Numerical Modeling of 3D Seismic Wave Propagation around Yogyakarta, the Southern Part of Central Java, Indonesia, Using Spectral-Element Method on MPI-GPU Cluster

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Abstract. A strong tectonic earthquake with a magnitude of 5.9 Richter scale has been occurred in Yogyakarta and Central Java on May 26, 2006. The earthquake has caused severe damage in Yogyakarta and the southern part of Central Java, Indonesia. The understanding of seismic response of earthquake among ground shaking and the level of building damage is important. We present numerical modeling of 3D seismic wave propagation around Yogyakarta and the southern part of Central Java using spectral-element method on MPI-GPU (Graphics Processing Unit) computer cluster to observe its seismic response due to the earthquake. The homogeneous 3D realistic model is generated with detailed topography surface. The influences of free surface topography and layer discontinuity of the 3D model among the seismic response are observed. The seismic wave field is discretized using spectral-element method. The spectral-element method is solved on a mesh of hexahedral elements that is adapted to the free surface topography and the internal discontinuity of the model. To increase the data processing capabilities, the simulation is performed on a GPU cluster with implementation of MPI (Message Passing Interface).

1. Introduction
On 26 May 2006 at 22:54 UTC, the Yogyakarta earthquake occurred with moment magnitude $M_w$ 6.4 [1]. The earthquake has caused severe damage to the densely populated area. About 6,000 people were killed, 50,000 were injured, and between 0.5 and 1 million homeless. The total loss was estimated at over 3 billion U.S. dollars [2]. Due to its huge damages on human casualties, buildings and materials, the active fault system must be well investigated and characterized to prevent future seismic hazards.

In recent years, numerical modeling using GPU computing have been successfully used to simulate the seismic wave propagation, such as study of fluid saturated porous media [3, 4], high-order finite-difference simulation [5], and finite-difference numerical modeling in realistic topography [6]. However, numerical modeling of 3D seismic wave propagation in Yogyakarta basin has not yet been available. For Yogyakarta basin, it poses several challenges. The notable topography around the city makes the issue more difficult. It also covers a large area, so that it needs more data processing power capability.
To accommodate a considerable surface topography, we used the spectral-element method (SEM) to simulate the seismic wave propagation in Yogyakarta basin. It used a weak formulation for solving elastic wave equation and naturally incorporates free surface conditions. The method has been successfully applied in many areas of seismology [7, 8].

In this study, we present numerical modeling of 3D seismic wave propagation in Yogyakarta basin to observe its seismic response due to varying surface topography and its implication on earthquake hazards.

2. 3D Model and Mesh Implementation
The model we used for simulation covers most of the southern part of Central Java with dimension of 59.3 km × 59.4 km horizontally and from +0.96 to -30 km vertically. It spans from -8.15° to -7.61° latitude and from 110.15° to 110.68° longitude (Figure 1). Surface topography was imported using NASA Shuttle Radar Topographic Mission (SRTM) with an original resolution of 3 arcsec (~90 m).

For meshing purposes, we converted the geographic coordinate system into the UTM (Universal Transverse Mercator) coordinate system. Our model lies in the 49S UTM projection zone.

To incorporate high-resolution topography, we used mesh doubling as a function of depth [9]. Figure 2 shows mesh implementation of our model. Three consecutive mesh doublings facilitate in an increase in element size with depth. We also added three additional flat interfaces, which correspond to the three mesh doubling layers. We used this technique in order to accommodate a finer mesh near topography and decrease the number of elements in the model which lead to a reduction of the computational burden. The first interface was added at the depth of 750 m to facilitate a finer mesh near the surface. Note that resolution of the mesh in the surface is not controlled by shear-wave, but by surface-wave because surface-wave speed is lower than shear-wave speed. The second interface was added at the depth of 1750 m to facilitate a transition layer between two mesh doublings. The third interface was then added at the depth 3750 m to facilitate the third double layer. It has constant element size to the bottom of the model which could significantly decrease the number of elements in the model.

We used 3D homogeneous wave velocity model based on the one-dimensional (1-D) spherically symmetric Earth models [10] as a preliminary study. The compressional- and shear-wave speeds is 5800 m/s and 3200 m/s respectively. The density in the model is 2600 kg/m³.

Figure 1. Topography map of Yogyakarta basin. It spans from -8.15° to -7.61° latitude and from 110.15° to 110.68° longitude. Surface topography is imported using NASA Shuttle Radar Topographic Mission (SRTM) with an original resolution of 3 arcsec (~90 m).
3. Simulation of the 26 May 2006 Yogyakarta Earthquake ($M_w 6.4$)

The focal mechanism and properties of the source were obtained from The Harvard Centroid Moment Tensor (CMT) solution with $M_w 6.4$. The epicenter of the earthquake is located at $-8.03^\circ$ latitude and $110.54^\circ$ longitude and the hypocenter is 21.7 km. The 3D moment-tensor inversion indicated the fault striking $323.11^\circ$, dipping $76.62^\circ$, and raking $-176.02^\circ$.

We used the SPECFEM3D software package [11] and decomposed the model into 213696 hexahedral elements. In each spectral element we used the polynomial degree of $N = 4$, and thus each element contains $(N + 1)^3 = 125$ Gauss-Lobatto-Legendre (GLL) integration points. Total number of GLL points in the model is 14,124,456. The minimum and maximum distances between Gauss-Lobatto-Legendre integration points in the model are 43.17 m and 991.42 m respectively. We used a Gaussian source time function with a half-duration of 3.7 s, and therefore a maximum frequency is 0.27 Hz. The time step used was $\Delta t = 2$ ms, and we propagated the signal for 30000 time steps, thus total simulation time is 60 s.

The simulation was carried out on a GPU cluster with 4 NVIDIA Quadro K4000 graphics cards and 24 core processors Intel Xeon CPU E5-620 @2.4 GHz using MPI (Message Passing Interface) and CUDA (Compute Unified Device Architecture) at Computational and Seismic Laboratory, Geophysics Sub-Department, Universitas Gadjah Mada.

4. Results and Discussion

Snapshots of the simulation for the norm of all three components of the velocity wave field are displayed in Figures 3. We observed two consecutive wave fields with a strong amplitude travel toward the Yogyakarta basin in the northwest direction at $t = 20$ s (Figure 3d). The mountainous areas in the northwestern part of the model caused the waves to reflect back to the basin. After $t = 30$ s (Figure 3f), some wave fields still trapped and reflected in the basin and travel to the north, northeast and southwest direction follows the basin geometry.
Figure 4 shows resulting synthetic seismograms recorded at the surface located at -7.74° latitude and 110.28° longitude for East (a), North (b), and Vertical (c) component of velocity. All the synthetic waveforms are low-pass filtered with a corner frequency of 1 Hz. The station has a horizontal distance of 43 km from the source.

As a preliminary study, we aim to analyze how varying topography in our model governs the propagation of seismic wave. Although we have accomplished much, there are some limitations in our implementation. For example, mesh implementation on the surface still insufficient to access the full effect of topography. In our future works, we intended to develop our mesh implementation. To increase mesh resolution and access the full effect of topography, we use an unstructured hexahedral meshing technique. We also enlarge the dimension of the model we wish to take into account of possible earthquake and/or seismic damage, and include all currently available relevant seismological information available in our model.

5. Conclusions
We presented the numerical modeling of 3D seismic wave propagation around Yogyakarta using spectral-element method on MPI-GPU cluster. We used a mesh doubling technique to incorporate high-resolution topography and accommodated a finer mesh near the surface. We observed two
consecutive wave fields with a strong amplitude travel toward the basin. Furthermore, the basin and surrounding mountains significantly increase the duration of shaking in the Yogyakarta area.

In our future works, we intend to develop our mesh implementation, enlarge the dimension of the model, and include all currently available relevant seismological information in our model.

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