propagate northeastwards in the Rokko mountain region at a relatively faster speed of approximately 3 km/s and eastwards on the Kobe side at a very low speed of less than 1 km/s (T = 7.5, 9.75, 15.7 s). At 9.75 s, another directivity pulse is being generated from the second large slip (asperity) on the fault at 10 km below Kobe (see, top panel of Fig. 3). These two pulses are amplified significantly in the thick, low-velocity sediments below Kobe and form longer tails in the basin. A surface wave is produced at the edge of the mountain/basin interface by the conversion of an S-wave propagating upward from the source to Rokko mountains side. The surface wave then enters the sedimentary basin, resulting in stronger ground shaking by constructive interference between the basin waves propagating upward from the source to Kobe side. These signals propagate through Kobe from west to east by multiple reflections inside the basin, which causes a large and very long ground shaking in the densely populated areas.

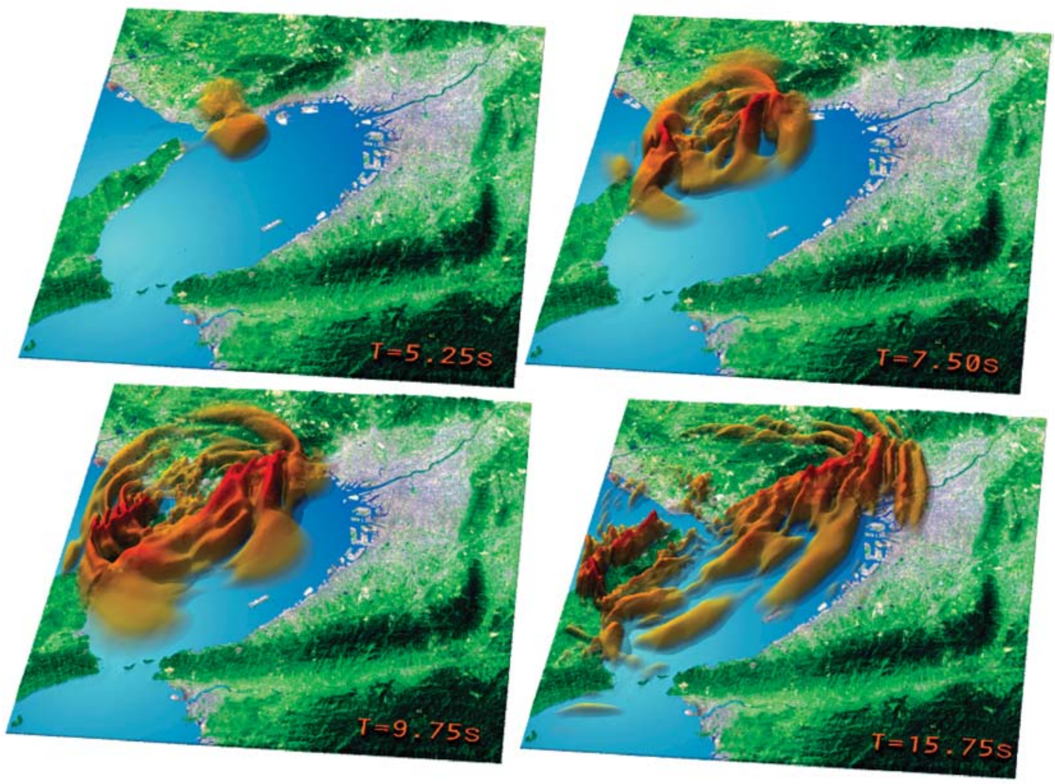

Fig. 2 Progression of seismic wave propagation of horizontal ground velocity motions derived from the simulation (The time is shown at the bottom-right corner of each frame).

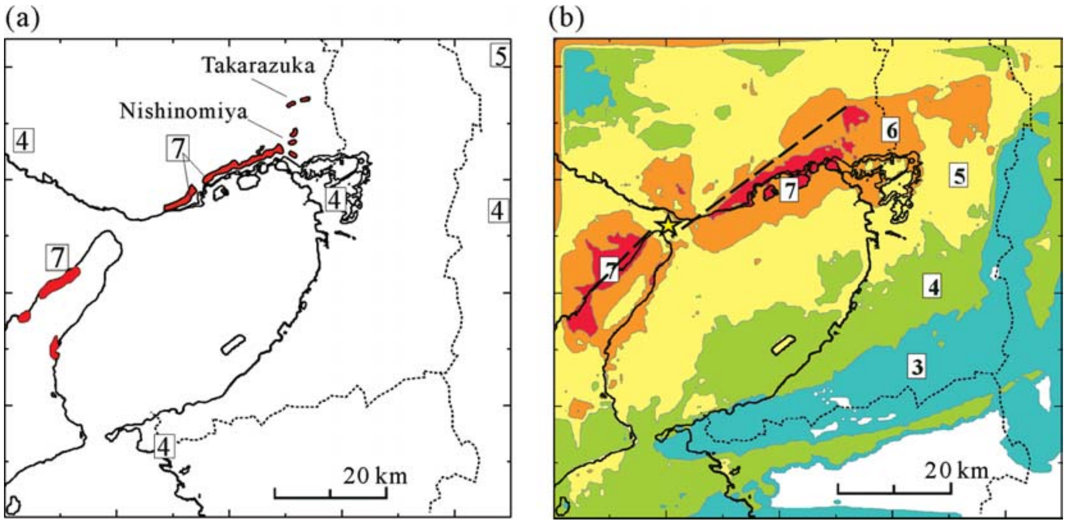

Fig. 3 (a) Distribution of JMA intensity on a seven-point scale. Purple zones indicate the area of intensity 7 (damage belt).
(b) Simulated intensity using a detailed 3D subsurface structure of the Kobe-Hanshin area.

The pattern of seismic intensity distribution derived through the present simulation is shown in Fig. 3, where a narrow and long zone of JMA intensity 7 is clearly seen to the southeast of the fault zone. The simulation result is similar to the observations in terms of intensity-7 zones with the width of the belt (approximately 1 to 2 km), and some pockets of localized intensity-7 zones at eastern side of the main damage belt, such as those at Takarazuka and Nishinomiya. In contrast, these observations were not reproduced well in the previous simulations due to their coarse mesh model [1].

Conclusion

As demonstrated by the 1995 Kobe earthquake, the generation of strong ground motions, and the consequent damage, are strongly affected by the interaction between the heterogeneous subsurface structure and the complex source rupture history. Therefore, the prediction of strong ground motions for future events requires a good understanding of the seismic wavefield resulting from such heterogeneities by analyzing observed waveforms by dense seismic array and corresponding computer simulations.

Recent accomplishments at high-performance computing facilities such as the Earth Simulator have made it possible to conduct realistic simulation of seismic wave propagation on a regional scale for relatively higher frequencies of over 1 Hz. In the present study, the generation process of strong motion damage in the 3D basin structure during the 1995 Kobe earthquake has been clearly demonstrated by a large-scale FDM simulation using a high-resolution subsurface structural model of Kobe. A good match between simulated and observed intensity patterns during the earthquake demonstrates the effectiveness of computer simulation for accurate reproduction of seismic wave propagation for the possible future earthquake scenarios, such as the large earthquake anticipated to occur in Tokyo.

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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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1995年兵庫県南部地震(Mj7.2)の波動伝播と強震動のシミュレーションを、地球シミュレータの240ノードを用いた並列計算により実施した。兵庫県南部地震の強震動被害の最大の特徴は、神戸−阪神地区の市街地に現れた、幅1～2 km長さ25 km以上の震度7の大被害域(震災の帯)であった。震災の帯の発生には、平野の3次元深部基盤構造の影響が大きく関係していると考えられるが、10年前に実施した精度の低いシミュレーションではよく再現することができなかった。そこで、地球シミュレータと、震災後に詳しく調査された最深の地下構造モデルを用いて、兵庫県南部地震の再現を試みた。新しい計算は当時のもの1500倍の規模になる。地球シミュレータ計算により、震源断層から放射された地震波が平野で強く増幅されるとともに、六甲山／平野境界で発生した表面波との増幅干渉によって、神戸市街地の狭い帯状の地帯に強い揺れ(震災の帯)が生成される様子を良く再現することに成功した。

キーワード: 強震動, 兵庫県南部地震, 地震災害, 波動伝播, 地震