World of Knowledge

Effects of Topography and Basin on Seismic Wave Propagation in the Taipei Metropolitan Area

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The Invisible Risk in Taipei Basin

Taipei city in Taiwan is one of the most densely populated metropolitan areas situated on top of a shallow sedimentary basin. Over the past twenty years, seismic disasters in the Taipei metropolitan area, particularly the 21 September 1999 Chi-Chi (M_W 7.6) and 31 March 2002 east coast (M_W 7.0) earthquakes, have caused significant damage with considerable casualties. Furthermore, recent studies suggest that moderate earthquakes near the basin also have the potential to cause strong ground shaking throughout the city.

Compared to the Los Angeles basin, the Taipei basin is small, about 20 km x 20 km at the surface, and relatively shallow, with a maximum depth of less than 1000 m (Figure 1). It is surrounded by varied topography, including mountains, tableland, and a volcano group, collectively producing changes in elevation varying between sea level and about 1120 m. There are two major discontinuities in the basin: the SongShan formation and the basin basement (Figure 1). The SongShan formation is a shallow, low shear-wave speed sedimentary layer. The basin is surrounded by Tertiary basement with a deepest extent of about 700-1000 m. Taipei city's high-rise buildings, including the world's current tallest building Taipei 101 in the eastern part of the basin, make the heavily populated region particularly vulnerable to earthquakes.

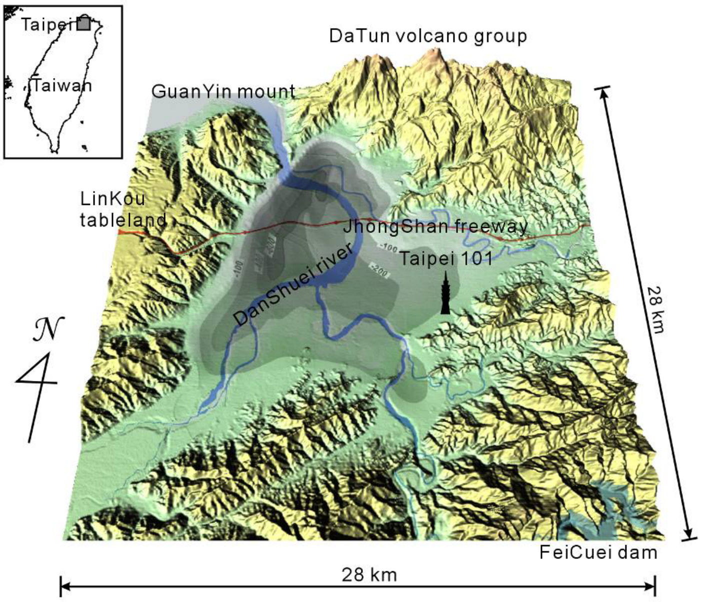

Figure 1. Map view of the Taipei basin. The depth of the basement is represented by gray colors. The red line shows the JhongShan freeway across the basin. The location of the world's current tallest building, Taipei 101, is indicated in the eastern part of the basin.

In recent years, numerical simulations have been successfully used to study the complex nature of strong ground motion due to earthquakes and the related seismic hazard. However, for the Taipei basin, slow, laterally variable sedimentary layers and sharp transitions between shallow sediments and the underlying basement pose a considerable numerical challenge. Furthermore, the notable topography around Taipei city makes the issue even more daunting. To accommodate the considerable surface topography as well as the highly variable low wave-speed sedimentary basin, we use the spectral-element method (SEM) to simulate seismic wave propagation in the Taipei metropolitan area. The SEM is a numerical technique developed more than 20 years ago to address problems in computational fluid dynamics. It is based upon a weak formulation of the equations of motion and naturally incorporates topography. The biggest challenge for the successful application of the SEM lies in the design of the mesh. In this study, we present a new mesh implementation to improve mesh quality and related numerical stability. Based upon this implementation, realistic topography and complex subsurface structures can be efficiently incorporated within the SEM mesh.

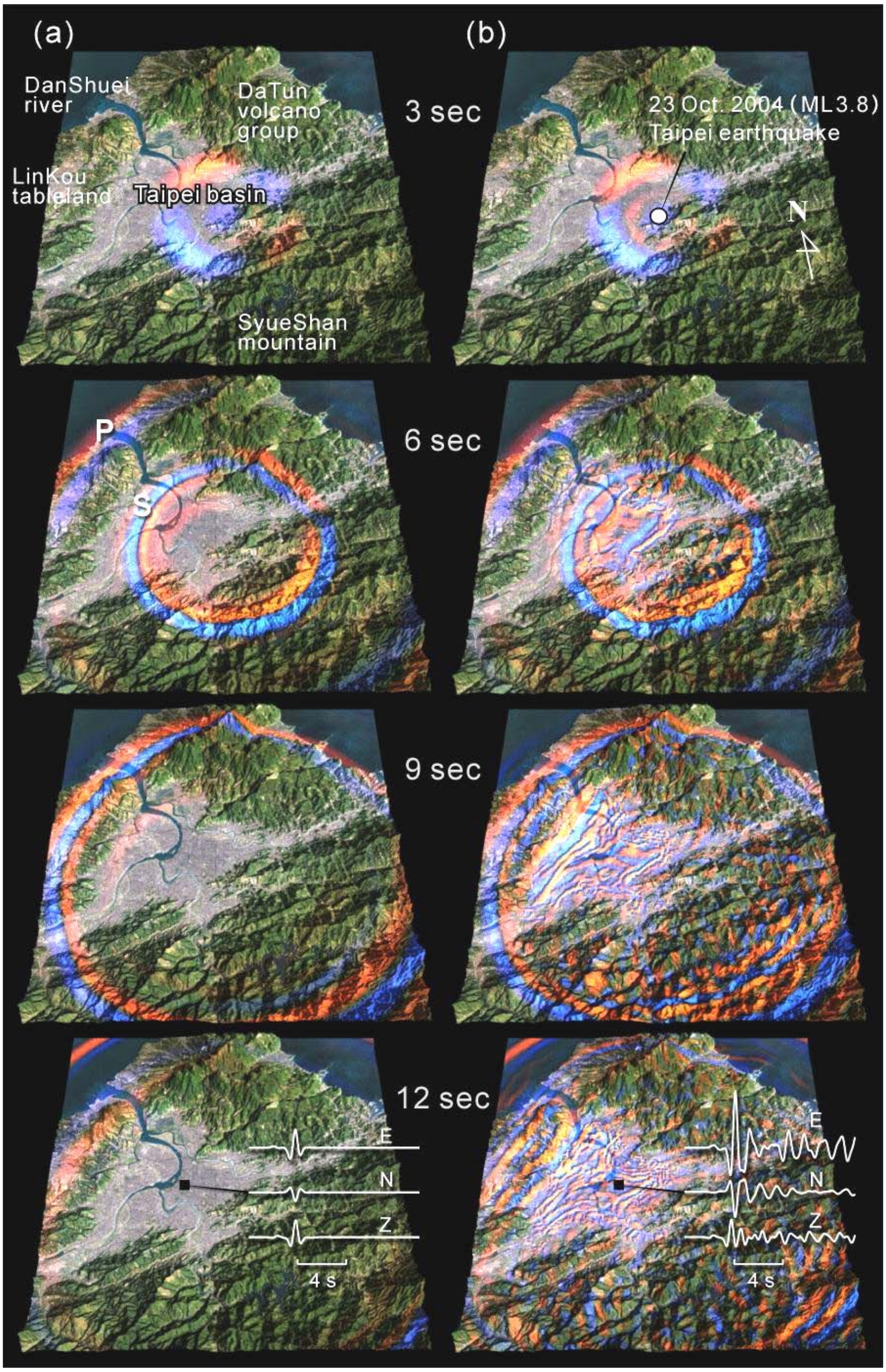

Figure 2. Snapshots obtained based on two models. (a) 3-D velocity model with a flat ground surface. (b) 3-D velocity model with basin and surface topography. The vertical component velocity wave fields are displayed. Red colors indicate positive velocities and blue colors indicate negative values. The synthetic waveforms at lower bottom show the velocity records at TAP001 station. The simulated wavefield is based upon spectral-element method. Total used grid in the model is about 297 millions, requires 38 GB of distributed memory. On the IBM eServer (10 nodes 20 processors, in IESAS), the average computing time for 30 seconds simulation is about 36 hours.

Three Dimensional Wave Propagation Simulation

To assess the quality of the Taipei basin model, we consider the 23 October 2004 Taipei earthquake by using a point source with a half-duration of 0.5 s. Figures 2a and 2b illustrate the differences between a simulation based upon a 3-D velocity model with and without topography and basin. It is obvious that topography can produce complex wave propagation behavior, with seismic energy reflected and refracted by the mountains, especially in the eastern part of the basin. One can observe a major reflection coming from a southeastern direction, following the trend of mountains that borders the basin to the east. Note that compressional (P) waves (around 3 s) are not significantly affected by topography, but that shear (S) waves (around 6 s) produce obvious reflections. Additional mountain-reflected waves can be identified after approximately 9 s. These reflected waves propagate back into the basin, thus producing longer shaking in the city of Taipei.

The effects of basin geometry and low wave-speed sediments on strong ground motion can easily be observed in snapshots of the simulated wavefield. Snapshots for a model with both a basin and topography (Figure 2b) illustrate that ground shaking within the basin is relatively strong and very complex. When the waves travel in the basin, short-period surface waves (Rayleigh waves) which propagate after the S-wave are clearly observed (6 s). These surface waves are generated by reflections and mode conversions between the basement and the free surface. The duration of shaking is increased relative to the flat model because waves are trapped and reflected within the low wave-speed sediments. Furthermore, complex reflections caused by the topography that surrounds the basin further increases the duration of shaking (after 9 s).

The influence of the basin is very clear from an analysis of the PGA amplification factor. Compared to the amplification factor in mountainous areas (which is about ±50%), the sediments in the basin amplify the shaking by more than 100%. Some areas within the basin have particularly anomalous amplification values, e.g. the southeastern part of the basin and the northern part of the basin. Note that the amplification values in these areas can be more than five times larger than those shown in Figure 2a. Compared to the result for the model without a basin, the major phases have longer traveltimes due to the low wave speeds in the basin. Strong later phases can be observed for more than 10 s in the synthetic waveforms as a result of a combination of basin amplification and mountain reflections.

Summary

The Taipei city is situated on the top of a sedimentary basin which is also surrounded by varied topography. To understand the wave propagation characteristics in the city through the numerical simulation, we developed a new spectral-element mesh implementation to accommodate topography and complex basin geometry for the Taipei metropolitan area. The simulation result demonstrated that topography can change PGA values in mountainous areas by ±50% compared to the response of a half-space. To accommodate the small, low wave-speed sedimentary basin, we systematically adjusted the mesh in the vicinity of the basin edges. The meshing technique developed in this study can probably be used to construct a spectral-element mesh of all of Taiwan or elsewhere in future studies. By considering both the low wave-speed sediments in the Taipei basin and the surrounding mountains, our results indicate that the Taipei basin can amplify ground motion by a factor of up to five compared to a model without a basin and topography. Furthermore, the basin and surrounding mountains significantly increase the duration of shaking in the Taipei metropolitan area. Through the analysis of numerical modeling results, we expect to establish our ability for seismic hazard assessment within the Taipei metropolitan in the future.