Pseudospectral simulation of seismic wave propagation

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Abstract

Seismic waves observed at the earth's surface are strongly affected by the influence of heterogeneity in the crust and upper-mantle structure along the propagation path, as well as the site amplification effect in the surficial layer. In order to predict the strong ground shaking from urban-attack earthquakes, it is therefore required a high-resolution numerical method that can evaluate these seismic disturbances in the heterogeneous media. The pseudospectral method (PSM) is an attractive high-accuracy numerical technique, which has recently been applied for the simulation of wave propagation in 2-D and 3-D heterogeneous media. In this note we show some example of the PSM modeling of strong ground motion for recent damaging earthquakes to show the feasibility of the method. We further introduce a current improvement of the PSM computation for the large-scale modeling by use of parallel computers.

Introduction

The pseudospectral method (PSM; e.g. see Reshef et al. 1998 and references herein) is an alternative numerical simulation technique to the traditional schemes such as finite-difference and finite-element method, which has successfully been applied for the wave propagation simulation in 2-D and 3-D heterogeneous media. Since the PSM uses the fast Fourier transform (FFT) for calculating spatial derivatives in equations, it offers very accurate results, even employing a large grid intervals in the simulation model, compared with the low-order finite-difference schemes. Thus the PSM is very suitable for large scale modeling of seismic wave propagation, especially for 3-D problems.

Recently, with the advantage of computer power, the PSM modeling has gradually been used for the practical applications such as for the strong ground motion simulation of 1985 Michoacan, Mexico earthquakes (Furumura and Kennett 1998), and 1995 Hyogo-Ken Nanbu (Kobe), Japan earthquakes (Furumura and Koketsu 1998).

Numerical modeling of Mexican subduction-zone earthquakes

The great 1985 Michoacan, Mexico earthquake (Mw 8.1) was one of the most destructive in modern history and its notable character was that at the basin of Mexico

City, located over 350 km from the epicenter, there was a very strong ground shaking almost comparable to that in the epicentral region that lasted for several minutes. Considerable effort has long been expended to explain the origin of unusual ground shaking at the basin of capital city and caused the severe damage of over 10000 casualties, and a quite amount of simulation studies have been made to explain the strong ground shaking that lasted at the basin of Mexico City during the damaging earthquake (see review e.g. Chávez-García and Bard 1998). However, such simulation results, in which only the seismic amplification in the basin is taken into accounted, fail to provide satisfactory explanation of the unusual long duration of ground motion.

In order to examine the way in which the heterogeneous crust and upper-mantle structure along the long propagation path, from the coast to the Mexico City, may influence the complex wave propagation character in Mexican mainland, Furumura and Kennett (1998) conducted 2-D modeling of seismic P and SV wave from 1995 Copala, Guerrero earthquake (Mw 7.4) by use of a 2-D anelastic PSM code. The 2-D model covering a zone of 512 km wide by 128 km deep that is discritized by a uniform grid intervals of 0.5 km representing crust and upper-mantle structure in Mexican mainland and the basin of Mexico City. To represent the 1995 Copala event, they used a seismic double-couple source representing a low-angle thrust-fault source excited 17 km below the surface, and the source imparts seismic P and SV waves of dominant period around T=2 s.

They are able to demonstrate by 2-D the modeling of the Mexican subduction zone earthquakes that the origin of the long arrivals comes from the Sn and Lg wave trains, both are produced efficiently from shallow subduction earthquakes and are strongly enhanced during their propagation within the laterally heterogeneous waveguide induced by the subduction of Cocos Plate beneath the Mexican mainland. These S phases are then strongly enhanced by transmitting through low-velocity surficial layer of Mexican Volcanic Belt from the amplification of S waves in the low-velocity surficial layer associated with S-to-P conversions. Finally, a further amplification of long and large input wave in the basin of Mexico City, with very soft soil underlain by nearly rigid bedrock with a strong[impedance contrast, gives rise to the destructive strong ground shaking.

Strong motion simulation of 1995 Hyogo-ken Nanbu (Kobe), Japan earthquake (Mw 6.9)

The 1995 Kobe earthquake is the most damaging in Japanese history, and its notable feature is that most of the damage and over 6000 casualties occurred within a narrow zone (damage belt). The damage belt is about 2 km wide and 25 km where the Japan Meteorological Agency (JMA) defined their highest seismic intensity scale VII.

Usually a fault rupture propagation generates strong ground motions along the direction of propagation, however, the damage belt of Kobe earthquake is migrated noticeably from the fault trace into the center of Kobe city.

In order to review the generation mechanism of the damage belt and shift in the strong motion zone, Furumura and Koketsu (1998) curried out numerical simulations of 3-D seismic wavefield by a 3-D PSM modeling. The subsurface structure below Kobe is represented by four-layer model which has a scale of 51.2 km by 25.6 km by

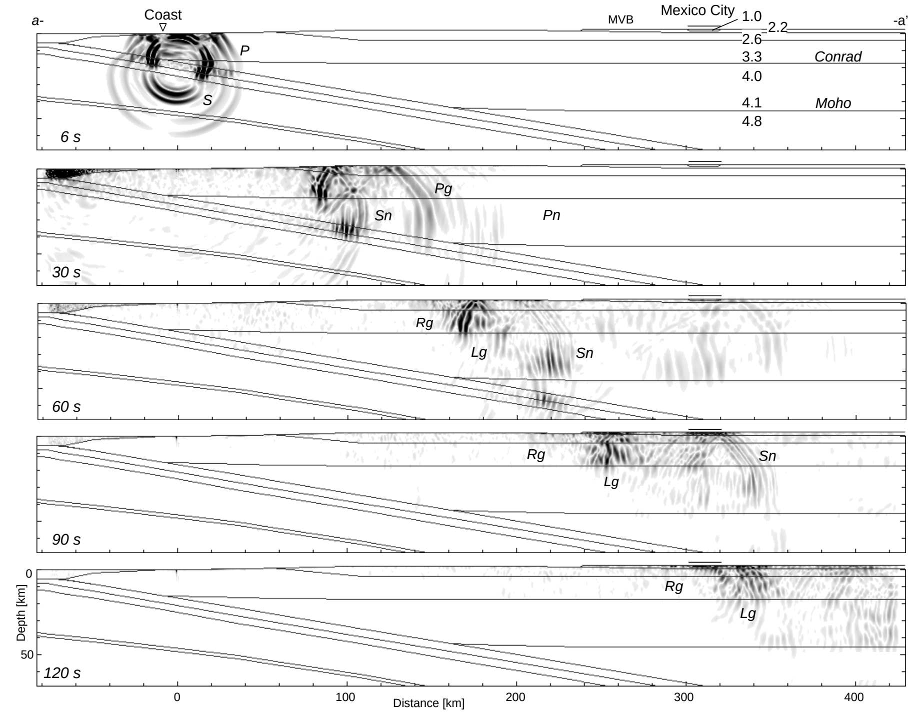

Figure 1: Vertical profile of 2-D simulation model of 1985 Copala, Guerrero Earthquake. The 2-D region across the Mexican mainland from south (left) to north (right), and snapshots of the seismic wavefield of P (gray) and SV (black) components as a function of distance from the source and time. The location of Mexico City basin ranged between 300 to 320 km from the epicenter is illustrated in the figure. The gray line superposed on the wavefield snapshot denote structural boundaries such as surficial layer (Mexican Volcanic Belt; MVB), Conrad, Moho and the boundary of descending Cocos plate. Remarkable P and S phases and S-wave velocity (Vs) of each layer is shown in the figure.

25.6 km volume discritized at a grid interval of 0.2 km. They assigned a slow shear-wave velocity (Vs) of Vs=0.55 km/s in the basin and a higher velocity of Vs=3.2 km/s in the bedrock. The seismic source model derived by a source rupture inversion study (Yoshida et al. 1996) is embedded into the simulation model which imparts seismic wave with a maximum period of T=1.0 s. The 3-D equation of motion, including anelasticity (Q), is solved by parallel PSM code. The 3-D simulation took memory of about 0.5 GB and CPU time of 50 hours to complete the 25 s of simulated ground motion using a DEC Alpha workstation (500 MHz clock speed).

They showed by the 3-D simulation of ground motion that the migration of damage zone is caused by the strong amplification and ray bending effect in the sedimentary basin below Kobe (see Inoue and Miyatake 1997) in corporation with the multipathing effect (see e.g. Kawase 1996) of seismic wave at a basin/bedrock boundary.

Although their results simulates the shape of the damage belt fairly well, the peak ground velocities are only half of those observed. This arise because they

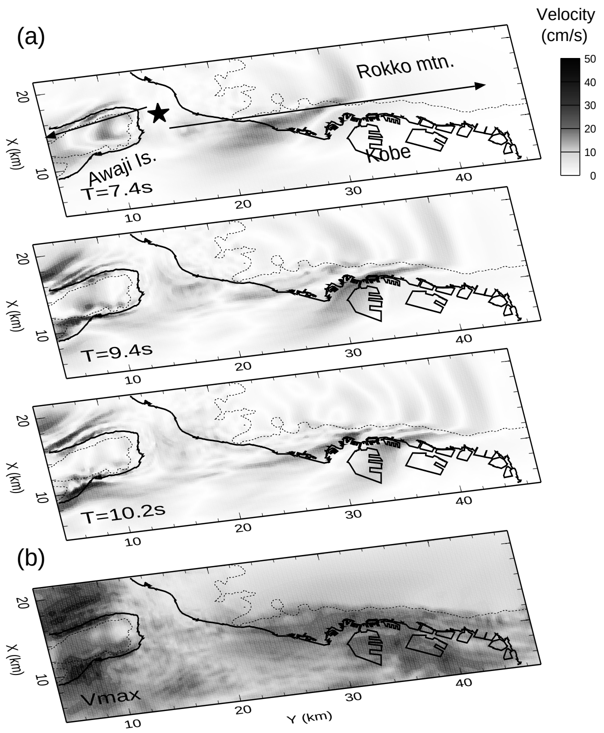

Figure 2: The area of 3-D simulation region covering Kobe and its neighboring cities. Dot line indicate a bedrock/basin interface. The fault rupture initiate beneath the Akashi strait (star) and propagated bilaterally towards Kobe and Awaji island (arrow). (a) Snapshots of simulated fault-normal (X-component) ground velocities in at 7.4, 9.4 and 10.2 s after the fault rupture initiation. (b) The *Vmax* panel at the bottom displays the distribution of peak ground velocities at the surface during the 25 s of the simulation. Note that snapshots shows the development of two large pulses with long tails in the basin, and result in about 20 km long zone with ground shaking over 40 cm/s.

cannot include near-surface low-velocity layers of Vs $<$ 0.2 km/s due to current computational limitations.

Parallel PSM computing - Concluding remarks

The results described above suggests that a comprehensive study of the source characteristics, wave propagation path, and site amplification effects should be undertaken when evaluating strong ground motion from regional earthquakes. Consequently, we are keen to apply large-scale 3-D modeling in practically in order to improve the resolution of the simulation.

However, even using the PSM the large scale 3-D simulation is still very expensive. We therefore developed a parallel PSM code for the large scale modeling that can be implemented onto current state of parallel computers (Furumura et al. 1998).

The parallelism is based on a partition of 3-D model into a number of piecewise of equal size data, and each subregion is mapped onto the processors in its local memory. Each processor is responsible for the calculation of wavefield in the subregions with exchanging data between processors. This inter-processor communications is performed by use of a MPI parallel-computing library (Gropp et al. 1995). Note that similar studies on parallel PSM, although the parallel algorithm is slightly different in each other, are also found in e.g. Liao and McMechan (1993) and Shung and

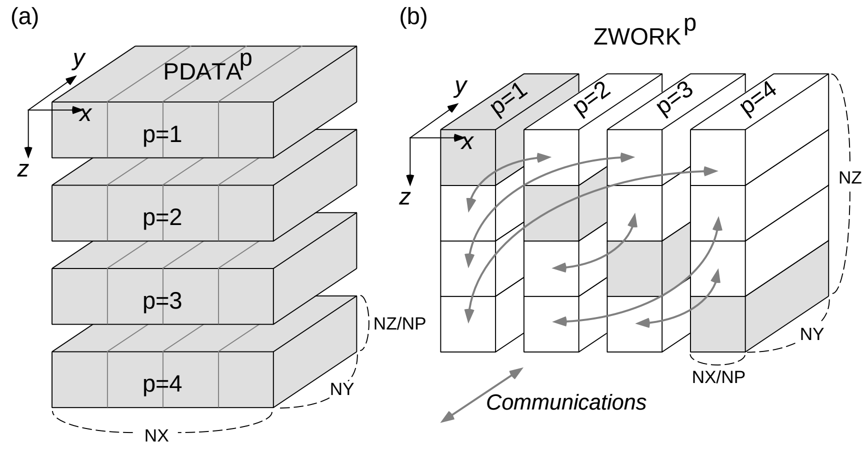

Figure 3: Schematic illustration of the domain partition of the 3-D wavefield for the parallel PSM computing using four-processors. The 3-D region is sliced horizontally into four pieces of equal size ($\mathrm{PDATA}^{P}(p = 1,..,4)$) and they are mapped onto four processors. The wavefield in each subdomain is calculated by each processor, individually, except for z-differentiation in equations. (b) Configuration of array data ZWORK^{p} assigned to each processor for the calculation of z-derivatives. Since each processor has only the part of the data shaded in the figure in its local memory, inter-processor communication is performed to swap data with the other processors. After calculating the z-differentiation, the results are returned to the other subdomain.

Forsyth (1998).

We have implemented the parallel PSM code on both parallel computers such as Thinking Machine CM-5 and Cray CS 6400 (shared memory) as well as a cluster of workstation connected by an Ethernet. The results show that the computational speed linearly increase as a number of processor increase, demonstrating the efficiency of the parallel algorithm.

We therefore expect that the trend of steady increasing computer power and parallel-computing algorithms will bring closer to use the high-resolution 3-D simulation for practical applications even at relatively short periods.

Acknowledgments

This research was funded by grant in aid for Scientific Research (No.10128202, 10740213) from the Ministry of Education, Japan.

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