

PSM/FDM hybrid simulation of the 1999 Chi-Chi, Taiwan, earthquake

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Abstract

Numerical 3D simulation of strong ground motion for the 1999 Chi-Chi, Taiwan (Mw 7.6) earthquake was conducted by using the parallel PSM/FDM hybrid method. Comparisons between simulation results and a remarkable data sets from dense strong motion network in Taiwan demonstrate clearly that the variation in the subsurface structure and the complexity in the fault slip distribution played very important role on the generation of the strong ground motion; The directivity effect of rupturing fault produced large S-wave pulses along the direction of fault rupture. Large velocity gradient in the upper crust of Taiwan propagate the S-wave for longer distances without attenuation. The seismic wave is finally amplified further by the site amplification effect of basin structure, and caused the severe strong motion damage.

1999 Chi-Chi, Taiwan Earthquake

The Chi-Chi, Taiwan, earthquake of 21 Sep. 1999 (Mw 7.6) caused severe damage over a large area in Taiwan island. A huge amount of data set from over 600 accelerometers of Taiwan Strong Motion Network, which has been installed widely in whole Taiwan island, provides an excellent tool for understanding the strong motion character. Figure 1 shows the peak horizontal ground velocity (PGV) distribution of the earthquake. Severe ground shaking over 100 cm/s is discerned along the surface rupture which extends about 85 km from south to north with a maximum vertical offset of 8 m at the north end.

The faulting of the shallow-angle reverse-fault source also generated significant surface waves. Large amplitude Rayleigh wave with a predominant period between 4 to 6 sec (see waveform CHY094.R in Fig. 1) caused severe damage to the petroleum reserve tank at Taichung harbor area. Also, at the Ilan basin and the coastal plane area, well developed fundamental-mode Love wave of amplitude over 50 cm/s and a predominant period around 4 sec was excited (TCU008.T and ILA056.T).

Although the Taipei basin is located over 120 km from the epicenter, it had also suffered severe damage with a tall of many buildings. The strong ground motion in Taipei demonstrated that the damage was caused by the severe ground shaking over 20 cm/s dominating in the frequency range between 1 to 4 sec, which is well correlated with the resonant frequency of the Taipei basin (Wen and Peng, 1998).

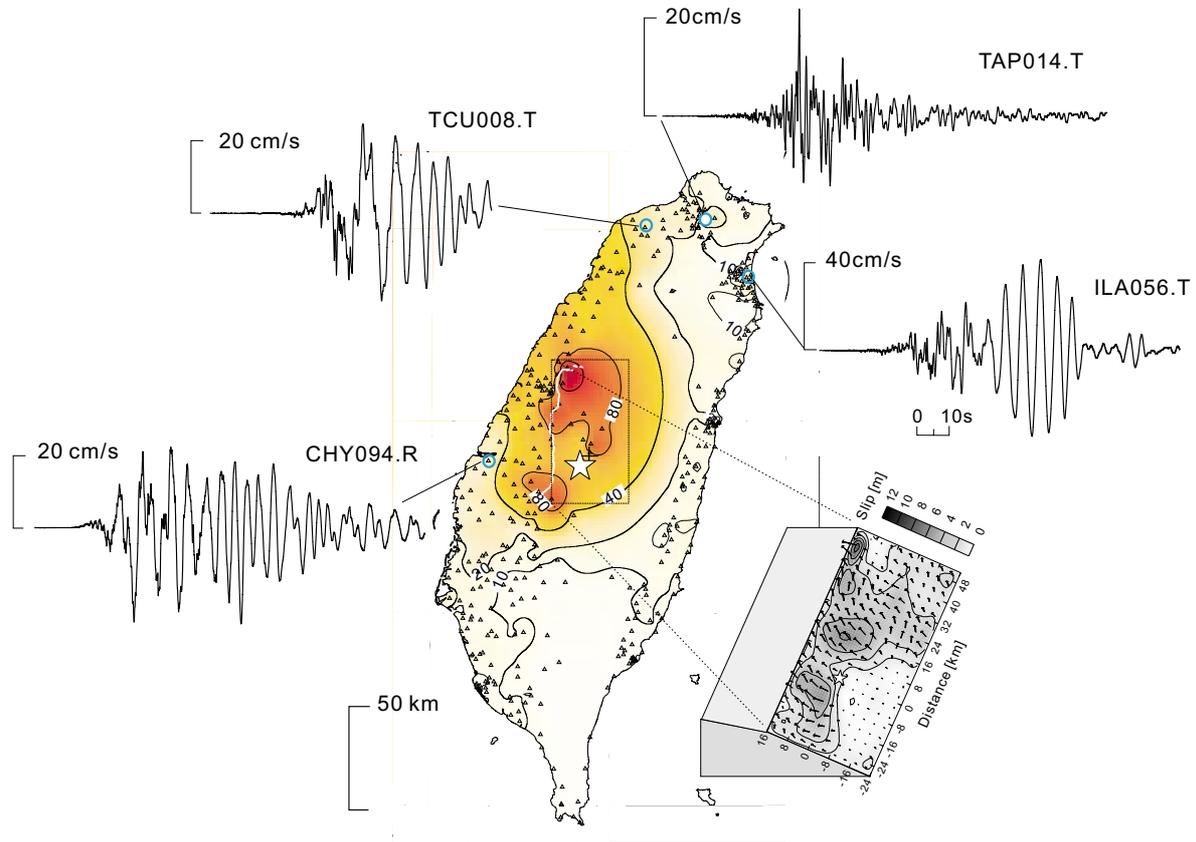


Figure 1: Strong ground motion record at regional distances during the 1999 Chi-Chi earthquake. Typical example of velocity seismograms of radial (R) and transverse component (T) at regional distances. The PGV of horizontal motion in cm/s and the source-slip model of Yagi and Kikuchi (2000) are also illustrated.

Seismic wave propagation in Taiwan

In order to see the wave propagation character in Taiwan that caused the severe damage even at the distant place (e.g. Taipei), we first compare the PGV decay along the direction to south and north from the epicenter (Fig. 2). We applied the waveform to the band-pass filter with a central period of $T=1$ s, to see the propagation character of body wave rather than the long-period surface wave. Since all stations used here are located on the same geology of coastal plane area, the influence of site amplification effect should be neglected.

The PGV curve of northern stations (Fig. 2a) shows more gentle decay than the southern stations (Fig. 2b), which is found in the horizontal motion more distinctly. The abnormal elevation of the PGV at the epicentral distance between 40 to 130 km along northern station profile should be due to the arrival of wide angle ScS and SmS reflections from the Conrad and Moho discontinuities, respectively. The importance of the SmS reflections on the cause of strong motion damage has already been recognized at San Francisco and Oakland regions during the 1989 Loma Prieta earthquake (Somerville and Yoshimura 1990). But this is more evident in Taiwan of tectonically young geology having a very large velocity gradient in the crust (Fig. 3).

The propagation of the diving S-phases in Taiwan are clearly demonstrated by the 2D simulation of the pseudospectral method (PSM) using a standard crustal structure model of Taiwan (Rau and Wu, 1995; Fig. 3) and an isotropic line source with a central frequency

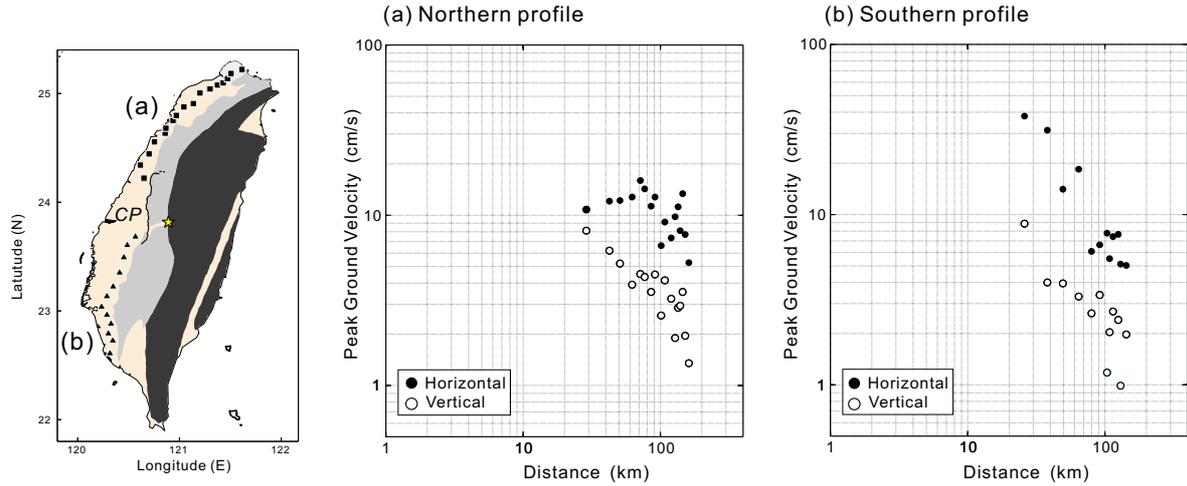


Figure 2: PGV decay of horizontal and vertical motion of 1 s waveform as a function of distance from the epicenter for (a) Northern station and (b) Southern station. The location of stations are displayed in the left map.

of 1 Hz. Figure 3 displays the simulated PGV value of horizontal and vertical motion as a function of distance from epicenter and source depth of $H=7$ km and $H=4$ km. We see large ground amplification in the horizontal motion at the epicentral distance around 80 and 120 km, which is produced by the arrival of the critical ScS and SmS reflections, respectively.

The localized ground amplification by the critically reflected S phases are not so clear for the shallower ($H=4$ km) source, and we see simple decay of the PGV at larger propagation distances. This is because that the S-wave energy radiated from the shallow source is trapped in the low-velocity structure below the free surface, which produce a long-period surface wave. As a consequent the S-wave radiating deep into the crust is very weak to produce the large amplitude diving S-wave. The simulation result of the shallower source is well correlated with observed PGV decay curve in the south of Taiwan (Fig. 2b). At the south of epicenter the fault slip is almost concentrated on the shallower part of below 7 km from the free-surface (Fig. 1).

PSM/FDM hybrid parallel simulation of strong ground motion

We finally conducted a numerical 3D simulation of seismic wave propagation to see the character of the wave propagation in 3D complex subsurface geology of Taiwan.

We employed here the parallel PSM/FDM hybrid technique (Furumura and Koketsu, 2000; Furumura et al., 2000) for the large scale simulation of seismic wave propagation by using a parallel computer. The 3D model is divided into a number of subdomains, with some overlapping area between neighbor region, which are assigning over many processors. The fast Fourier transform (i.e. PSM) is used for the calculation of spatial derivatives of the horizontal (x,y) components, and accuracy-optimized 8th-order finite-difference method (FDM) is used in the vertical (z) directions. The message-passing library (MPI) is used to exchange data in the overlapping area between subdomains. The PSM/FDM hybrid calculation offers good speed-up rate compared to the traditional parallel PSM (e.g. Furumura et al., 1998) even using a large number of processors.

The 3D simulation model is 225 km by 122 km by 57 km, which covers the area from

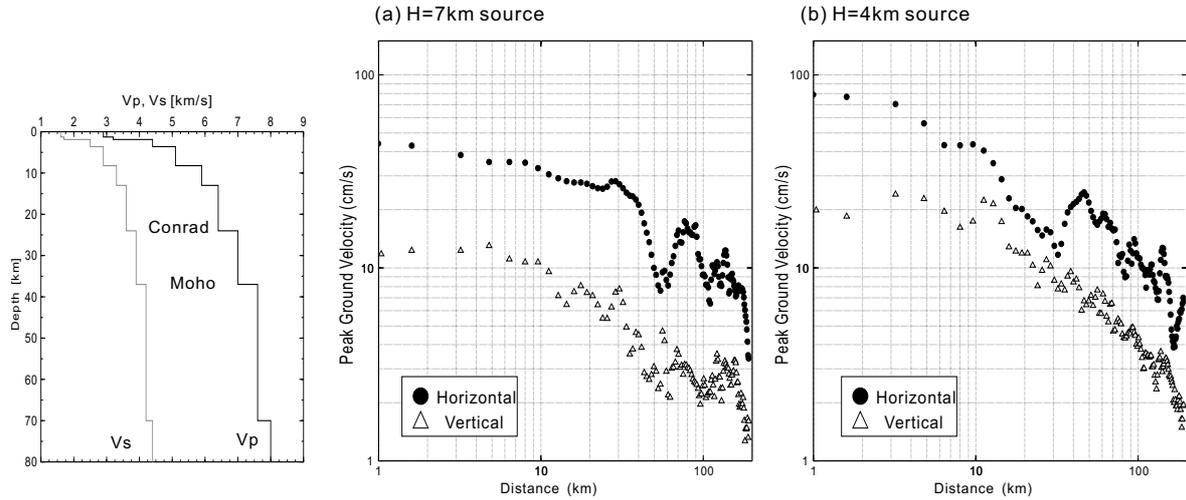


Figure 3: The PGV of horizontal and vertical component calculated by the 2D modeling for (a) H=7 km and (b) H=4 km depth source. Velocity structural model of V_p and V_s is illustrated in left.

the center to the north of Taiwan. The 3D model is discretized by a uniform grid interval of 0.45 km in horizontal direction, and a small grid size of 0.225 km is used in the vertical direction where the accuracy-optimized FDM is used. The crustal structure model used is based on the 1D Taiwan standard model, and some modification was made from a knowledge of geology, near-surface velocity structure (Chung and Yeh, 1997), and lateral variation of the Moho depth (Chen, 1996) (Fig. 4). This model includes low velocity ($V_s=0.9$ km/s) and high attenuation ($Q = 50$) superficial layer at the coastal plane area. We used the seismic source model of Yagi and Kikuchi (2000) which is derived by the inversion of far and near-field waveform. Since the fault source imparts seismic wave with a maximum period of 1.5 s, the PSM/FDM hybrid calculation treats seismic wave propagation with 3 and 6 grid points per shortest wavelength in horizontal and vertical coordinates, respectively. The parallel computing used a memory of about 5 GByte and a CPU time of 63 hours by using 16 processors of a SGI Origin 2000 parallel computer.

Figure 5 compares the observed and simulated PGV distribution of horizontal motion and waveform obtained by the 3D simulation. We applied a low-pass filter with a cut-off frequency of 0.66 Hz to the waveform to eliminate the higher frequency noise from the simulated waveform. The character of the simulated waveform reproduce the observations fairly well, but the peak amplitude and the duration of the ground oscillation are somewhat underestimated. We see the broad zone of large ground amplitude over 40 cm/s extending at the coastal plane area, which is also well correlated to the observations. The simulation also recovers some pocket of abnormal ground oscillation zone at the distance range of about 80 and 120 km at the north of the epicenter, which are produced by an attack of large amplitude diving S-wave. This area are fairly correspond to the severely damaged area during the earthquake.

Conclusion

It has long been recognized that the character of the seismic wave within a period range between 1 to 4 sec, which is directly relate to the strong motion damage at urban areas, is

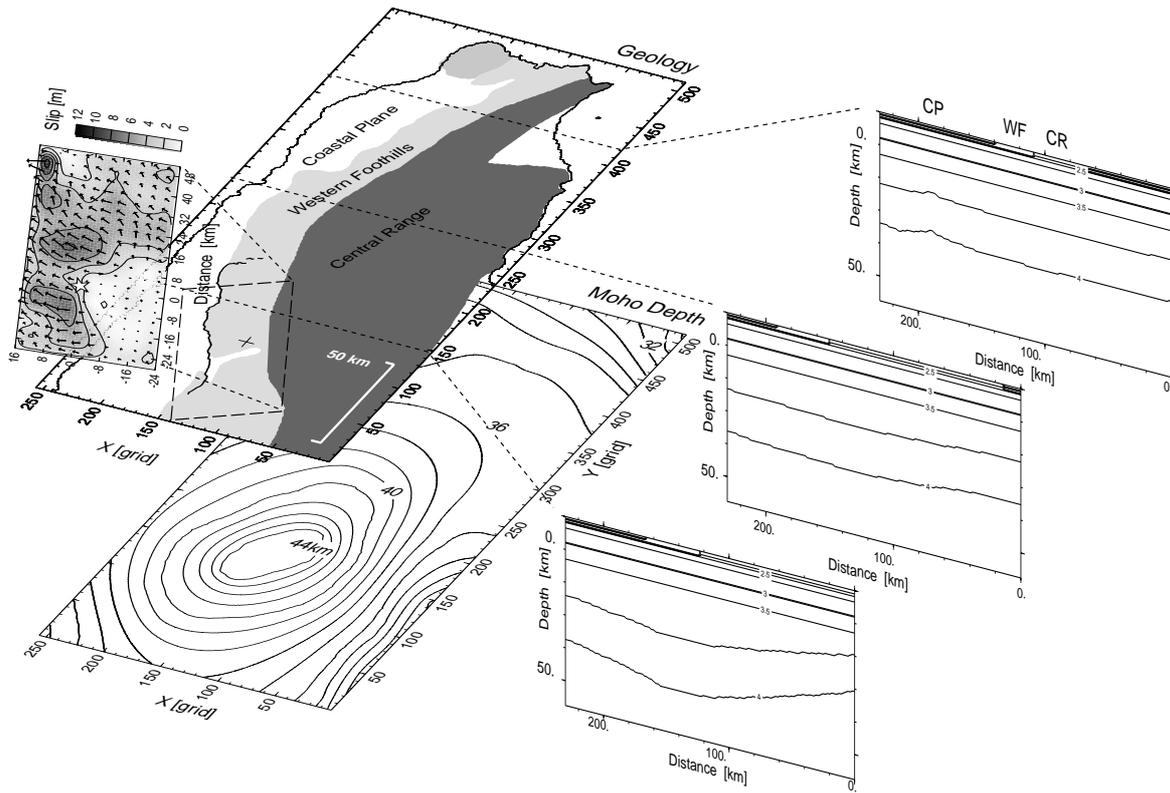


Figure 4: 3D velocity structural model assuming lateral variation of (a) surface geology, (b) Moho depth. The source-slip model of Yagi and Kikuchi (2000) is displayed in left.

controlled primarily by the site amplification effect of very shallow structure. But the simulation results of the 1999 Chi-Chi, Taiwan earthquake demonstrate clearly that the seismic wave in this frequency range is also severely influenced by the path effect of heterogeneous crust and upper-mantle structure along the propagation path. Therefore, the comprehensive study of the source characteristics, site amplification as well as path effect should also be undertaken when evaluating the strong ground motion for large earthquakes.

Acknowledgements

The authors acknowledge to Y. Yagi and K. Kikuchi for providing their source slip model. We used the strong motion waveform CD-ROM distributed by the Seismology Center, Central Weather Bureau, Taiwan (Lee et al., 1999). This work is supported by grant in aid from Japan Ministry of Education and support from the Earth Simulator Project initiated by Science and Technology Agency, Japan.

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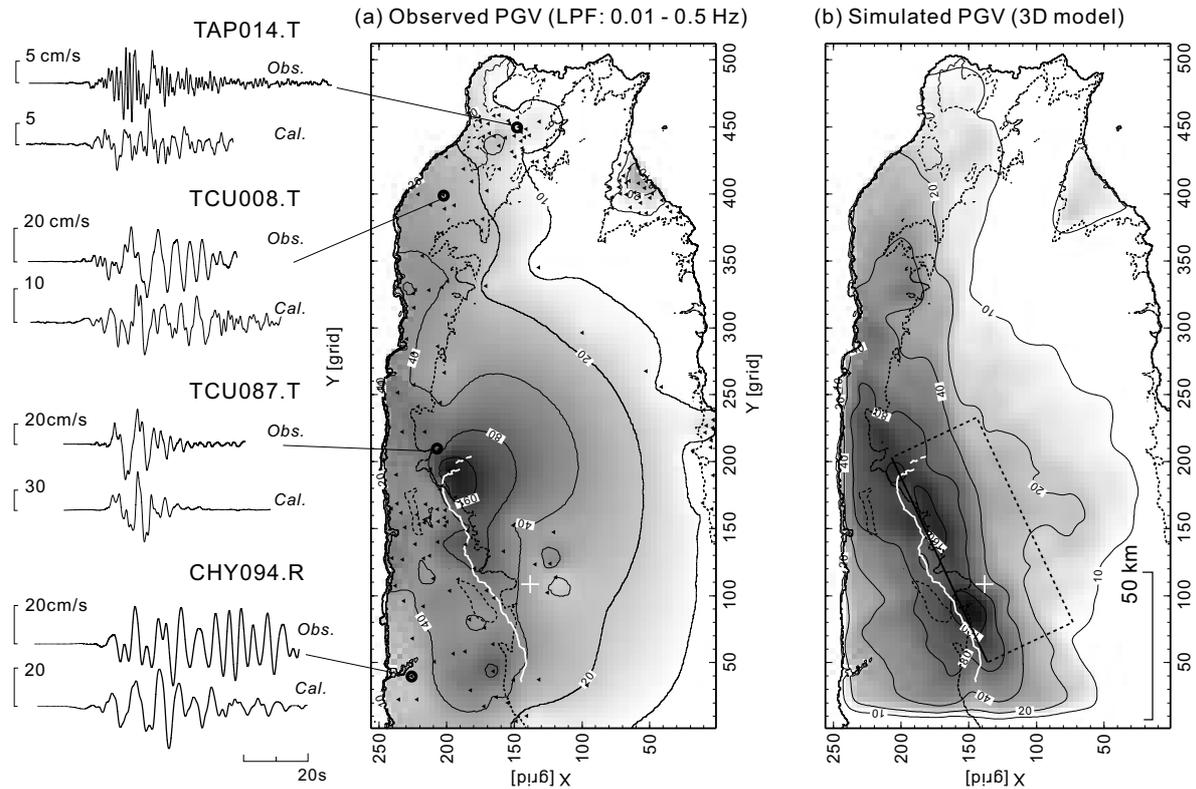


Figure 5: (a) Simulated and (b) observed PGV of horizontal motion in cm/s. Dashed line indicates the area of the fault slip. White cross and white line shows the hypocenter and surface break, respectively. Simulated velocity waveform of transverse (T) and radial (R) components at four stations are compared with observed record.

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