The 2015 World Congress on
Advances in Structural Engineering and Mechanics (ASEM15)
Incheon, Korea, August 25-29, 2015

Generation of earthquake ground motions at dam sites based on numerical simulation of wave propagation from source

*Jin-Ting Wang[1)], Chun-Hui He[2)], Luo Gan[3)] and Chu-Han Zhang[4)]

[1), 2), 3), 4)] *Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China*
[1)] *wangjt@tsinghua.edu.cn*

ABSTRACT

The input of the Ground motions is a key factor for the earthquake design of new dams and earthquake safety evaluation of existing dams. This paper suggests that the earthquake ground motions at dam sites may be generated by deterministically (numerically) simulating the rupture of a potential source as well as the propagation of seismic waves. Conceptually, this procedure could strictly take into account the effects of source mechanism, propagation path and local site on ground motions. The generated ground motions are more realistic than those obtained by the widely-used seismic hazard analysis procedures based on the attenuation relations. The ground motions near Pacoima dam due to the 1994 Northridge earthquake of magnitude 6.7 are first simulated using a large-scale spectral element method (SEM) model (56×49×25 km) with about 6-billion degree-of-freedom to verify the proposed idea. The ground motions along a dam canyon in Southwestern China are then analyzed for a hypothetic potential source. The results show that the ground motions along the canyon are significantly varied, which should be considered in the earthquake-resistant design and safety evaluation of dams.

1. INTRODUCTION

The determination of ground motion parameters (PGA, spectrum, time history) has always been a very vital issue for the seismic analysis of high dams. Besides, the spatial variation of the ground motions along canyons should be taken into consideration (Alves and Hall 2006; Wang et al. 2013). In the current practice of dam engineering, ground motions are determined by using probabilistic or deterministic seismic hazard analysis which is based on empirical attenuation relations. However, these approaches fail to properly handle a specific earthquake event which is composed of physical processes such as source-rupture, wave propagation, and local site effects.

With the development of seismological simulations and predictions, accompanied with the rapid improvement of computer power, adopting a pure numerical earthquake simulation for an engineering site becomes feasible (Graves et al. 2011; Cui et al. 2013;

[1), 4)] Professor
[2)] Ph.D Student
[3)] Graduate Student

Baker et al. 2014). The spectral element method (SEM) is a widely-used approach for the large-scale computation of seismic wave propagation (Komatitsch and Vilotte 1998; Lee et al. 2009; Magnoni et al. 2014; He et al. 2014). By combining the flexibility of the FEM and the precision of the spectral method, it has been proved that five points for one wave length is accurate enough if the 4^{th} order shape function is applied (Komatitsch et al. 1999).

In this paper, the SEM is used to generate broadband earthquake ground motions at dam sites based on the “end-to-end simulation”. The ground motions near Pacoima dam due to the 1994 Northridge earthquake of magnitude 6.7 are first simulated with a large-scale model (56×49×25 km). The simulated ground motions are compared with the records. A dam at Southwestern China is then taken as an example. The ground motion distribution along its canyon is investigated for a hypothetical causative fault.

2. KEY ISSUES FOR GROUND MOTION SIMULATION

Using a pure numerical method for the estimation of ground motion parameters should include the physical processes of source excitation, wave propagation, and local site responses. Therefore, the integrated SEM model for wave field simulation at dam sites contains three key issues: the source model, the wave velocity model, and the topography model.

For the source model, the finite fault source is applied herein and the causative fault plane is divided into a serial of sub-faults (Irikura 1986), each of which is regarded as a double-couple point source. The temporal history of the source excitation is simplified as a triangle or Guassian function.

The medium is depicted by the wave velocity model. To give the detailed spatial distribution of wave velocity and density of the earth, a huge amount of seismological inversions and geological prospecting is needed. Fortunately, the velocity model for Southern California in America is available (Plesch et al., 2011). This is one reason that we take the Northridge earthquake as example to validate the feasibility of the numerical end-to-end simulation

Situated in the mountain area, the ground motions at a dam site are always significantly affected by the ambient topography. Thus the high definition topography for a dam site is indispensable. The publicly shared Digital Elevation Model (DEM) provides the global data with resolution up to 30m, and some local data obtained with LiDAR can even reach 2m (Lee et al. 2009). As a kind of high order finite element method, the SEM is able to handle topography easily. However, there obviously exists a trade-off between the high resolution mesh and the computation cost.

3. NUMERICAL MODEL FOR THE NORTHRIDGE EARTHQUAKE

The magnitude 6.7 Northridge earthquake on Jan 17th 1994 occurred in the densely populated Los Angeles metropolitan area and an abundant number of ground motions were captured by the instruments. For decades many studies have been conducted focusing on rebuilding the wave field with various methods and theories (Hartzell et al., 1996; Graves and Pitarka, 2010). In this paper we are trying to simulate the broadband ground motions using the SEM.

We use the finite fault model inversed by Krishnan et al. (2006) whose parameters are shown in Table 1. And the slip distribution is shown in Fig 1. The integrated velocity model CVM-H (Plesch et al., 2011) for Southern California is used, and the topography is denoted by the 90m resolution DEM. Four stations: JENG (34.3118° N，118.496° W), PACD (34.3335° N，118.396° W), SCS (34.311° N，118.49° W) and SCSE (34.312° N，118.482° W) are selected to validate the model. The SEM model covers a region of 56km×49km×25km with an average mesh size of 125m (see Fig 2). The total degrees of freedom are 6.62 billion and the computation is performed on 144 CPUs for 44 hours.

Table 1 Parameters for the finite fault

parameter	value
fault attitude (strike/dip)	122/40 (degrees)
fault size (length×width)	18×20 (km)
number of sub-faults	42×42

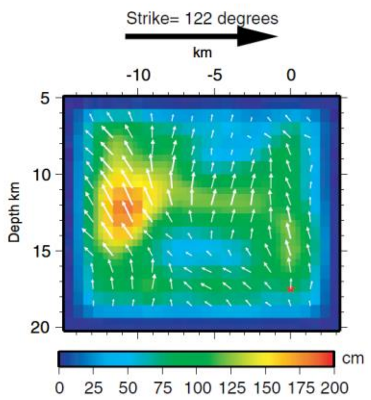


Fig 1 Slip distribution for the finite fault source. The star denotes the epicenter (Krishnan et al. 2006)

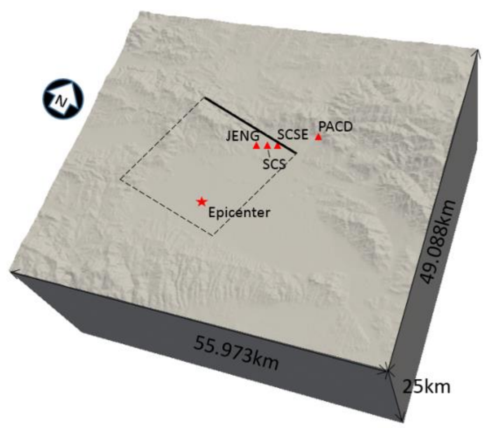


Fig 2 The model scale and the locations of the fault and stations

In Fig 3, the velocity histories for the four stations are compared, where the red lines are the SEM synthetics and the black lines are the records. The length of the histories is 30 seconds. From the comparisons between the synthetics and records, it can be observed that the histories basically match. Comparing the three components, it can be found that the vertical components are worse matched than the horizontal components for all the four stations. This may due to the error of the source inversion. Among the four stations, the consistency of PACD station is the most unsatisfied. This station located at the downstream side of the Pacoima dam and the complicated canyon topography may lead to the discrepancy between the synthetics and records. Complex topography is a significant engineering problem. Multi-scale mesh may be used, namely, high resolution mesh for the near field and coarse mesh for the far field, to deal with this problem in the further investigation.

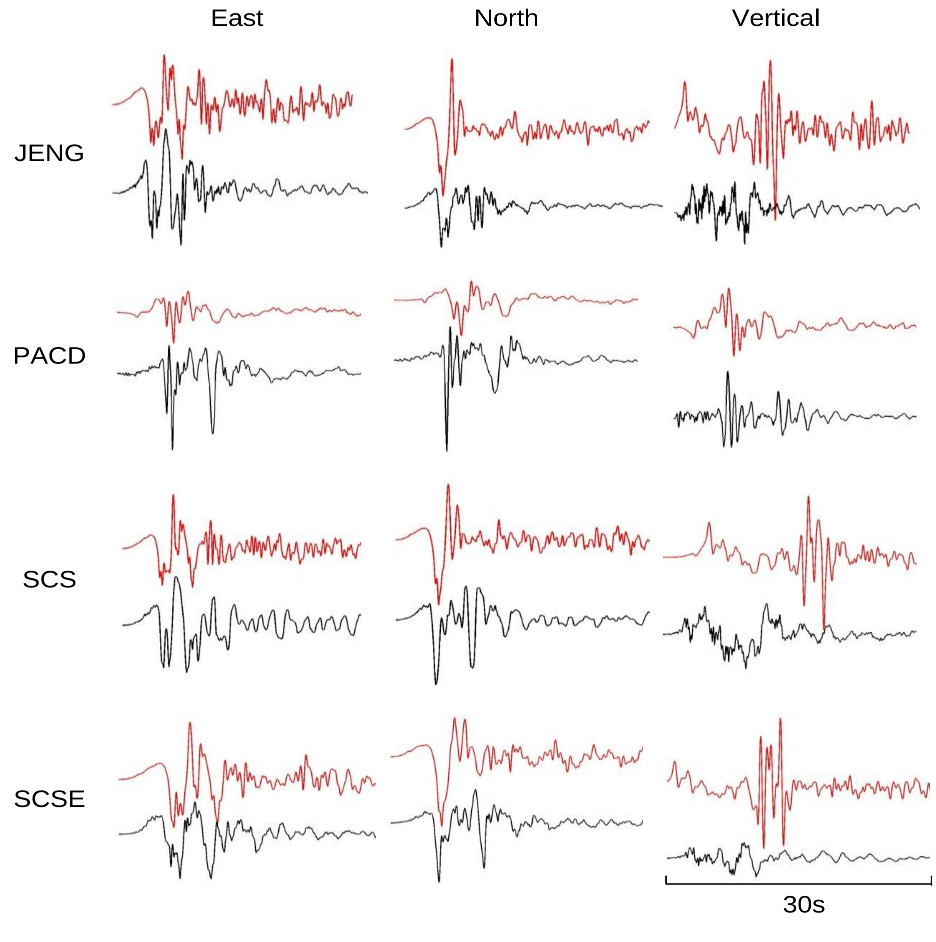


Fig 3 Comparison of velocity histories between synthetics and records

Fig 4 shows the spectra of synthetics and records of the four stations. Similar to the histories, the spectra comparisons also show a better match for horizontal components, and the simulation for station PACD seems not good enough. Excluding the above mentioned deficiencies, the other matches in frequency domain are satisfying. It is worth mentioning that our simulated results contain high frequencies up to 8 Hz (see Fig 4), and these SEM-computed high frequency components are comparable to records, proving that it is feasible to use a pure numerical method to implement high frequency simulations for engineering application.

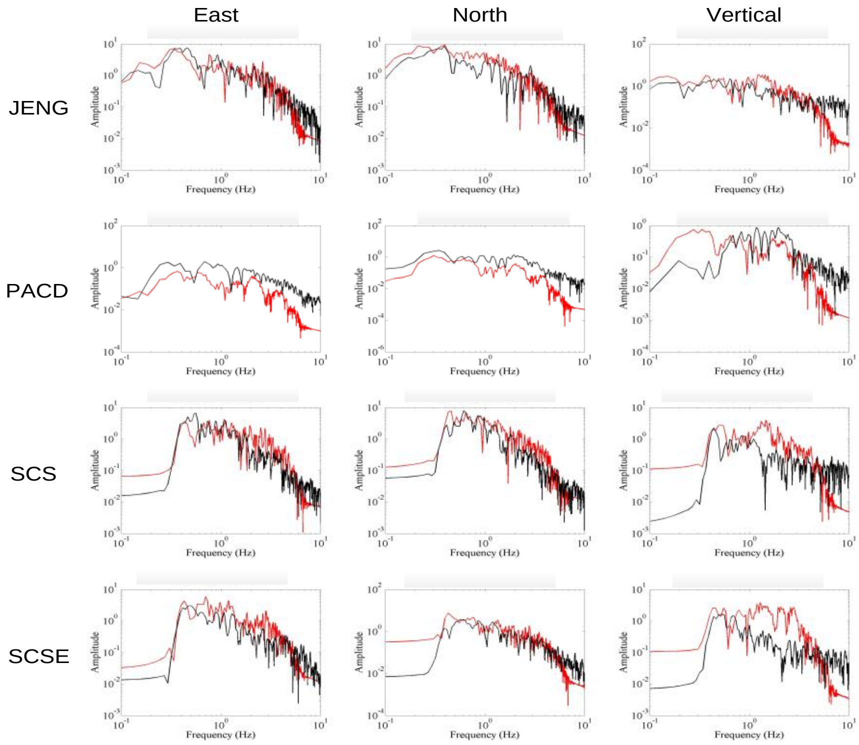
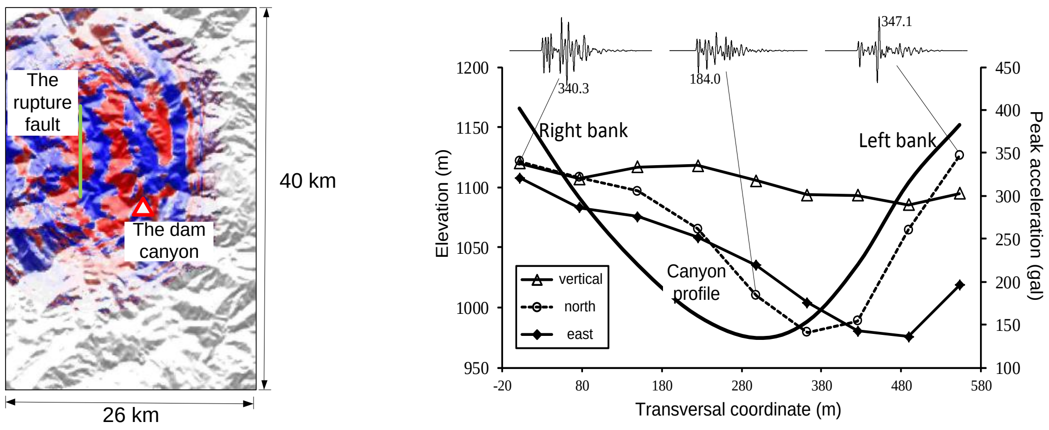


Fig 4 Comparison of velocity spectra between synthetics and records



(a) (b)

Fig 5 The simulation scale and locations of the source and the site(a) and the distribution of the PGA of three components along the canyon(b)

4. INVESTIGATION OF THE SPATIALLY VARIED GROUND MOTIONS AT CANYONS

In this section, we take an arch dam, situated only 5km far away from a seismogenic fault, in Southwestern China as an example. The spatially varied ground motions along the dam canyon are investigated. A hypothetic causative fault (strike-slip mechanism with the size of 10km×9km) and the corresponding magnitude are set to study the spatial non-uniform ground motions, as shown in Fig 5(a). The three component ground motions due to an Mw 6.0 event are demonstrated in Fig 5(b). It could be concluded that the spatial distribution of ground motions is not uniform because of the topographic effects. In addition, three components may differ from each other in the distribution form. The horizontal components approximately vary as the shape of the canyon while the vertical component almost keeps the same along the canyon.

5. CONCLUSIONS AND REMARKS

With the development of seismological theories and methods as well as the rapid growing capacity of computers, the large-scale deterministic numerical earthquake simulation will get widely used for engineering designs. The SEM model used in this paper could offer dam engineers the ground motions containing the source mechanism, the propagation and local site effects, showing an advantage over the traditional approaches such as the conventional PSHA. Based on the analyses of two examples, the following conclusions are drawn:

(1) The SEM may provide results with sufficient accuracy for certain sites even at high frequencies (up to 8 Hz);

(2) The ground motions along canyons are significantly varied, which should be considered in the earthquake-resistant design and safety evaluation of dams

However, it should be noted that the analysis results are highly depended on the precisions of the models (especially source model and velocity model). Therefore this method is only successfully used in the area where the models are accessible (e.g., Southern California, US). Another problem restricts the application of the SEM on engineering design is the coupling of multi-scale. The regional seismological size generally is a few to dozens of kilometers but the dam size is only hundreds of meters. We are working on the transition from coarse mesh to fine mesh in order to solve this problem.

ACKNOWLEDGEMENTS

This research is financially supported by the National Natural Science Foundation of China (Nos. 51179093 and 91215301), and the Specialized Research Fund for the Doctoral Program of Higher Education (No. 20130002110032). The authors express their sincerest gratitude for the support.

REFERENCES

Alves, S. W., Hall, J. F. (2006), "Generation of spatially nonuniform ground motion for nonlinear analysis of a concrete arch dam," *Earthq Eng Struct Dyn*, **35**(11), 1339-1357.

Baker, J. W., Luco, N., Abrahamson, N. A., et al. (2014), "Engineering uses of physics-based ground motion simulations," Proc. 10th National Conference in Earthquake Engineering, Earthquake Engineering Research Institute, Anchorage, Alaska.

Cui, Y., Poyraz, E., Olsen, K. B., et al. (2013), "Physics-based seismic hazard analysis on petascale heterogeneous supercomputers," Procs. Supercomputing Conference, Denver.

Graves, R. W., Pitarka, A., (2010), "Broadband ground motion simulation using a hybrid approach," *Bull Seismol Soc Am*, **100**(5A), 2095–123.

Graves, R. W., Callaghan, S., Deelman, E., et al. (2011), "CyberShake: A physics-based seismic hazard calculations for southern California s," *Pure Appl Geophys*, **168**(3-4), 367-381.

Hartzell, S., P.C. Liu and C. Mendoza, (1996) "The 1994 Northridge, California, earthquake: Investigation of rupture velocity, risetime, and high-frequency radiation," *Journal of Geophysical Research-Solid Earth*, **101**(B9), 20091-20108.

He, C. H., Wang, J. T., Zhang, C. H., et al. (2014), "Simulation of broadband seismic ground motions at dam canyons by using a deterministic numerical approach," *Soil Dyn Earthq Eng*, doi:10.1016/j.soildyn.2014.12.004.

Irikura, K. (1986), "Prediction of strong acceleration motion using empirical Green's function," Proc. 7th Japan Earthq Eng Symp, Tokyo.

Komatitsch, D., Vilotte, J. P. (1998), "The spectral element method: an efficient tool to simulate the seismic response of 2D and 3D geological structures," *Bull Seismol Soc Am*, **88**(2), 368–392.

Komatitsch, D., Vilotte, J. P. Vai, R. et al. (1999), "The spectral element method for elastic wave equations-application to 2-D and 3-D seismic problems," *Int J Numer Methods Eng*, **45**, 1139-1164.

Krishnan, S., Ji, C., Komatitsch, D. et al. (2006), "Case studies of damage to tall steel moment-frame buildings in Southern California during large San Andreas earthquakes," *Bull Seismol Soc Am*, **96**(4), 1523–37.

Lee, S. J., Chan, Y. C., Komatitsch, D., et al. (2009). “Effects of realistic surface topography on seismic ground motion in the Yangminshan region of Taiwan based upon the spectral-element method and LiDAR DTM,” *Bull Seismol Soc Am*, **99**(2A), 681–693.

Magnoni, F., Casarotti, E., Michelini, A.,et al. (2014), “Spectral-element simulations of seismic waves generated by the 2009 L'Aquila earthquake,” *Bull Seismol Soc Am*, **104**(1), 73-94.

Plesch, A., Tape, C., Graves, R. et al. (2011), “Updates for the CVM-H including new representations of the offshore Santa Maria and San Bernardino basin and a new Moho surface,” Southern California Earthquake Center Annual Meeting, Proceedings and Abstracts, vol. 21.

Wang, J. T., Lv, D. D., Jin, F., et al. (2013), “Earthquake damage analysis of arch dams considering dam-water-foundation interaction,” *Soil Dyn Earthq Eng*, 49, 64-74.