Soil Dynamics and Earthquake Engineering 76 (2015) 136–144

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Simulation of broadband seismic ground motions at dam canyons by using a deterministic numerical approach

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ARTICLE INFO

Article history:
Received 20 June 2014
Received in revised form
17 October 2014
Accepted 9 December 2014
Available online 31 December 2014

Keywords:
Spectral element method
Source mechanism
Velocity model
Topography
Spatially varying ground motions

ABSTRACT

As a deterministic numerical approach for simulation of earthquake ground motions, the spectral element method (SEM) is applied to generate a broadband acceleration array for dam-canyons instead of the traditional empirical or stochastic methods. Specifically, the SEM analysis model with an extra fine mesh is used for the Pacoima Canyon to simulate the entire path starting from earthquake source rupture via the propagation medium to the local site. The source and the 3D earth model (velocity structure) are validated through the modeling of the Newhall earthquake on 28 October 2012 at a frequency of up to 8 Hz. Subsequently, the San Fernando earthquake records on 13 January 2001 are further used to study the effects of propagation path in simulation. Finally, the spatially varying ground motions at the Pacoima Canyon are obtained for different source mechanisms. The results show that the source mechanism and the local site topography significantly affect the distribution of the peak accelerations along the canyon.

1. Introduction

The importance of seismic safety of dam-canyons is well-recognized owing to the catastrophic consequences of dam failure during strong earthquakes. Three main factors affect the earthquake safety evaluation of high dams, i.e., (1) the input mechanism of ground motions; (2) the dynamic analysis model for dam-foundation-water systems; and (3) the dynamic behavior of materials. Among those, the input mechanism of earthquake motions is the most difficult topic of study due to the complexity of source mechanism and local site conditions of dam-canyons. Researchers have obtained earthquake records of a few dams by which the methods of dam-canyon interaction analysis may be examined [1,2]. However, the responses resulting from the recorded ground motions are quite different compared with conventional analyses [3]. Furthermore, the lack of appropriate strong motion records from dam-canyons for seismic safety evaluation is crucial for most high dam projects, particularly those under construction. The analyses following the design code may provide a lower bound of safety but they fail to disclose the realistic response of dam-canyons. Therefore, using the deterministic numerical approach to perform a quantitative broadband simulation that considers the influences of source mechanism, propagation path, and site effects is necessary for important high dam projects.

Currently, the hybrid methods are commonly employed to generate broadband motions (0.1–10 Hz) in seismology [4–6]. In this case, the low-frequency portion (0.1–1 Hz) is computed using the deterministic numerical method, such as the finite difference method (FDM) [4,5,7], while the high-frequency portion (1–10 Hz) can be obtained using the stochastic method based on Boore's omega-square spectrum [8,9]. The shortage of the hybrid methods is that the FDM is unable to handle free surface well, and the stochastic approach does not consider neither the source mechanism nor the realistic topography. In 1998, Komatitsch and Vilotte [10] first presented the spectral element method (SEM) in seismology. The SEM may be seen as the high-order finite element method that uses a specific nodal expansion basis. It combines the flexibility of incorporating complex topography of the finite element method and the accuracy of pseudo-spectral methods. In practice, one element per wavelength has been found very accurate when working with a polynomial of degree 4 [11]. In addition, the SEM is easy to perform with parallel computing on clusters because of its diagonal mass matrix [12]. Therefore, the SEM is widely used in global- and regional-scale earthquake simulations [13–18]. Earthquake simulations at a global scale are conducted up to period of minutes. The computation area for regional earthquakes covers a scale of hundreds of kilometers (i.e., Southern California) [15,16,18]. Due to the constraints of the large-scale velocity model resolution and element mesh size, the upper limit of frequency range is only approximately 0.5–1 Hz.

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http://dx.doi.org/10.1016/j.soildyn.2014.12.004
0267-7261/

This study simulates the rupture-structure process using the SEM to produce high-frequency ground motions for dam-canyons. The rupture-structure process (from source, via propagation path and local site, to structure) is called an “end-to-end simulation”, which has been used in the analyses of several structures. Krishnan et al. [18] studied the behavior of tall moment-frame buildings under seismic loads with the SEM simulation reaching 0.5 Hz. Hall et al. [19] simulated the broadband responses of near-source flexible buildings by combining the finite element method for low frequencies and the actual records for high frequencies. Substructures subject to earthquake fault rupture were investigated by applying 2D analytical and finite element methods with the assumption of an idealized fault rupture [20,21]. Lee et al. [17] studied the topographic effects of Taiwan region using the SEM, for example, a small area (4.2 km × 3.9 km) in the Yangminshan region with the highest frequency of 10 Hz at 2 m mesh resolution. However, the velocity model and the source are both hypothetical in their studies, and no comparison was made between the synthetic results and actual records.

The above-mentioned rupture-structure investigations may be suitable for long-period tall buildings but not for arch dams, due to the following factors: (1) the frequency band of ground motions simulated for arch dams should be up to 5–10 Hz, which is much higher than that of tall buildings; and (2) the span of arch dams are generally large thus the spatial non-uniformity along the canyon cannot be disregarded. To obtain high frequency waves, the fine mesh and velocity model are essential. On the other hand, topography should also be incorporated into the SEM mesh because it affects ground motion distribution along the canyon. The canyon site topography for most arch dams is roughly of V- or U-shape. Previous studies have assumed such topography to be a regular shape, such as a semicircle or semi-ellipse [22–25], with a single type of incident wave. These assumptions simplify the realistic topography and the realistic seismic waves.

Herein, a near-field event, the Newhall earthquake on 28 October 2012 of magnitude 3.9, is simulated by employing the SEM. Realistic topography is preserved based on the high-resolution Digital Elevation Model (DEM) from the USGS National Elevation Database [26]. High-frequency waves are obtained by using a fine mesh and high-quality velocity model. A good fit is achieved between the simulated results and the recorded ground motions up to 5–6 Hz in the frequency domain. Considering the high frequency up to 8 Hz, the generated ground motions are still acceptable although it requires further investigation for more accurate results. Meanwhile, the ground motions at the same position are also generated by the stochastic approach for comparison. Further, the San Fernando earthquake on 13 January 2001 is simulated to analyze the effect of propagation path on the accuracy of the results. Finally, the spatially varying ground motions at the Pacoima Canyon are obtained for different source mechanisms.

2. Pacoima dam and Newhall earthquake

Pacoima dam, which is located at the Pacoima Creek in the San Gabriel Mountains of Los Angeles, California, has endured numerous earthquakes, some of which were recorded by the accelerometers installed at the dam body and abutments. The performance of the dam during earthquakes has been studied extensively [1,3]. The strong ground motions of the Northridge earthquake on 17 January 1994 of magnitude 6.7 are preferred as seismic input for the dam in response analysis. However, the detailed rupture process may affect the high-frequency radiation given that the size of its rupture fault is 20 km × 25 km. A small earthquake (magnitudes 3–5) is commonly tested to reduce the variables. Because it has a small rupture area, the rupture process can be ignored and treated instead as a point source. Another advantage of using a small earthquake is that the material will behave linearly, which makes the responses easier to predict.

The Newhall earthquake on 28 October 2012 (34.352°N, 118.466°W, depth 4.0 km) is a small event with a magnitude of 3.9. The source mechanism (strike 139°, dip 68°, and rake 137°), the total seismic moment ($M=4.03\times10^{21}$ dyn cm) as well as the moment tensors ($M_{xx}=-3.834$, $M_{xy}=-1.589$, $M_{xz}=0.827$, $M_{yy}=1.757$, $M_{yz}=1.611$ and $M_{zz}=2.076$ with $Scale=1.0\times10^{21}$ dyn cm) are obtained from the Southern California Earthquake Center (SCEC) [27], where the subscripts x, y and z represent north, east, and down direction, respectively. Following reference [28], the Gaussian function (a smoothed triangle) is used as the source time function, as shown in Fig. 1. The half-duration is determined as $2.4\times10^{-6}M^{1/3}$ [29], where M is in N m. For the Newhall event, the half-duration is 0.17 s. From Fig. 1, it can be seen the corner frequency of the source spectrum is around 10 Hz.

The epicenter of the Newhall earthquake and the Pacoima dam is shown in Fig. 2. There are two stations (CE24207 and CE24407) recorded the ground motions during the Newhall earthquake within the simulation area (see Section 3.1) and their data are publicly available online [30]. CE24207 is an acceleration array installed in the Pacoima dam body; thus the records are not realistic ground motions. CE24407 is located at the left abutment of the Pacoima dam, as shown in Fig. 2. Therefore, the simulated velocities are compared with the recorded data from CE24407 to verify the simulation model described in the next section.

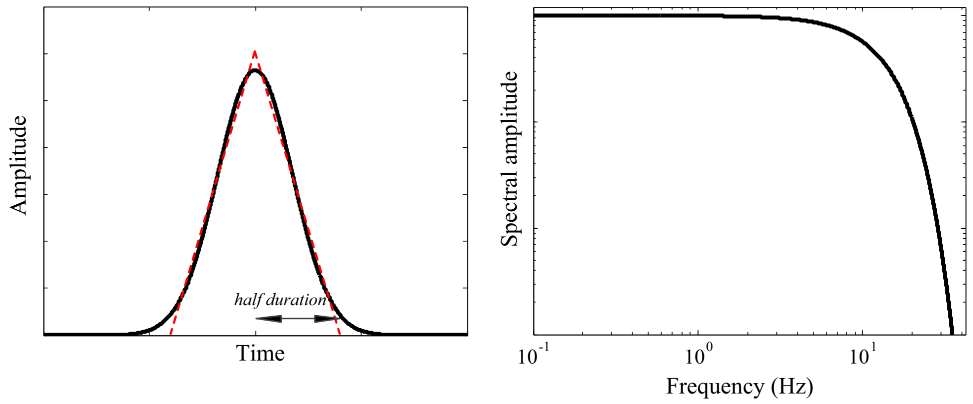

Fig. 1. Time history and spectrum of source function.