A Rapid Approach for the Prediction of Seismic Ground Motion in Urban Areas

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Abstract: Rapid prediction of seismic ground motion can help with the assessment of seismic damage during earthquake emergencies. A numerical simulation is a powerful tool for achieving this end. However, existing methods for such simulations need a large number of seismic ground motion records. Moreover, their performance depends on large-scale computing resources, so they cannot meet the requirement of near real-time prediction of seismic ground motion. This paper proposes a rapid method for predicting seismic ground motion based on the 3D transfer function. This approach obtains the transfer function by solving the site seismic response under three impulse function excitations, calculated by different pre-event 3D physics-based numerical simulations. The approach only needs one seismic record in the study area and can quickly yield the seismic ground motion of the whole study area. The proposed approach is verified by modeling site response to an assumed earthquake, which was affected by the 2008 Wenchuan M7.9 event. The results confirm that the proposed method has sufficient accuracy in near real-time prediction of seismic ground motion.

Keywords: Urban regional scale; Post-event ground motion prediction; 3D physics-based numerical simulation; 3D transfer function.

1. Introduction

Major earthquakes can cause severe casualties and property loss [1, 2]. Therefore, emergency response is of great significance to reduce such disasters [1–4]. However, to put such measures in place in a timely and effective manner, we must first determine the extent and severity of earthquake damage. On-site investigation is the traditional method for accomplishing this goal. It does, however, necessitate a large number of experienced professionals and takes a long time, which limits the speed and effectiveness of rescue [5–7]. Rapid and accurate seismic ground motion prediction can help allocate personnel and rescue resources immediately after a devastating earthquake, assisting earthquake emergency decision-making to some extent. Thanks to the rapid development of computer technology, 3D large-scale physics-based numerical simulation (PBS) has been widely used. Its results can be validated with actual seismic records [8–13]. To further this approach, this work proposes a rapidly predicting seismic ground-based on 3D transfer function (TF). The 3D transfer function is
obtained by solving the site seismic response under three impulse function excitations, which different pre-event 3D PBS can calculate as the key ingredients of the approach. The proposed approach is verified by modeling of the real-time seismic response of the 2008 Wenchuan M7.9 earthquake in the Wudu basin, Sichuan province, China. The results confirm that the proposed method has sufficient accuracy in near real-time prediction of seismic ground motion.

2. Method

Let \( u(t) \) be the specific seismic input, which is composed of three independent polarized waves: \( u_x(t) \), \( u_y(t) \), and \( u_z(t) \). Each of the polarized waves is a unit pulse function with the same or different dominant frequency. Let \( y_{ij}^{(k)}(t) \) be the ground motion at node \( k \) on the axis \( j \) when the 3D site is only subjected to one of the three polarized waves \( u_i(t) \). Different pre-event 3D PBs can obtain the seismic ground motion. The 3D TFs in the frequency domain is expressed as

\[
trf_{ij}^{(k)}(f) = y_{ij}^{(k)}(f)/u_i(f)
\]

where \( trf_{ij}^{(k)}(f) \) is the 3D TFs at node \( k \) on the axis \( j \) when the 3D site is only subjected to one of the three polarized waves \( u_i(t) \), and \( y_{ij}^{(k)}(f) \) and \( u_i(f) \) are Fourier transforms of \( y_{ij}^{(k)}(t) \) and \( u_i(t) \), respectively.

Next, we calculate the frequency-domain response of the same 3D site to the seismic event by

\[
\begin{bmatrix}
Y_{x}(f) \\
Y_{y}(f) \\
Y_{z}(f)
\end{bmatrix} = \begin{bmatrix}
trf_{xx}^{(i)}(f) & trf_{xy}^{(i)}(f) & trf_{xz}^{(i)}(f) \\
trf_{yx}^{(i)}(f) & trf_{yy}^{(i)}(f) & trf_{yz}^{(i)}(f) \\
trf_{zx}^{(i)}(f) & trf_{zy}^{(i)}(f) & trf_{zz}^{(i)}(f)
\end{bmatrix} \begin{bmatrix}
U_x(f) \\
U_y(f) \\
U_z(f)
\end{bmatrix}
\]

where \( Y_{ij}^{(i)}(f) \) represents the seismic motion at node \( k \) in the frequency domain on the axis \( i \), \( U(t) = [U_x(t), U_y(t), U_z(t)] \) is the real seismic excitation, and \( u_i(f) \) is the corresponding seismic input in frequency domain on the axis \( i \). Then the time-domain seismic response of the whole site to different seismic events can be obtained by inverse Fourier transforms of \( Y_{ij}^{(i)}(f) \).

If we have one station's records (reference station) of the study area, then the real seismic excitation can be obtained by the inverse function of the 3D TFs and the ground motion of the reference station, which can be expressed as

\[
\begin{bmatrix}
U_x(f) \\
U_y(f) \\
U_z(f)
\end{bmatrix} = \begin{bmatrix}
trf_{xx}^{(S0=1)}(f) & trf_{xy}^{(S0=1)}(f) & trf_{xz}^{(S0=1)}(f) \\
trf_{yx}^{(S0=1)}(f) & trf_{yy}^{(S0=1)}(f) & trf_{yz}^{(S0=1)}(f) \\
trf_{zx}^{(S0=1)}(f) & trf_{zy}^{(S0=1)}(f) & trf_{zz}^{(S0=1)}(f)
\end{bmatrix}^{-1} \begin{bmatrix}
Y_{x}^{(S0=1)}(f) \\
Y_{y}^{(S0=1)}(f) \\
Y_{z}^{(S0=1)}(f)
\end{bmatrix}
\]

where \( Y_{ij}^{(S0=1)}(f) \) is the seismic motion at the reference station in frequency domain along axis \( i \). Then the time-domain seismic input can be obtained by inverse Fourier transforms of \( u_i(f) \).

3. Case Study

The Mw7.9 Wenchuan earthquake struck China on May 12, 2008, with the epicenter in the Longmenshan range, which is adjacent to the Sichuan basin [14]. (Figure1). It impacted the Wudu basin, which is 160 kilometers northeast of the epicenter. Limestone and sandstone are the main lithological units in this area. The Fujiang River flows from north to south through the Wudu basin, forming an alluvial fan in the shape of a spindle-shaped sedimentary body that extends southward and covers Wudu town. Geological borehole exploration in the Wudu basin was carried out to obtain detailed geological data for the study area (Figure 2). The soil samples were taken from the boreholes for laboratory tests to determine the wave velocity and dynamic parameters of soil layers at the sites (Table 1), followed by the Chinese code GB50021-2001 [15].
Figure 1. (a) A Map showing Sichuan province, China. (b) The epicenter of the mainshock of the 2008 Wenchuan earthquake (red star) and aftershocks (solid red circles) recorded by the accelerometer monitoring stations at Wudu town, the coseismic fault rupture (red lines), and the study area (yellow rectangle).

Figure 2. Shaded map showing topography relief of the study. The solid red triangles are sites of ground motion recordings (Sta 1 to Sta 6). Blue solid circles are geological exploration drilling holes (Site 1 to Site 10).

Table 1. Wave velocity and dynamic parameters of soil layers in different lithologic units

| Lithologic unit | Density (Kg/m$^3$) | $c_p$ (m/s) | $c_s$ (m/s) | $E_d$ (MPa) | $G_d$ (MPa) | $\sigma_d$ |
|-----------------|--------------------|-------------|-------------|-------------|-------------|------------|
| Artificial fill | 1700               | 321         | 128         | 78          | 28          | 0.429      |
| Fine sand       | 1650               | 308         | 135         | 88          | 31          | 0.427      |
| Silt            | 1850               | 465         | 172         | 156         | 55          | 0.418      |
| Silty clay      | 1880               | 504         | 187         | 187         | 66          | 0.414      |
| Pebble          | 2200               | 991         | 413         | 1039        | 373         | 0.358      |
| Siltstone       | 2400               | 1230        | 513         | 1754        | 628         | 0.333      |

4. Numerical Modeling

4.1 3D Velocity Model
To effectively satisfy the requirements of 3D numerical simulation, we set up, at a depth of 20 m of the basin, a transitional layer with a thickness of 20 m. The shear wave velocity of this transition layer increases linearly from 500 m/s to 2250 m/s with depth. According to Zhang et al. (2020), the average dip angle of the basement of the basin is less than 45°. The 3D velocity model for the Wudu basin is displayed in Figure 3, which is 9.2 km long in the east-west direction and 8.5 km long in the north-south direction, respectively. For the convenience of 3D numerical simulations, the 3D velocity model for the Wudu basin is assumed as purely elastic.
4.2. Finite-Element Simulation

The finite-element method was used as our numerical technique. The seismic input is a unit displacement Dirac pulse with cutoff frequency 10 Hz, which is selected according to the frequency characteristics of observational data. Considering that the algorithm based on a structured grid is easier to get high parallel efficiency, we use a structured grid to discretize the 3D velocity model. Each discrete element in the 3D model is 1/8 – 1/10 of the minimum wavelength corresponding to the input seismic wave's cutoff frequency [16 –18]. When using a numerical method to simulate seismic site response, it is necessary to apply constraints at the cutoff boundary of the site to reduce the reflection of outward-propagating waves back into the model. In this study, we adopt an improved 3D viscous-spring artificial boundary applied on the cutoff boundary. The seismic input was converted into equivalent input seismic load acting on the local site model, as described in Zhang et al. (2017) [18].

5. Comparison of Observations and Simulation Results

Figure 4 shows the comparison of the six stations' observed and calculated acceleration time histories. In all three directions, the calculated accelerograms of Sta 1 match the observed ones. The five stations in the Wudu basin have calculated accelerograms that do not match the observed ones. In the N–S direction, the differences between the calculated and recorded Sta 6 accelerograms are fairly obvious, and the relative error with recorded data of Sta 6 in the E–W direction is 15.90 percent. Furthermore, the calculated records' maximum amplitude of motion is all smaller than the observed values.

The Fourier amplitude spectral accelerations of the calculation are compared with the observed ones (Figure 5). For Sta 1, the Fourier amplitude spectra of calculated accelerations all agree well with the observed ones in the three directions. Likewise, the calculated results of Sta 2 to Sta 5 in the frequency band of 0.1–1.0 Hz agree well with the observation ones, and the trend of Fourier acceleration amplitude spectrum of the calculated results in the frequency band of 1.0–10.0 Hz are similar to the observation data. However, there are significant differences between the computed acceleration Fourier amplitude spectra of Sta 6 in the E–W and N–S direction and the observation ones.

The calculated results of station 1 are in good agreement with the recorded ones in the frequency and time domain because the seismic input motion is obtained by combining the inverse function of the 3D TF and the actual seismic motion of the Sta 1. The Wudu basin is a shallow dish-shaped basin with a small variation in surface elevations, a very thin overburden (about 20 m), and the medium in
each layer is approximately horizontally stratified, according to the geological exploration data. The five stations in the basin are located in the western part of the basin, with Sta 6 being the closest station to the basin's edge. Compared with other stations in the basin, the main reason for the significant differences between the calculated results and the recorded ones of Sta 6 is that this station is located near the Jiangyou Taibai middle school, surrounded by a large number of buildings and other stations are located in the artificial fill (close to or located in farmland).

**Figure 4.** Comparison of the observed (solid red line) and calculated (black dotted line) acceleration time histories of six stations. The east-west records are in the left column, north-south records are in the middle column, and vertical ones are in the right column. For each trace, the value of the maximum amplitude (black) and the relative error with recorded data (red) are shown in the upper right corner.

**Figure 5.** Comparison of the Fourier amplitude spectral accelerations of the observations (solid red line) and calculations (black dotted line). The east-west records are in the left column, north-south records are in the middle column, and vertical ones are in the right column.

### 6. Discuss and Conclusions

This study proposes a 3D TF method for faster prediction of seismic ground motion. The 3D TF is obtained by solving the site seismic response to three impulse function excitations. This method only needs one station's records in the study area and can quickly calculate the ground motion of the whole study area. The real-time seismic response of an earthquake in the Wudu basin, Sichuan, China, is simulated to test the proposed method. As a result, the following conclusions can be drawn:

1. The proposed method has an acceptable prediction capability. Compared with the true recorded ground motion, the relative error of PGA at sites is only 1.13%. Even in complex regions, the maximum relative error of PGA is only 15.9%.

2. The proposed method has high computational efficiency. The 3D TFs of a site need to be simulated only three times (which can be calculated by different pre-event 3D PBS). When necessary,
the ground motion of the site can be obtained by combining the actual excitation (through the inverse function of the 3D TFs and the ground motion of the reference station).

(3) When the proposed method is used to calculate the seismic response of a 3D site, the scale of the study area is not a limitation to the model's accuracy. The 3D TFs of the sites are obtained by numerical simulation, where the effect of seismic source and propagation path are converted into equivalent input seismic load acting on the site. Applying the finite-element method as a reference, the large-scale site can be divided into many small-scale sites. Each can be calculated separately to obtain the local 3D TFs, the local 3D TFs are assembled to get the global 3D TFs.

It should be noted that because the current study focuses on the rapid prediction of ground motion at 3D large-scale sites, it only discusses the applicability of this method at linear sites where seismic waves propagate as plane waves with vertical incidence.

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