16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N°3311

Registration Code: S-A1441941363

LARGE-SCALE WAVE PROPAGATION SIMULATION FROM FAULT RUPTURE TO DAM STRUCTURES

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Abstract

Determination of ground motion is a key issue for seismic design of new dams and safety evaluation of existing dams. In the current practice of dam engineering, the parameters of ground motion, including peak ground simulation and spectrum, at a given dam site are usually determined based on attenuation relationships. This paper proposes a "rupture-dam" approach to evaluate the seismic response of dams, in which ground motion is synthesized based on large-scale wave propagation simulation from fault rupture to canyons instead of attenuation relationships. Firstly, the ground motions along the canyon are generated by numerically computing the seismic waves radiated from source rupture via propagation path to local site. Subsequently, the seismic responses of dams are analyzed to the generated ground motions. This approach may offer ground motion for a specific dam, which takes into account the effects of source mechanism, propagation path, and local site on the seismic response of dams. Based on this concept, we integrate multifarious models to implement the rupture-dam simulation: the source model and velocity model are adopted from achievements in seismology; the realistic topography is represented by NASA's global digital elevation model; and the wave equations of motion are solved by the modified spectral element method code SPECFEM3D. With these models combined, the ground motions containing source-propagation-site effect are provided as the input of high dams, and the dynamic analysis of dam-reservoir-foundation system is conducted using the finite element model. The 210-m Dagangshan dam in Southwest China is analyzed as an example. The results show that the dam responses are affected by both the directivity and the spatial varying of ground motion at the canyon. These factors should be rationally considered in the seismic safety evaluation of dams.

Keywords: Concrete dam; ground motion; seismic response; source rupture; wave propagation

1. Introduction

After proposed by Cornell in 1968 [1], probability seismic hazard analysis (PSHA) is widely used for the seismic safety evaluation for engineering projects, in which the ground motion is obtained by attenuation relationships. However, the ground motion predicted by attenuation relationship may bring in bias when applied to a specified site. This bias sometimes is unacceptable for vital key projects (such as nuclear power plants and huge reservoirs). The most dangerous seismogenic fault to a site is usually able to be spotted from probability de-aggregation and geological survey. Therefore, a deterministic approach performed from the source to the site considering the physical mechanism is a natural alternative. For instance, John Hall *et al* [2, 3] studied the steel frame response to the shaking caused by a near field finite fault with a hybrid approach. As the developing of computational seismology, large-scale numerical simulation provides us another option, namely, pure numerical methods. Krishnan *et al* [4] accomplished an "end-to-end" simulation of the frame response in the 1994 Northridge earthquake considering the finite rupture based on the spectral element method (SEM). However, their model took no account of the high resolution topography, which plays an important role in dynamic response of arch dams, and the frequency simulated is relatively low (~1 Hz).

Arch dams are generally located in steep canyons, where the seismic wave field is dramatically influenced by topography amplification [5]. Studies on the dynamic responses of arch dams subject to spatially-varying ground motions reveal that the dams behave differently compared to uniform seismic excitations [6]. However, the realistic non-uniform ground motion records at dam canyons are rare. Additionally, ground motion records are highly field-characterized. Therefore, determination of ground motion at site is a big challenging in seismic design of new dams and safety evaluation of existing dams.

Aiming at solving this problem, this paper proposes a "rupture-dam" approach to evaluate the seismic response of dams. The ground motion for a specific dam is determine by deterministically simulating the seismic wave propagation from source via medium to site using a numerical model, as shown in Fig. 1. By this way, the effects of source mechanism, propagation path, and local site on the seismic response of dams are taken into account.

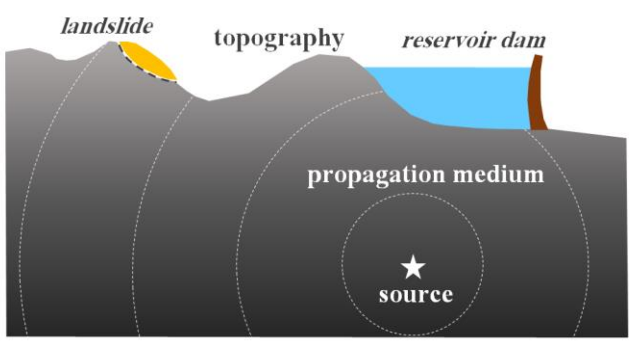


Fig. 1 – Schematic map for rupture-dam simulation

2. Simulation model of ground motion

In this paper, the 210-m Dagangshan dam in Southwest China is taken as an example. The closest active fault is only 4.5 km away from the dam site, and it has an upper bound magnitude of M_W 7.4. Therfore, the horizontal design peak ground acceleration is as high as 558 cm/s^2 for the dam.

2.1 Source rupture

Following Wells and Coppersmiths [7], the relationship between rupture area and magnitude may be expressed as

$$\log(RA) = -3.42 + 0.90M_{\mathrm{w}} \quad (1)$$

where *RA* denotes the rupture area; and M_{w} is the moment magnitude.

According to Eq. (1), the rupture area is obtained as 60 km in length and 28 km in width. The rupture is divided into 1 km×1 km sub-faults. It is assumed that the finite fault rupture progress starts from the centroid as shown in Fig. 2, and the slip weight value is inversely proportional to hypocenter distance *R*. Correspondingly, the rise time is positively related to the slip. To avoid the fictitious frequency introduced by the discrete triggering of the continuous fault plane, the slip and rise time values are disturbed with a random variable, as shown in Fig. 3.

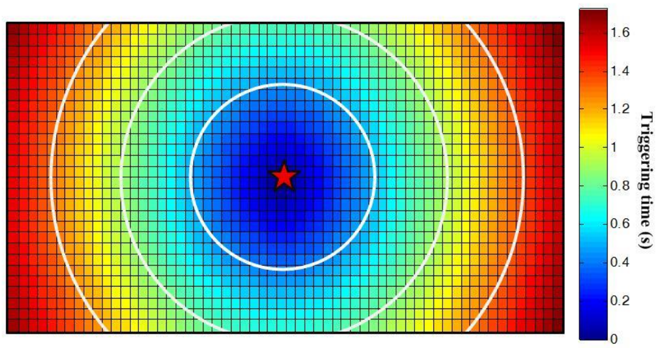


Fig. 2 – Rupture progress on the fault plane

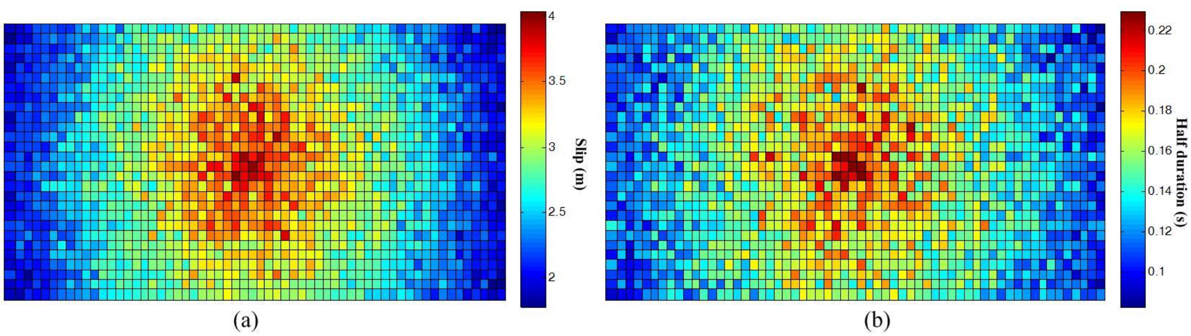


Fig. 3 – Distribution of (a) slip and (b) rise time of sub-faults on the fault plane

2.2 Propagation media

Up to date there still remains a lack of high resolution 3D velocity model for the Sichuan area in China. Hence, the 1D velocity structure is adopted herein by integrating the inversion results of the eastern margin of the Tibet Plateou presented by Wang *et al* [8] and Xu *et al* [9], repectively. The velocity and density of each layer in the model is given in Table 1.

Table 1 – Integrated velocity structure of the study area [8, 9]

Depth(km/s)	**Density(kg/m^3)**	**P-wave velocity(km/s)**	**S-wave velocity(km/s)**
0-2	2490	5.9	3.0
2-13	2640	5.9	3.2
13-15	2720	6.0	3.2

2.3 Surface topography

The topography is modeled with the online-public digital elevation model (DEM) database with the resolution up to 30m. For the Dagangshan dam canyon with a 600-m width, the 30-meter mesh is enough for expressing the canyon shape.

2.4 Solution model

The SEM [10, 11] is selected for the wave simulation due to its advantages over the others such as finite element and difference method: (1) the high flexibility for topography or medium interfaces; and (2) the high accuracy and efficiency. The open-source SEM program SPECFEM3D is used.

Fig. 4 shows the numerical solution model used in this paper and 9 receivers deployed along the dam base. From the profile of the fault, it can be seen that the whole rupture is discretized into an array of point sources and each point source represents a sub-fault. Both of the velocity structure and surface topography are included. Summaries of the global model information are as follows: 288×240×40 spectral elements are distributed on 120 processors; the total DOFs add up to 0.54 billion; and the whole computation takes 2.7 hours to finish 20,000 time steps.

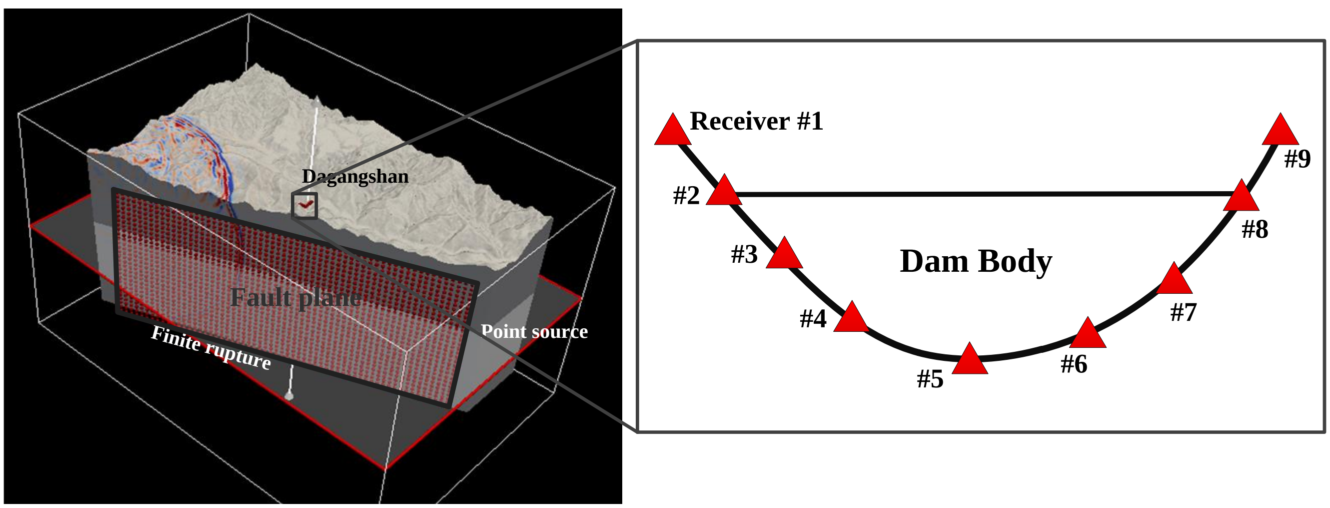


Fig. 4 – Three dimensional numerical model and the receivers deployed in the dam canyon

3. Simulation results of ground motions

Upon the numerical simulation, the motion histories of all the nodes in the SEM model are computed in three components. The north components of the 9 receivers deployed along the canyon are plotted in Fig. 5. The horizontal component acceleration histories at the bottom of the dam canyon (Receiver #5) are presented in Fig. 6. The peak value of the east-west (cross-stream) and north-south (stream) acceleration components are 390 cm/s ^{2} and 593 cm/s ^{2}, respectively. This indicates that ground motions vary along different directions. This phenomenon is conventionally not taken into consideration in earthquake-resistant design, which may be have a significant effect on the seismic response of high dams.

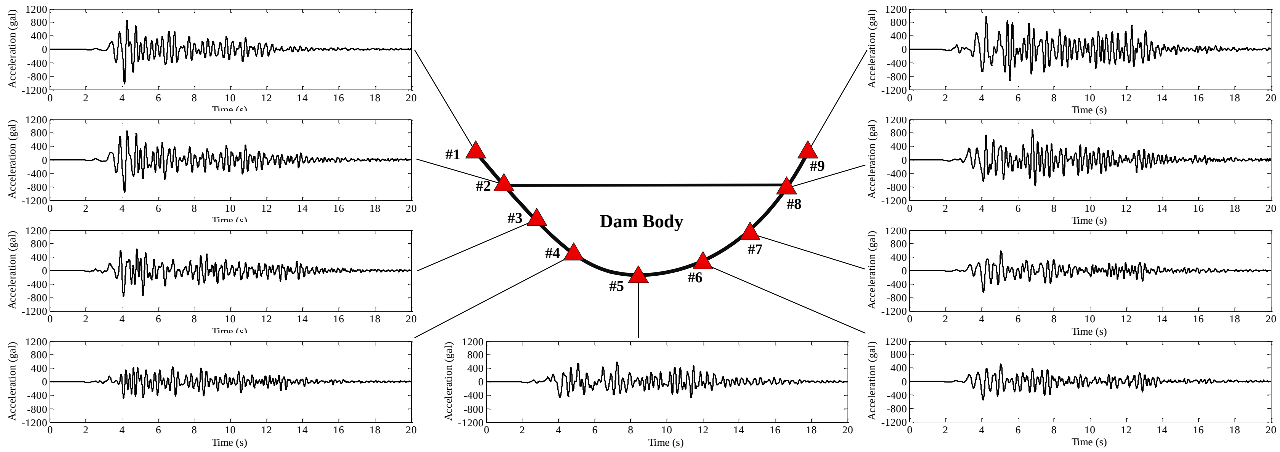


Fig. 5 – North components of the 9 receivers at the dam canyon

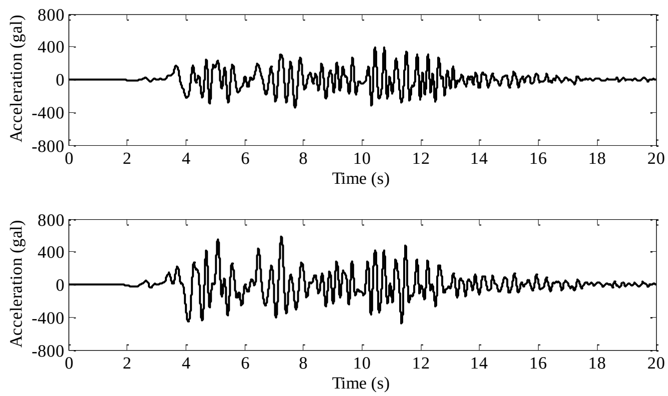


Fig. 6 – Acceleration histories of east component (upper) and north component (lower) at Receiver #5

The peak values of all the 9 histories in the north direction are plotted in Fig. 7 (the circles connected by the dashed line). Based on these 9 histories, accelerations at the other points on the dam base surface are obtained (as the red solid line shows in Fig. 7) through a Lagrange interpolation approach. The distribution of the acceleration presents a pattern of lower amplitudes in the canyon while larger at the ridges, which is consistent with the general observation results in seismology.

4. Ground motions input to the dam structure

Once the ground motion field at the dam canyon is generated by the SEM, the seismic response of the dam can be analyzed by the finite element method. Two ways may be used to achieve the earthquake input in the finite element analysis [12]. One way is that the seismic ground motion is input to the model through the nodes on the truncated foundation boundaries. The other way is to directly input free-field ground motion at the dam-foundation interface.

Herein, the second way is adopted. As illustrated in Fig. 8, the free-field is input at the dam-foundation interface, in which (a) determines the free-field response via truncated boundary input without the dam structure; (b) derives the equivalent forces on the dam-foundation interface by specifying the boundary condition at the dam-foundation interface; and (c) analyze the dam responses due to the forces obtained in (b). It should be noted that for both steps (b) and (c), the boundary conditions Γ should be the same.

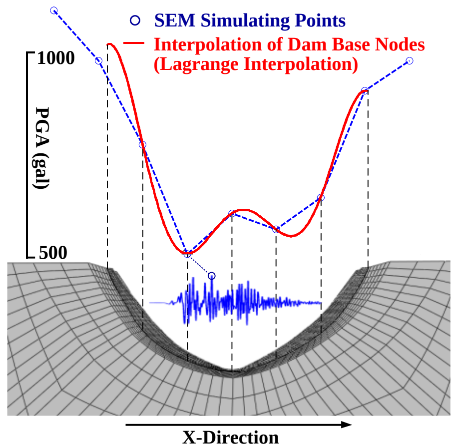


Fig. 7 – Lagrange interpolation of the dam base ground motions

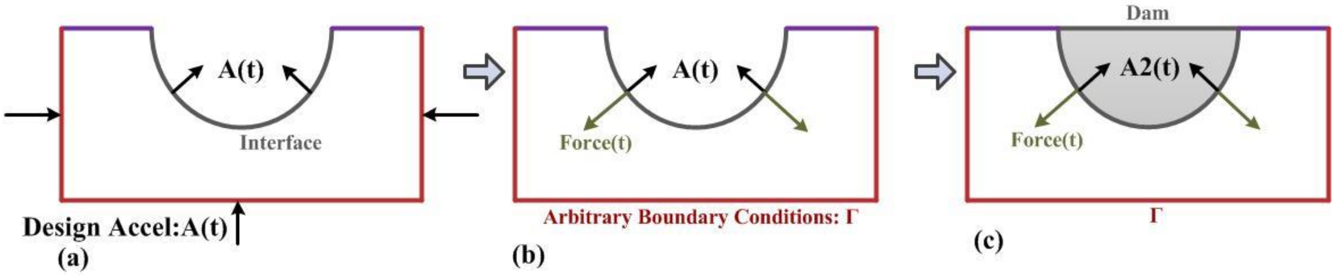


Fig. 8 –Procedure for the free-field input at the dam-foundation interface

5. Dynamic response of dam

The finite element model (Fig. 9) is made up of 26,265 dam elements and 10,885 found elements (all 8-node brick element). Loads, including gravity, water pressure, sediment pressure, and horizontal earthquake, are taken into account.

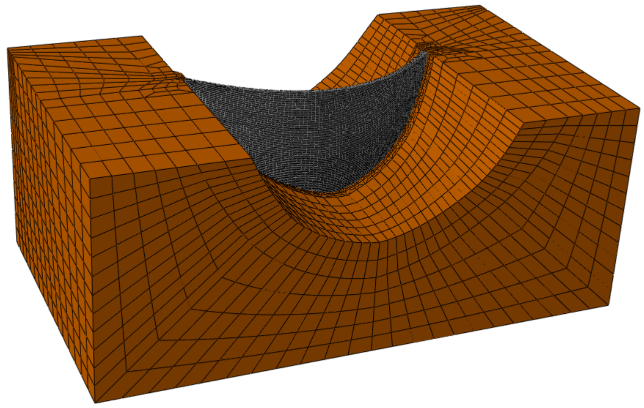
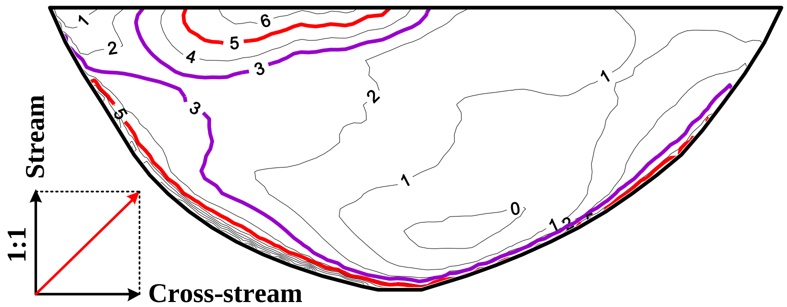


Fig. 9 – Finite element model of the Dagangshan arch dam

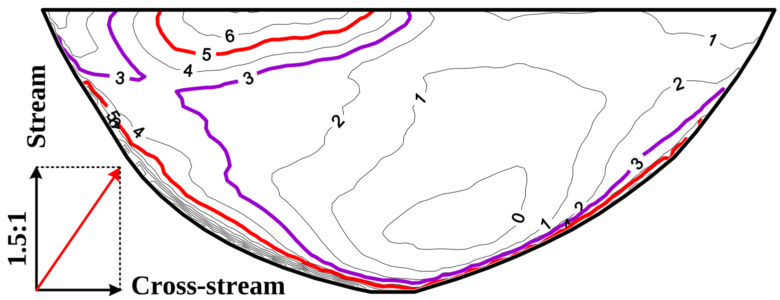
5.1 Effect of directivity

The ground motions calculated by SEM shown in Fig. 5 provide us an access to investigate the dam responses to realistic ground motion excitation. In this section, the spatial non-uniform ground motion effects are ignored and the effects of discrepant component amplitudes are studied separately. As given in Section 3, the ratio between the stream and cross-stream components is approximately 1.5 (593/390). The histories at Receiver #5 are used as spatially uniform input at the dam-foundation interface as showed in Fig. 8. To make a comparison, another case is set up with the same horizontal magnitude, and but the ratio is adjusted to be 1.0 (502/502).

The maximum principal stress distributions are presented in Fig. 10 for two cases. From Fig. 10, it can be observed that the overall distribution patterns are close for the two cases, presenting higher stress at left and lower at the right of the upstream face, and the maximum value appears at the center-left of the dam crest. However, the peak stress is slightly larger when the stream component peak acceleration comes as 1.5 times as the cross-stream one.



(a)



(b)

Fig. 10 – Stress distributions of upstream face corresponding to stream/cross-stream acceleration ratio of (a)1.0 (hypothetic) and (b)1.5 (actual) (Unit: MPa)

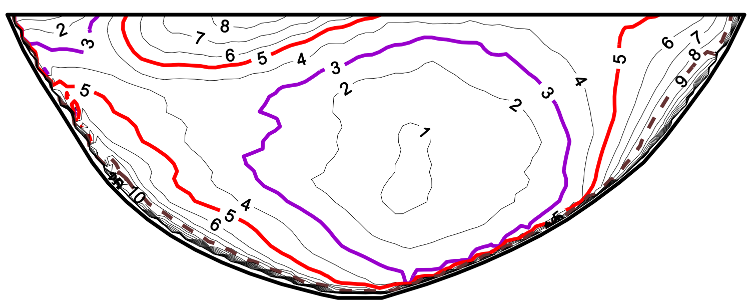


Fig. 11 – Stress distribution subjected to spatially non-uniform input (Unit: MPa)

5.2 Effect of spatially-varying excitation

Based on the original accelerations achieved by SEM simulation, the spatially-varying ground motions along the dam canyon shown in Fig. 7 are further taken into account. The stress results to non-uniform input are given in Fig. 11. Comparison of Fig. 11 with Fig. 10(b) shows that the stress distribution is similar for the uniform and non-uniform ground motions. However, the non-uniform ground motion results in a larger peak stress. The differential is about 2 MPa compared to the uniform ground motion. In addition, within the area close to the dam-foundation interface, the stress increases caused by non-uniform ground motions are more apparent. The principal tensile stress at the right abutment reaches 9 MPa, whereas it is below 5 MPa when the uniform input is applied.

6. Conclusions

This paper proposes a "rupture-dam" approach, which combines the seismic wave simulation by SEM and the dynamic analysis of arch dams by FEM, and successfully implements the computation from source rupture to dam response. In the proposed model, the rupture process of the causative fault is simulated, and both the velocity structure of propagation path and realistic topography are taken into consideration. Thus the effects of these factors on the dynamic response of the arch dam can be investigated comprehensively.

Taking the Dagangshan dam as an example, the impacts of directivity and spatial varying of ground motions are studied based on the proposed model. Two conclusions are drawn:

(1) The discrepancy between the component amplitudes due to directivity affects the dam responses. When the stream acceleration is larger than the cross-stream one, the dynamic response of the dam is more severe than that under identical horizontal seismic loads.

(2) The spatial varying of ground motion along the dam-foundation interface has a significant influence on the seismic response of the Dagangshan dam. When spatially non-uniform ground motions are applied to the dam-foundation interface along the canyon, the peak stress value can be 2 MPa higher.

The approach proposed in this paper may overcome the shortcoming of conventional attenuation relationships, in which the site characteristics are difficulty to incorporated. It is a promising method for maximum credible earthquake analysis of key dams. However, the accuracy of the numerical simulation of seismic waves heavily relies on the models describing the source and propagation path. Therefore, more efforts are needed from researches in both seismological and engineering fields.

7. Acknowledgements

This research is financially supported by the National Natural Science Foundation of China (No. 51639006), the Specialized Research Fund for the Doctoral Program of Higher Education (No. 20130002110032), and Tsinghua University Initiative Scientific Research Program (No. 20131089285). The authors express their sincerest gratitude for the support.

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