Simulating Seismic Wave Propagation by Considering Topography and Irregular Boundary between Soil Layers in 3-D Elastic Finite-Difference Modeling in Yogyakarta-Bantul Area, Indonesia

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Abstract

The cities of Yogyakarta and Bantul located in central and southern parts of the Yogyakarta Special Provence, lying in the sedimentary basin that is made up of the young volcanic deposit of Merapi volcano of Quaternary alluvium age. The purpose of this study is to simulate the peak velocity of the strong ground motions in the Yogyakarta- Bantul basin during the 2006 Yogyakarta earthquake using 3D elastic finite-difference method. To analyze seismic wave propagation in geological structures, it is possible to consider various numerical approaches. Among them, FDM model is the dominant method in the modeling of earthquake motion. Moreover, it becomes more important in the seismic exploration and structural modeling. We perform the full elastic wave-field simulations for the Yogyakarta- Bantul basin by using a three-dimensional discontinuous finite-difference method. The Opak River Fault runs NE-SW of the study area and was calculated the striking 0°, dipping 90° with an average rake of 0°. The peak ground velocity map illustrates that significant amplification occurs in the basin. Our study indicates that the complex Yogyakarta- Bantul basin geometry and fairly velocity dominate the amplification of the seismic motion and wave propagation behavior that result in extraordinary strong shaking patterns in the Yogyakarta- Bantul metropolitan regions. Finally, the peak ground velocity (PGV) map will relate to the damage area of the study regions for the future earthquake.

Keywords: 3-D elastic Finite Difference Method, Strong Ground Motion, Yogyakarta-Bantul Basin, peak ground velocity

Introduction

The Yogyakarta- Bantul area is located in the south of the volcanic arc of Java Island, Indonesia. It is only about 30 km far from the Merapi volcano with the elevation of 2911 m above sea level in the north and it is the most active volcano in Indonesia. It is about 10 km from the coast of the Indian Ocean in the south. It is situated at the center of the Yogyakarta Special Province and in the middle part of Yogyakarta depression. This depression is actually a graben, as NE-SW elongated depression zone, which was filled by Merapi volcanic sediments. It is initiated by extrusions of two major volcanic centers; Kulon Progo Mountains and Southern Mountains, during Cenozoic and was formed as a volcano-tectonic depression since Oligo-Miocene or earlier (Karnawati, *et. al.*, 2006). The Yogyakarta Special Province has four major regencies and Yogyakarta area which is located between Latitude 7˚ 24' S - 8˚ 00' S and Longitude 110˚ 001' E - 110˚ 36' E as shown in Fig. 1. The area of Yogyakarta City is 32.5 square kilometers (12.5 square miles), and about 480 square kilometers as the total.

General Geology of the Research Area

The geology of the Yogyakarta- Bantul depression area is influenced by active tectonic activities such as the volcano and subduction of Indian-Australia oceanic plate below the Eurasia plate. To the west, an intensively faulted dome of andesitic breccia and lava flows occurred. Meanwhile, to the east at the Yogyakarta depression area, steep mountains of volcanic rocks as well as limestone with karst landscape are exposed (Karnawati, *et. al*., 2006). Fig. 1 shows the topography of Yogyakarta- Bantul depression area.

Yogyakarta- Bantul depression area is mainly composed of the lithologic units of Pre-Tertiary, Tertiary and Quaternary age. The Pre-Tertiary rocks constitute as the basement and consist of metamorphic rocks, and these units are restrictedly cropped out in the north of Southern Mountains region. In Yogyakarta- Bantul depression area, the most dominant rock units are volcanic rocks and the young volcanic deposits which are derivatives of the Merapi volcano in the north (McDonald, 1984; and Rahardjo, *et. al*., 1995). The different lithologic units were resulted by the Tertiary Orogeny in this area. The rocks exposed in the western part of the province range in age from Middle Eocene to Pliocene while those in the Eastern part from Oligocene to Pliocene.

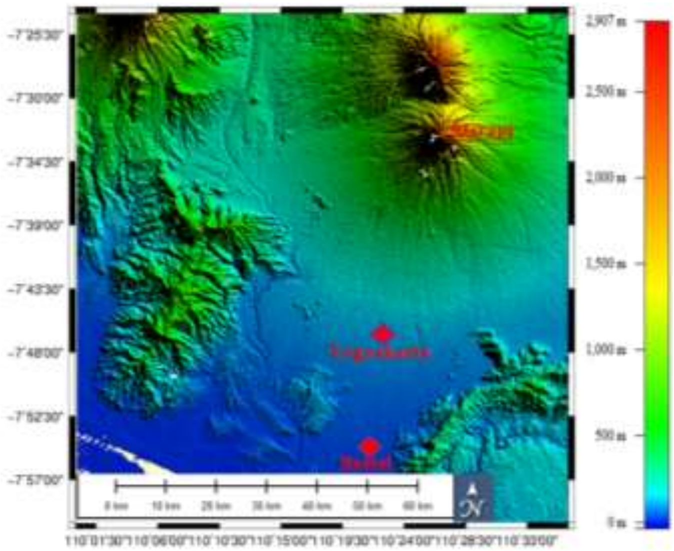

Fig. 1. Location map of the research area illustrating topography of Yogyakarta-Bantul depression area

Seismicity of Java Island

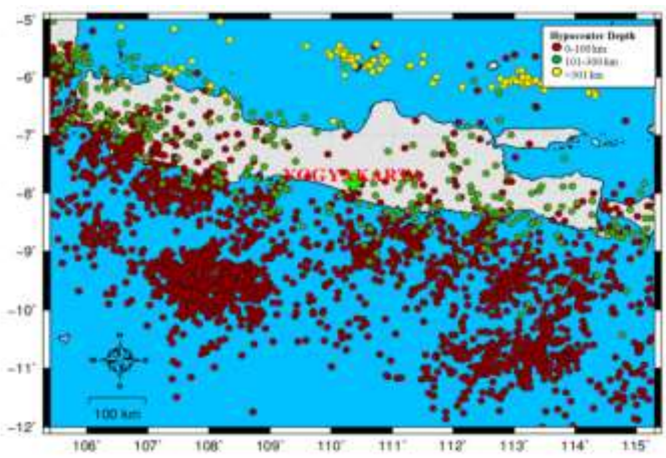

Fig. 2. Historical seismicity in Java Island (Mw>4.0 and 1840-2018)

Earthquake sources can be identified from records of historical earthquakes and previous seismicity. Historical accounts of ground-shaking effects can be used to confirm the occurrence of past earthquakes and to estimate their geographic distributions of intensity. When sufficient data are available, the maximum intensity can be determined and used to estimate the location of the earthquake epicenter and the magnitude of the event. Although the accuracy of locations determined in this way depends strongly on population density and the rate of earthquake recurrence, a geographic pattern of epicenters providing strong evidence for the existence of earthquake source zones. Since historical records are dated, they can also be used to evaluate the rate of recurrence of earthquakes in particular area. The seismicity of Java Island shows in Fig. 2.

Theory and Research Analysis

Performance of the uniform-grid finite difference operators

Free-surface boundary conditions often require careful consideration in finite-difference schemes because of concerns related to numerical stability and accuracy of the computed response (Alterman and Rotenberg, 1969; Ilan, *et. al*., 1975; Bayliss, *et. al*., 1986; Vidale, *et. al*., 1986; Kosloff, *et. al*., 1990; Zahradnik, *et. al*., 1993). It is described the techniques for implementing a plannar free-surface boundary for 3D problems utilizing fourth-order (or higher) spatial difference operators with the staggered-grid scheme. It is presented by a moment-tensor source formulation that uses stress components instead of particle velocity components at the source (Coutant, *et. al*., 1995). Compared to the velocity approach (Graves, 1996), the stress approach is simpler and easy to implement in the grid with variable spacing.

To assess the accuracy of the proposed finite-difference operators, it is implemented into the finite-difference scheme and performed several calculations to model the wave propagation in laterally homogeneous media. In the 3-D FDM model, the velocity seismograms are calculated for a double-couple point source with a focal mechanism of strike = 0°, dip = 90°, rake = 0°, and a bell-shaped source-time function $f(t) = [1 - \cos(2\pi t/T_0)]/T_0$ with a duration $T_0 = 1.58$ sec as shown in Fig. 3. The strike angle is measured with respect to the y direction in the 3D grid.

$$
\begin{array}{c}
0 : t < 0 \\
f^{s}(t) = \{1 - \cos(2\pi t/T_0)]/T_0 : 0 \le t \le T_0 \\
0 : t > T_0
\end{array}
\qquad (1)
$$

According to the study area model, the length, the width and the height of the research area are 60 km, 30 km and 21 km respectively. The uniform grid spacing of dx and dy are 0.5 km. The absorbing boundary of the study area is 20 km. Moreover, both of the length and width of the Opak River Fault are 32 km and 15 km. Observation at 17 stations on the free surface of the Yogyakarta area which includes the five regencies: Bantul, Gunungkidul, Yogyakarta, Kulonprgo and Sleman.

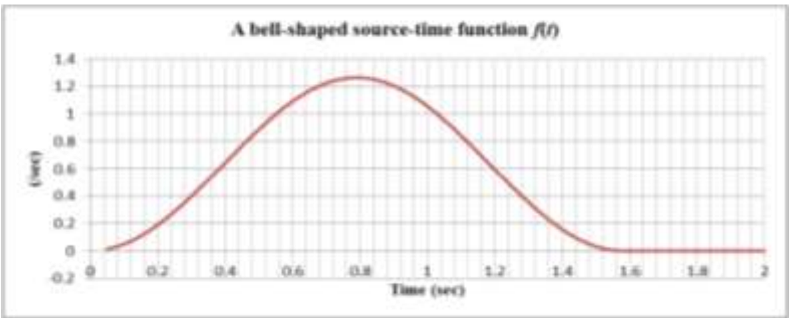

Fig. 3. A bell-shaped source-time function (T_0 = 1.58 sec)

The velocity seismograms are calculated for Vx, Vy and Vz components with the uniform-grid FD technique. Note that the FD calculations with uniform-grid spacing give essentially identical results. Fig. (4) shows the relationship of the shear wave velocity (Vs) and Damping ratio or earthquake value (Q). Moreover, Fig. 5 shows the study area model with Opak River Fault Line to simulate the strong ground motion by utilizing the 3-D elastic FD method. The parameters of the 3-layers model, the parameters of the focal mechanism and the simulation parameters in Table 1, 2 and 3. Observations are carried out at 17 sites in the study area, along the Opak River Fault in the high populated Yogyakarta-Bantul area which is covered by the young volcanic soft sediments. Bantul region is actually the highest damage area when the 27 May, 2006 Yogyakarta Earthquake (Mw 6.3) happened. Fig. 6 (one example for 17 stations) displays the 3-components synthetic velocity seismograms calculated by the 3D-FD method with uniform grid spacing.

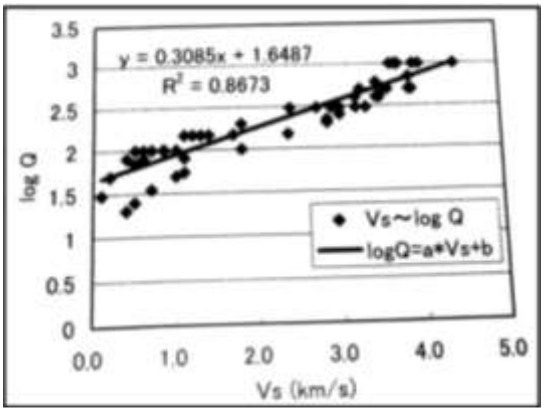

Fig. 4. The relationship of the shear wave velocity (Vs) and Damping ratio or earthquake value (Q) (Kiyono, 2005).

Table 1. The parameters of the 3-layers model

No.	Layer	ρ value	S-wave velocity (β)	P-wave velocity (α)	Q value (f_0 = 1.0 Hz)
1.	1st Layer	1.8 (g/cm^3)	360 (m/sec)	720 (m/sec)	18
2.	2nd Layer	2.0 (g/cm^3)	700 (m/sec)	1400 (m/sec)	35
3.	3rd Layer	2.3 (g/cm^3)	1500 (m/sec)	2400 (m/sec)	75

Table 2. The parameters of the focal mechanism

No.	Focal mechanisms	Parameter
1.	Strike (φ_s)	0°
2.	Dip (δ =90)	90°
3.	Rake (λ_s)	0°
4.	Source time function (T_0)	1.58 sec
5.	Seismic Moment (M_0)	1.79 x 10^{19} dyne.cm

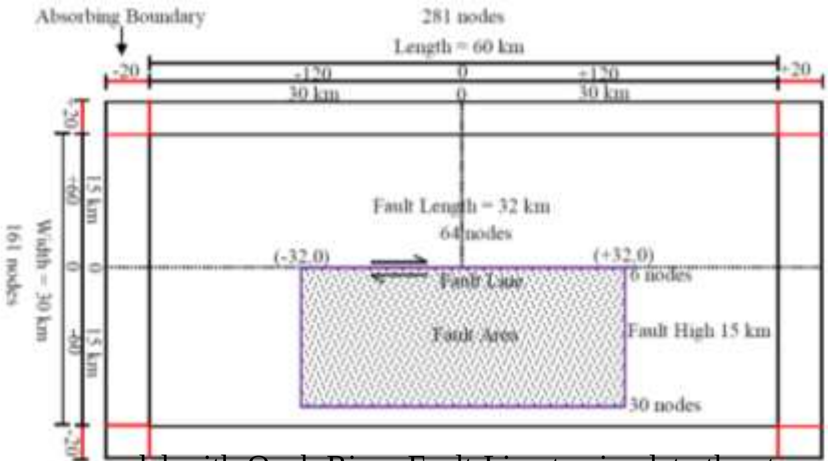

Fig. 5. The study area model with Opak River Fault Line to simulate the strong ground motion by utilizing the 3-D elastic FD method

Table 3. The simulation parameters

No.	Parameter	Value
1.	Spatial discretization, *dx*, *dy* and *dz* (km)	0.5
2.	Temporal discretization, Δ*t*, (sec)	0.05
3.	Total number of timesteps	2000
4.	Total number of array earthquake data	2000
5.	Input timesteps of ground motion	3
6.	Total array regarding boundary plane	61000
7.	Simulation time (sec)	100
8.	Computation time (hours)	8 and half
9.	Number of nodes, *nx*, *ny* and *nz*	120,60 and 42
10.	Absorbing boundary, nab, (km)	20

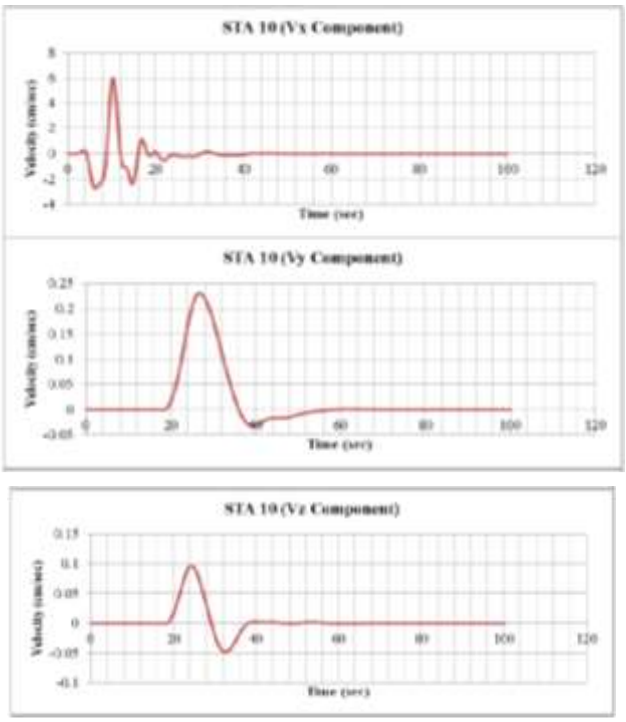

Fig. 6. The 3-components synthetic velocity seismograms calculated with the 3D-FD method with uniform grid spacing at station 10.

The distribution of peak ground velocity [PGV]

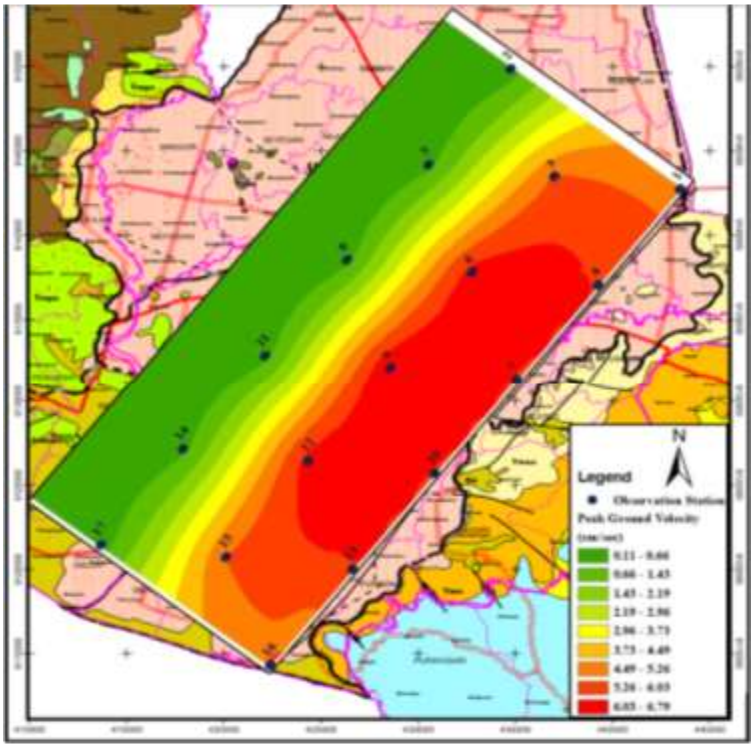

Fig. 7. Peak Ground Velocity map of the Vx component from the aerial source simulation results along the Opak River Fault

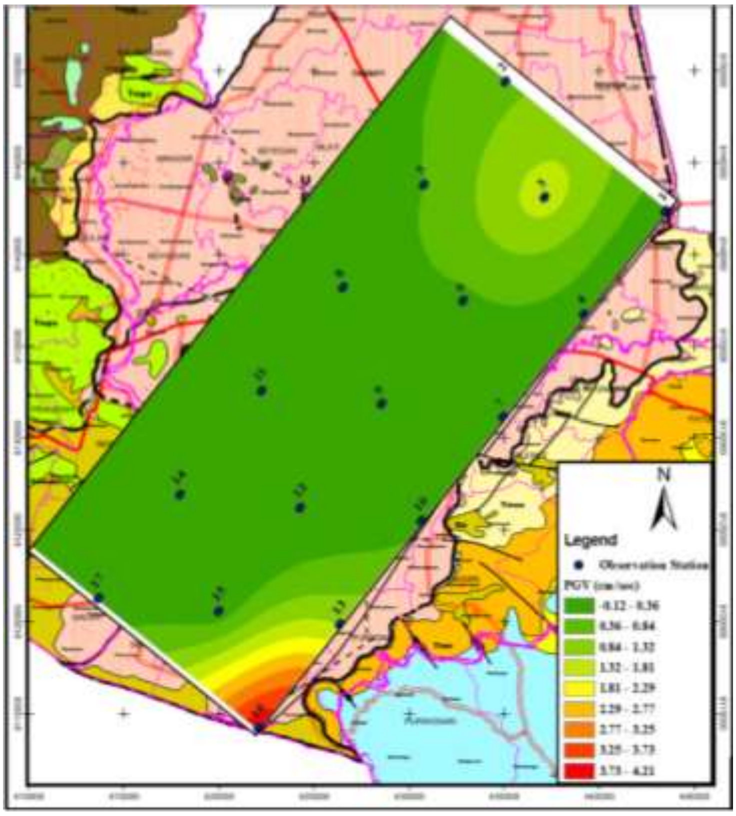

Fig. 8. Peak Ground Velocity map of the Vy component from the aerial source simulation results along the Opak River Fault

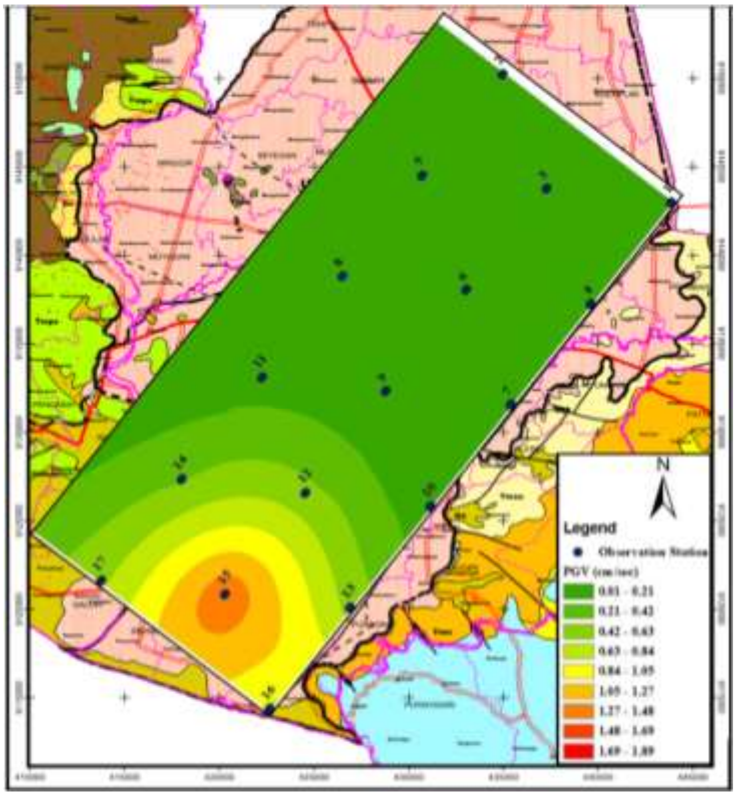

Fig. 9. Peak Ground Velocity map of the Vz component from the aerial source simulation results along the Opak River Fault

The peak ground velocity (PGV) of the Vx components is also useful parameter for characterization of ground motion amplitude. As shown in Fig. 7, the PGV values are varying from 0.1 to 6.79 cm/s. The high PGV value is related to the damage region for the future earthquakes. The high PGV (>4.49 cm/s) are observed at around the Yogyakarta city, Bantul city and along the Opak River Fault areas where the damage potential can be high in the future earthquake. Because these areas are located in the depression area composed by the soft sediment of the young volcanic deposit of Mt. Merapi volcano. The low PGV (<4.49 cm/s) are evaluated at the mountain areas although the rest of the study areas are the value of PGV between 0.1 and 0.6 cm/s.

In Fig. 8, according to the PGV values of the Vy components based on the 3-D FD method in the 17 observation sites, the south-west of the study area has high level of risk (2.76-4.21 cm/s). The eastern part of the research area has the medium level of risk (1.32-2.28 cm/s) while the middle part has the low level of risk (0.11-0.84 cm/s). The results show that a better distribution of the peak ground velocity, since the medium to high level of risk reflects the presence of the structures related to the Opak River Fault system. As shown in Fig. 9, the PGV value of the Vz components is generally ranging from 0.01 to 1.89 cm/s. The west portion of the research area, high damage area, shows high velocity value 0.84 – 1.89 cm/s. Most of the study area is influenced the low velocity value, 0.01 – 0.84 cm/s. Figs. 7, 8 and 9 are the Peak Ground

Velocity map of the Vx, Vy and Vz components from the aerial source simulation results along the Opak River Fault.

Conclusions

Depend upon results from overall research works, the following are concluded.

(1) The synthetic velocity seismograms are conducted to simulate the strong ground motion in Yogyakarta-Bantul area based on an aerial seismic source model of the finite-difference method (FDM). Especially, the *Vx*, *Vy* and *Vz* components of synthetic velocity wave form or PGV are calculated 0.11-6.79, 0.12-4.21 and 0.01-1.89 cm/s by the 3-D elastic FDM method respectively.

(2) The Peak Ground Velocity maps for *Vx*, *Vy* and *Vz* components will be basically influenced for future structural building development and high way, and mitigation of socio-economic impacts in research area. The heavy and high buildings with the high velocity especially for *Vx* components of ground motion will be severely affected during future earthquakes. The results from this study well approve that the high velocity is performed the thick sediment thickness and dominated in S-wave velocity. In the future seismic motion, the high velocity will be mainly related to the damage area of the Yogyakarta-Bantul region.

(3) It has been presented a simplified method for the simulation of the ground motion based on the 3-D elastic FDM method. It can be concluded that the method is effective for the prediction of velocity parameters of the ground motion for large earthquakes at research area. The results present the synthetic waveforms of velocity for the estimated target earthquake of the *Vx* component of 0.11-6.79 cm/s because the Opak River Fault is the strike-slip fault. Finally, it is concluded that it might be the high damage along the Opak River Fault within about 5 km of SW direction and 30 km of NE direction at research area in the future earthquake.

Acknowledgment

This research was carried out at the Graduate School of Engineering, Kyoto University, Japan and financially supported by the scholarship program (the Research Fellowship for Post-Doctoral Degree, RF-2015) of AUN/SEED-Net. We are grateful to JICA and AUN/SEED-Net for providing me opportunity and financial support to carry out this research.

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