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Assessment of the site effect of strong ground motion caused by 3D crustal structure in Beijing area for a scenario earthquake

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ABSTRACT

The three-dimensional (3D) site effect of earthquake strong ground motion in Beijing area was assessed with numerical simulation using the staggered grid pseudo-spectral time-domain method. The great Sanhe-Pinggu earthquake (M~8, with the maximum intensity of XI at the epicenter and VIII in city center of Beijing) is used as the scenario event in the simulation. The Sanhe-Pinggu earthquake occurred in September 2, 1679 is the largest historic event in the past 500 years within a 100-km radius from the center of Beijing. Comprehension of the ground motion scenario caused by this earthquake will provide valuable information for seismic hazard reduction in the metropolitan Beijing area. The numerical model is constructed based on up to date information of the seismogenic Xiadian Fault on which the 1679 M8 event occurred and regional crustal structure model. The simulation results are in fair agreement with the ground motion amplification map in terms of horizontal to vertical spectral ratio derived from microtremor studies.

Introduction

It has long been recognized that the structure and material property of the uppermost sediments is a fatally critical factor to determine the brutality of strong ground motion caused by earthquake shaking (Anderson, 1996; Kramer, 1996). Thus, study of the local site effects is a critical part in seismic hazard mitigation effort, and has resulted in the concept of seismic micro-zonation.

Historic earthquake records indicate that moderate to strong earthquakes have been frequently striking the greater Beijing area. During the past 500 years (the Ming and Qing Dynasties), there have been at least 11 earthquakes with the maximum intensity of VI or greater occurred within a 100-km radius centered at the Tiananmen Square, the center of Beijing City. The Sanhe-Pinggu (M~8) earthquake, the largest historic event, occurred 65 km ENE of Beijing, severely damaged the city on September 2, 1679 (Institute of Geophysics, 1990).

To quantitatively assess the seismic risk of Beijing area, especially at a few critical sites associated with the 2008 Summer Olympic Games, the numerical simulation is used to study the strong ground motion scenarios based on historic earthquake records. To improve the modeling efficiency and accuracy, the high-resolution near-surface sediment layer thickness information

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obtained by a microtremor measurement campaign conducted in summer 2007 (Chen et al., 2009) was incorporated into the crustal model. The resolution of the estimation of the sedimentary layer thickness can reach led than 10 meters for the best case, and varying about to 10-15% of the layer thickness estimate with a general trend of longer observation of microtremor leading to a better resolution in thickness estimation (Chen et al, 2009). With more constraints on near-surface geological information, a better job can be done to estimate the local site effects on strong ground motion in the greater Beijing area generated by the potential pending earthquake (the scenario event) similar to the 1679 Sanhe-Pinggu M8 event.

The Numerical Model

Figure 1 shows a map view of the modeled area, with the 2nd to 5th Beijing Beltways and main roads highlighted for reference. The epicenter of the Sanhe-Pinggu historical event and four other locations are highlighted: the Tiananmen Square, a national landmark located at the geographic center of Beijing city; the 2008 Summer Olympics Stadium, where the main events of the 2008 Summer Olympics Games were hosted. Wukesong Culture and Sports Center, an indoor arena hosted the 2008 Summer Olympics basketball preliminaries and finals; and the Beijing University of Technology (BUT), with its stadium hosted the Olympics Badminton Matches. Detailed shear wave velocity profiling experiments have been done at these three Olympics game-related sites (e.g., Wang et al, 2009). The thickness of the Quaternary sediment layer is also shown in Figure 1, with data taken from Jia et al. (2005), and Chen et al. (2009).

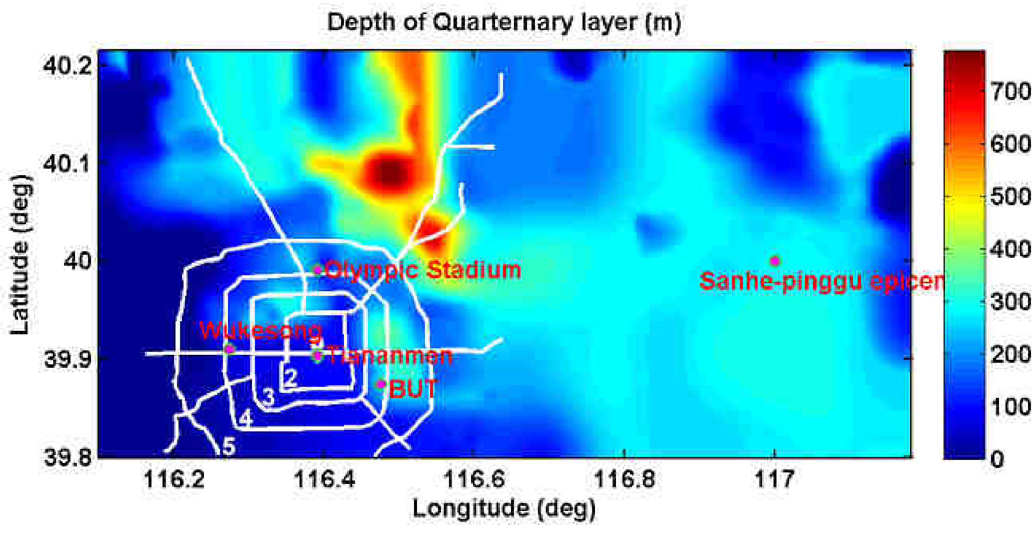


Figure 1. The thickness of the Quaternary sediment of the model, with Beijing City Beltways, the main roads, and four specific locations with particularly interests as discussed in the text

The staggered grid pseudo-spectral time domain (PSTD) method (e.g., Witte, 1989; Liu 1997; Liu and Arcone, 2005) was used to simulate the seismic wave propagation generated by a scenario earthquake based on the 1679 Sanhe-Pinggu M8 event. Our 3D model consists of a system of 512x256x64 grids, with dx=dy=dx=0.18 km. The model consists of three layers (Ding et al 2004): the Quaternary sediment layer (Vp = 1.56 km/s, Vs = 0.9 km/s), the Tertiary sediment layer (Vp = 4.5 km/s, Vs = 2.6 km/s), and the bedrock (Vp = 6 km/s, Vs = 3.46 km/s). The modeled surface area has a rectangular shape, with the southwest corner at (39.8000˚N, 116.1000˚E) and the northeast corner at (40.2149˚N, 117.1823˚E). For simplicity, a uniform density 2,500 kg/m^3 was assumed throughout the entire model domain.

The perfectly matched layer (PML) absorption boundary conditions (Berenger, 1994; Chew and Weedon, 1994) have been used in our modeling, and its thickness is 10 grid points, which is a good tradeoff for this case. The time step used is 7.5 ms, with a total of 11,466 time steps, equivalent to 85.995 seconds in time, which is sufficient for all the wave phases to propagate through the entire model domain.

The Source Parameters

The source parameters used for modeling the 1679 scenario event are listed in Table 1. Most of these parameters are either directly obtained, or indirectly derived, or inferred based on previous studies (Xu et al., 2002; Shen et al., 2004; Biasi and Weldon, 2006; Liu et al., 2007; Pan et al., 2009). The length and width of the fault are 60 km and 25 km, respectively. The length of the fault is in agreement with the magnitude and rupture length relation (Somerville et al., 1999; Biasi and Weldon, 2006). The particle velocity on the fault plane was used as the source, which is distributed over the modeled fault plane, and which decay in accordance with a sinusoidal relation to the surface and the lateral border of the model. The source time function that has been used is a Ricker wavelet with a central frequency of 1 Hz. The source has a rupture velocity 2.6 km/s, the S-wave velocity in the Tertiary sediment layer, but less than the shear wave velocity in the bedrock basement (3.46 km/s). The largest particle velocity used is 66.67 m/s, which is justified by the argument shown as follows.

To estimate the magnitude of the particle velocity caused by an earthquake rupture, it is reasonable to assume that a substantial portion of the elastic potential energy E_p has been converted to the kinetic energy E_k:

$$E_k \sim E_p \tag{1}$$

As we know, the kinetic energy of a volume element can be expressed as

$$E_k = \frac{1}{2} m \bar{v}^2 \tag{2}$$

And the elastic potential energy is

$$E_p = \frac{1}{2} \sum V \sigma_{ij} \varepsilon_{ij} \tag{3}$$

where m and V are the mass and volume of a volume element on the fault plane, respectively; σ_{ij} and ε_{ij} are stress and strain tensor components; and $\bar{v}$ is the average particle velocity over the whole fault plane. To model the strike-slip faulting, only the shear motion is involved so that the simplified Hooke's Law can be applied

$$\sigma_{ij} = \mu\varepsilon_{ij} \tag{4}$$

where μ is the shear modules, and only the shear components of stress and strain get involved in Eqn. 4. Moreover, the relation between seismic moment and stress tensor can be characterized as:

$$\sigma_{ij} = M_0 \frac{M_{ij}}{V}. \tag{5}$$

where M_0 is the scalar moment carrying the magnitude and dimension of the seismic moment caused by an earthquake rupturing, and M_{ij} is the moment tensor carrying the relativity of different motion with a maximum of unity. Then, from Eqns. 1-5, the average particle velocity on the fault plane can be estimated as:

$$\bar{v} = \frac{M_0}{V}\sqrt{\frac{1}{\rho\mu}} \tag{6}$$

From the M_0-M relation (Hanks and Kanamori, 1979; Deichmann 2006):

$$M = \frac{2}{3}\log M_0 - 10.7 \tag{7}$$

we can estimate M_0 (in dyne-cm here). Meanwhile, it can also be estimated by the relation of $M_0=\mu DA$. Consequently, we get the average velocity of $\bar{v}$, from Eqn. 6 with a given density ρ (~2700 kg/m^3), source volume (~270 km^3) and shear modulus μ (~10 GPa).

Table 1. Source parameters of the Sanhe-Pinggu scenario Earthquake.

Parameter	**Value**	**Parameter**	**Value**
Seismic Moment	1.48×10^{20} N-m	Area of Asperity	270 km^2
Stress Drop	20 MPa	Dip	SE78˚
Fault Length	60 km	Strike	N40˚E
Vertical Extension	25 km	Rake	219˚
Epicenter Location	39.9˚N, 117.0˚E	Rupture Speed	2.6 km/s

The epicenter of this great event was about 70 km east to northeast of the center of Beijing. The simulated seismic source is the distributed 5-m right-lateral, strike-slip rupture along the ~150 km long, NE oriented near-vertical Xiadian Fault. The seismic wave propagation is simulated for up to 1 second in frequency. To show the 3D effect, the strong ground motion expressed by peak ground velocity (PGV) was calculated based on the 3D model of the sedimentary layer thickness available at the time to carry out the computation of the ground motion generated by this scenario earthquake.

Result Discussion

The PGV and peak ground acceleration (PGA) at a given site are very useful for characterization of strong ground motion in earthquake engineering. Surface PGV and PGA plots in the Beijing city area are shown in Figure 2, with the top row showing the three-component PGV, and the bottom row showing the three-component PGA. Beltways and main roads are also shown for reference. It is noticeable that in the region shown in Figure 2, the most prominent PGV and PGA is in the east part. That is understandable, since the epicenter is ENE of the center of Beijing city.

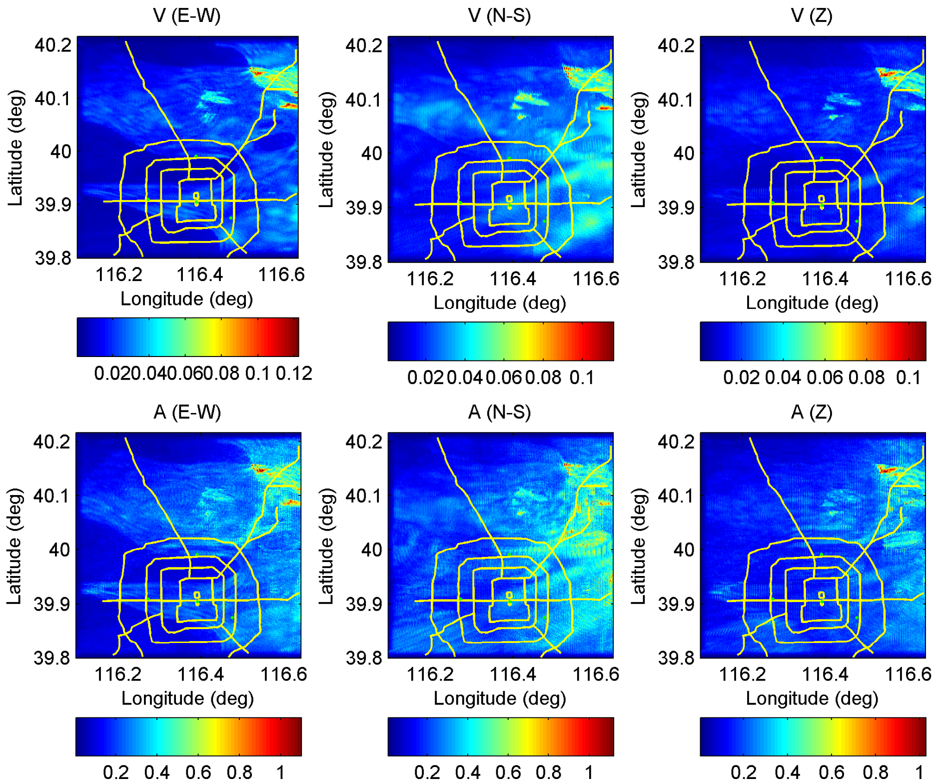


Figure 2. Top row: three component surface PGV (from left to right: East-West component, North-South component, and vertical component). Bottom row: three component surface PGA (from left to right: East-West component, North-South component, and vertical component)

In order to exclude the geometric spreading effect and focus on possible amplitude amplification due to the sediment layers the horizontal to vertical (H/V) PGV calculation is used as an indicator of local site effect. The result is shown in Figure 3, and we can see clearly from the rightmost plot in Figure 3 that there are strong amplitude amplification effects to the north of the city and in the southeastern corner of the Beijing city. These features appear to be associated with the 3D effect of the undulation of the sedimentary layer thickness in Beijing area. Actually, there are increasing number of case studies to compare the H/V ratio generated by the microtremor and by real earthquake events, and the features of the peak frequency and amplitude amplification are generally in agreement with each other (e.g., Horike et al 2002; Mucciarelli et al, 2003; Sawada et al, 2004; Upadhayay and Mori, 2013) and can be taken as a secondary reference for estimating the site effect. It is worthy to point out that during the 1976 Tangshan Earthquake, abnormally high amplitude ground motion were reported in the Haidian District (the NW corner between the 4th and the 5th Beltway), and the southeast corner of Beijing area (Ding et al., 2004), which is generally in agreement with the features in terms of horizontal to vertical spectral ratio (H/V) results from a recent microtremor study (Figure 4a, also in Chen et al., 2009).

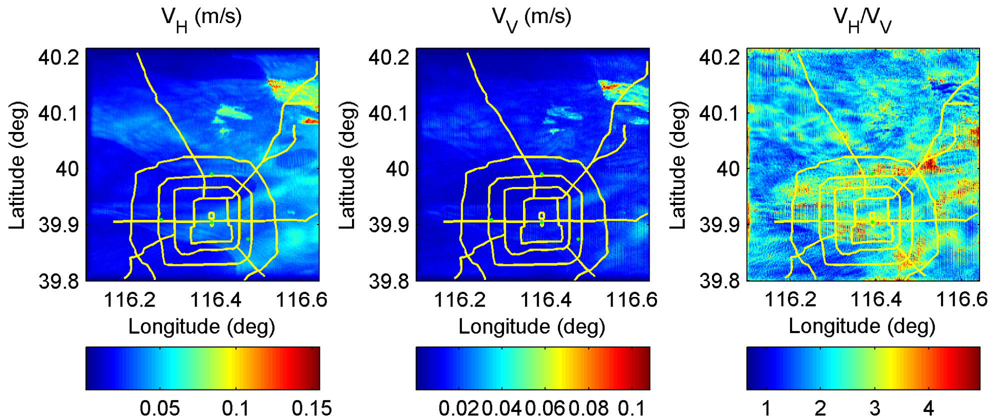
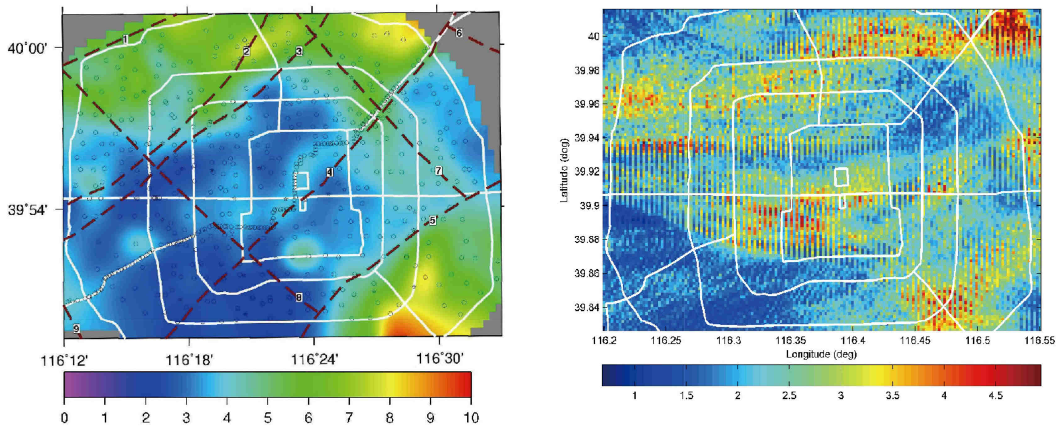


Figure 3. Horizontal PGV (Left); Vertical PGV (Middle); Horizontal PGV (Right) divided by vertical PGV (the H/V ratio)



(a) (b)

Figure 4. (a) the amplification factor of the horizontal to vertical spectral ratio at the predominant resonance frequency for Beijing area from microtremor measurements (Chen et al., 2009); (b) the horizontal to vertical ratio of PGA generated from the synthetic simulation of the 1679 M8 Sanhe-Pinggu scenario earthquake

Shown in Figure 5 are the three-component synthetic seismograms recorded at four sites: the

2008 Summer Olympic Stadium, Beijing Wukesong Culture and Sports Center, Tiananmen Square, and Beijing University of Technology (BUT). The sampling rate of these seismograms is 75 ms. In general, the amplitude decays with increase of the epicenter distance. Also, for all of the four sites the vibrations in horizontal directions are larger than the vertical vibration. These simulated features are reasonable based on the geological settings as discussed in previous sections.

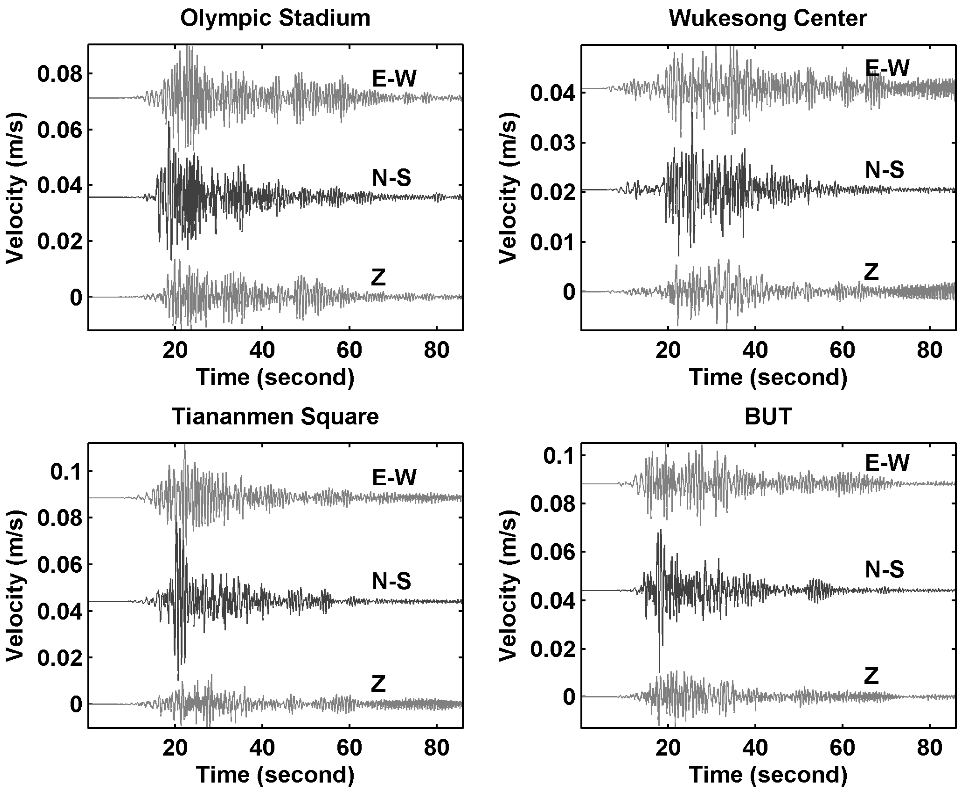


Figure 5. Three-component synthetic seismograms recorded at four sites (the 2008 Summer Olympic Stadium, Wukesong Culture and Sports Center, Tiananmen Square, and BUT), with a sampling rate of 75 ms

Conclusions

The staggered grid PSTD method was used to assess the site effect of crustal heterogeneities in Beijing area by taking the 1679 M8 Sanhe-Pinggu Earthquake as the scenario event. The high-resolution sediment thickness information in the metropolitan area of Beijing was obtained from microtremor measurements in this area. From the surface PGV and PGA studies, together with the H/V calculations, it is reasonable to assume that the observed ground motion amplification effects is possibly associated with local site effect caused by thicker or weaker sediment layer in the north part and the southeast corner of Beijing area, which have also been confirmed by real-world on site studies for the most recent regional events, such as the 1976 Tangshan earthquake. The result suggests that numerical modeling approach is an effective one for seismic hazard assessment and provides valuable information for mitigating losses for possible pending earthquakes in the future.

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