SEISMIC MICROZONATION OF SEMARANG, INDONESIA BASED ON SITE RESPONSE ANALYSIS USING 30 M SOIL DEPOSIT MODEL

by Windu Partono

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SEISMIC MICROZONATION OF SEMARANG, INDONESIA BASED ON SITE RESPONSE ANALYSIS USING 30 M SOIL DEPOSIT MODEL

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Article history
Received
18 January 2016
Received in revised form
8 March 2016
Accepted
18 March 2016

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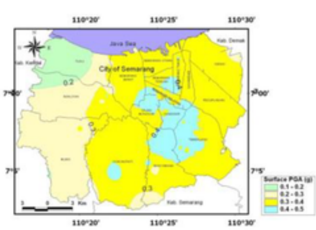
Graphical abstract



1.0 INTRODUCTION

Semarang is the capital city of Central Java Province. The city is located at 6°55'S to 7°8'S and 110°16'E to 110°29'E and covers an area of about 374 km². Based on the topographic relief the city can be divided into two different regions, a coastal plain area in the Northern part and the hilly area in the center and Southern parts.

Based on the earthquake data from 1900 to 2009, three different seismic sources that significantly influence Semarang and probably produce earthquake in the future are the Java subduction zone, subduction megathrust and benioff, and shallow crustal faults ([1], [2] and [3]). Four large earthquakes due to the subduction zone were reported by [3] and [4] including 7.9 Ms (1903), 7.2 Ms (1937), 7.9 Ms (1977) and 8.3 Mw (1943) events. The 2006 Yogyakarta earthquake of 6.3 Mw caused by Yogya fault (Opak fault) is the latest earthquake caused by shallow crustal fault. The tectonic environment for Semarang is quite similar with Yogyakarta. Lasem fault at the Eastern part of Semarang is the closest seismic source that can produce earthquake in the future. The 2006 Yogyakarta earthquake was an earthquake that caused thousands of casualties in Yogyakarta Province and Central Java Province [5]. Learning from Yogyakarta earthquake and recommendations from TRSHMI-2010, a comprehensive seismic microzonation for Semarang is then implemented for hazard mitigation and disaster preparedness. TRSHMI-2010 stated that Lasem fault is the nearest fault which has been proven as an active shallow crustal fault and probably can produce earthquake in the future. Figure 1 shows a map with seismic epicenter data within a radius 500 km which influences the seismic hazard in Semarang and the position of Lasem fault within the study area.

Following the work conducted by TRSHMI-2010 for developing national seismic hazard maps, seismic sources were divided into; subduction zone, shallow crustal fault, and background sources. In the subduction zone at south of Java, the Java segment of the Sunda arc lies between Sunda Strait in the west to the Bali Basin in the East. Old oceanic crust is converging with Java in a direction essentially normal to the arc at the rate of about 6.0 cm/year in the west Java trench and 4.9 cm/year in the east Java trench [2]. The Benioff seismic zone along the Java segment dips approximately 50° and extends to depths of about 600 km and a gap in seismicity exists in the segment between a depth of 300 and 500 km [2].

A comprehensive seismic microzonation research for Semarang had started in 2013 and the work is still going on, conducted using the following procedures:

1. Conducting literature review on geology, geophysics and seismology to identify activity of seismic sources in and around the city
2. Collecting and processing recorded earthquake data within a radius 500 km from the city
3. Collecting and processing geotechnical data for site class and shear wave velocity profile
4. Developing seismic risk map following the same concept used by TRSHMI-2010
5. Collecting and processing acceleration time histories of ground motion from worldwide historical earthquake records due to shallow crustal fault sources with magnitude 6.5 Mw and maximum distance 20 km for input motion in shear wave propagation analysis
6. Developing shear wave propagation analysis by implementing engineering bedrock elevation based on single station feedback seismometer measurement
7. Developing map of PGA and spectral acceleration at ground surface and amplification factor based on shear wave propagation analysis.

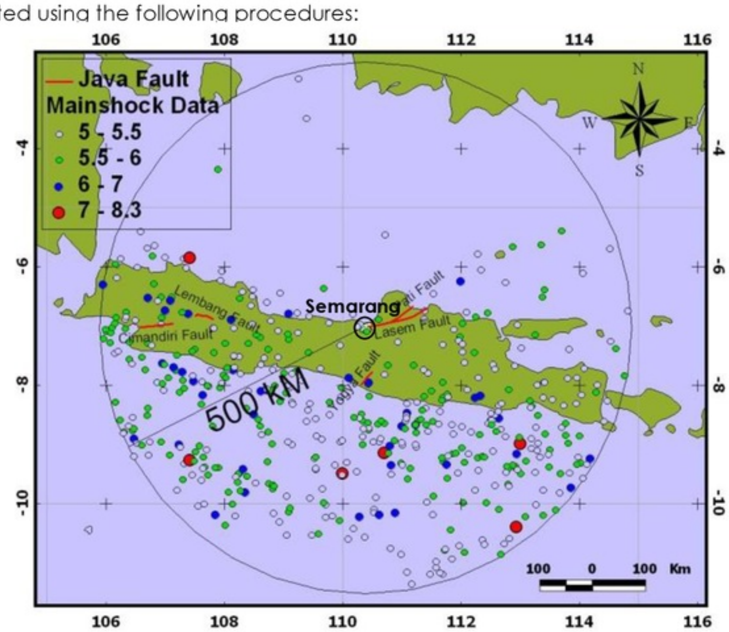


Figure 1 Seismotectonic map of Java Island in a radius of 500 Km from Semarang and the position of Lasem Fault

2.0 GEOLOGICAL AND GEOTECHNICAL CONDITION OF SEMARANG

The city of Semarang can be separated into three different lithologiest: volcanic rock, sedimentary rock, and alluvial deposits [6] and [7]. According to [6], the basement of Semarang consists of Tertiary Claystone of the Kalibiuk Formation and overlaid by Notopuro Formation which consists of Quaternary volcanic material. The northern part of the Semarang area is covered by Kali Garang deltaic alluvium up to a depth of 80 to 100 m in the coastal area [6] and [7]. The northern part of the city is composed by very young alluvium with high compressibility. Figure 2 shows the geological map of Semarang modified from original map prepared by [8].

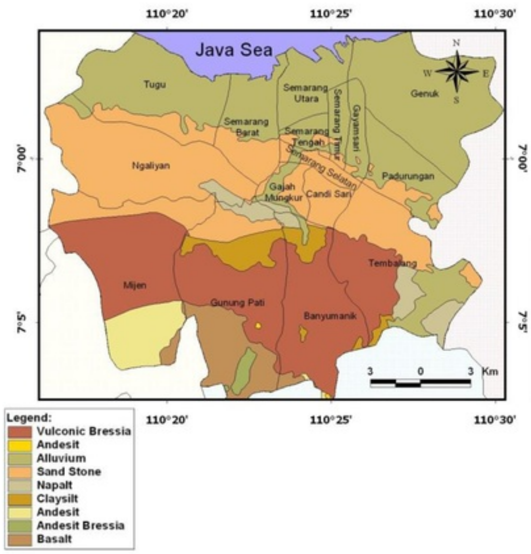


Figure 2 Geological map of Semarang, modified from [8]

Depth of engineering bedrock is one of the important parameters used to perform site response analysis. Identification of bedrock elevation for the study area is required because the elevation of bedrock is not well identified. To estimate the bedrock elevation, a simple single station feedback seismometer survey was performed using ambient vibrations at 218 different points in the city. In this study the elevation of bedrock is predicted using horizontal-to-vertical spectral ratio (HVSR) analysis for three component ambient vibrations (NS, EW and V) ([9], [10] and [11]). The depth of engineering bedrock can be predicted using two empirical formulas proposed by [12] and [13], Figure 3 shows the distribution of bedrock depth of the study area. The depth of engineering bedrock or the thickness of the soil deposit is increase from Southern part to the Northern part of the study area.

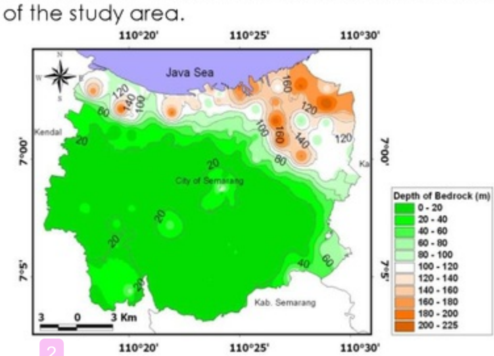


Figure 3 Contour map of depth of engineering bedrock identified by single station feedback seismometer

Site characterization (classification) was carried out by interpreting the results of field measurements including in-situ standard penetration test (SPT) and laboratory tests, following the same method used by [14]. To develop seismic microzonation, 190 boreholes investigation with a minimum 30 m depth was performed in all part of Semarang city [15]. The dynamic soil property was also conducted to encounter limited data of shear wave velocity profiles in Semarang. The shear wave velocity profile was estimated using SPT-N data and calculated using three empirical equations proposed by ([16], [17] and [18]). Site classification study for Semarang was also performed using the V_S30 value and following the standard method used by [14]. Figure 4 shows the map of site classification of the study area.

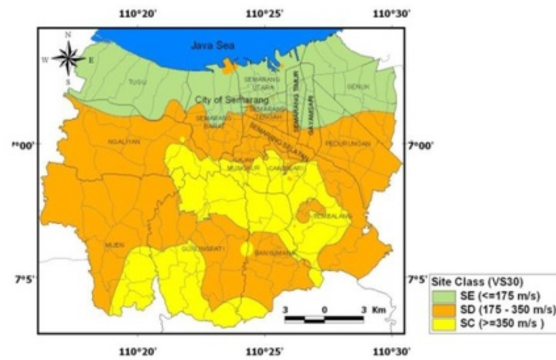


Figure 4 Site classification of Semarang using V_S30 value

3.0 SITE RESPONSE ANALYSIS

Site response analysis is performed for developing seismic microzonation maps of Semarang. Due to inadequate data of ground motion from Lasem fault earthquake, site response analysis for Semarang was carried out by selecting ground motion from worldwide historical earthquake records due to shallow crustal fault seismic sources. The scenario for shallow crustal fault source was implemented using magnitude 6.5 Mw and maximum distance 20 km. The maximum magnitude earthquake 6.5 Mw was conducted following the recommendations from TRSHMI-2010. Due to the limited earthquake records with magnitude 6.5 Mw, historical earthquake records with magnitude ranging from 6 to 7 Mw and maximum distance 20 km were collected for shallow crustal fault.

Each ground motion with certain magnitude and distance was represented by appropriate acceleration time-histories of ground motion records. Table 1 shows the selecting ground motion collected from worldwide historical earthquake database and used for site response analysis for Semarang. Modified acceleration time histories are then generated using the selected time histories and implementing spectral matching analysis using the same method proposed by [19]. To perform spectral matching analysis, target spectrum at bedrock was prepared using Deterministic Seismic Hazard Analysis (DSHA) and conducted using shallow crustal fault source with magnitude 6.5 Mw and maximum distance of 20 km.

Figure 5 shows 4 (four) target spectrums calculated using DSHA with magnitude 6.5 Mw and distance of 0–5 km, 5–10 km, 10–15 km and 15–20 km.

Table 1 Earthquake records used as input motion for site response analysis

No	Seismic Sources	Station	M[a] (Mw)	R[b] (km)
1	Imperial Valley (10/15/1979)	El Centro Array #8	6.53	3.86
2	Imperial Valley (10/15/1979)	Chihuahua	6.53	7.29
3	Imperial Valley (10/15/1979)	El Centro Array #11	6.53	12.56
4	Imperial Valley (10/15/1979)	El Centro Array #12	6.53	17.94
5	Superstition Hills (11/24/1987)	Parachute Test Site	6.54	0.95
6	Superstition Hills (11/24/1987)	Superstition Mtn Camera	6.54	5.61
7	Superstition Hills (11/24/1987)	Westmorland Fire Station	6.54	13.03
8	Superstition Hills (11/24/1987)	El Centro Imp. Co. Cent	6.54	18.2
9	Chi-Chi Taiwan (9/20/1999)	CHY074	6.2	6.02
10	Chi-Chi Taiwan (9/20/1999)	CHY080	6.2	12.44
11	Chi-Chi Taiwan (9/20/1999)	CHY028	6.2	17.63
12	Kobe Japan (1/16/1995)	Kobe University	6.9	0.9
13	Kobe Japan (1/16/1995)	Nishi-Akashi	6.9	7.08
14	Kobe Japan (1/16/1995)	Amagasaki	6.9	11.34
15	Kobe Japan (1/16/1995)	Fukushima	6.9	17.85
16	Victoria Mexico (6/9/1980)	Victoria Hospital Sotano	6.33	6.07
17	Victoria Mexico (6/9/1980)	Cerro Prieto	6.33	13.8
18	Victoria Mexico (6/9/1980)	Chihuahua	6.33	18.53

[a] Seismic magnitude
[b] Epicentral distance

The Lasem fault, an active fault near Semarang, is considered as the main shallow crustal that can significantly influence the hazard of the city. Due to the position of borehole points against fault trace, all borehole points were then distributed into four different distances to the fault trace (0-5 km, 5-10 km, 10-15 km and 15-20 km). Figure 6 shows the distribution of borehole points against Lasem fault trace. Site response analysis for each borehole points was conducted by using five different earthquake records (6.2 Mw, 6.33 Mw, 6.53 Mw, 6.54 Mw and 6.9 Mw).

From the depth of engineering bedrock and the depth of borehole investigation, it was found that not all boreholes reached the elevation of bedrock. The geotechnical data were collected from borehole

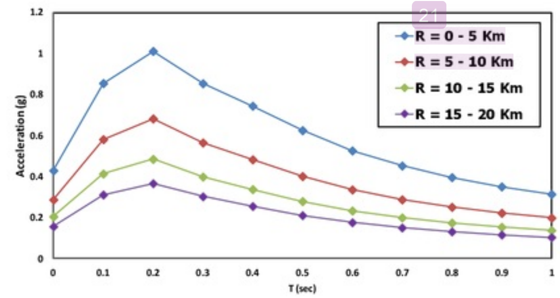


Figure 5 Target spectrum used for spectral matching analysis

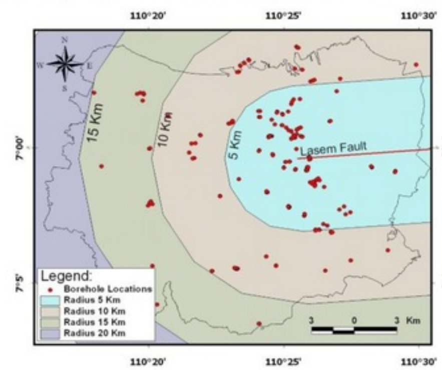


Figure 6 Distributions of borehole points against Lasem Fault trace

Site response analysis was implemented based on the assumption that all boundaries are horizontal and that the response of a soil layer is predominantly caused by shear wave propagating vertically from the underlying bedrock. In this study the general response analysis were performed using equivalent linear approach by modifying the Kelvin-Voigt model to account for some types of soil nonlinearities. The site response analysis was performed using the constitutive model proposed by [20] and [21] and by utilizing the free software NERA [22]. The propagation analysis had been performed using Equation (1), where ρ is soil density, η is viscosity and G is shear modulus.

$$\rho \frac{\partial^2 u}{\partial t^2} = G \frac{\partial^2 u}{\partial z^2} + \eta \frac{\partial^3 u}{\partial z^2 \partial t} \qquad (1)$$

Site response analysis using 1-D shear wave propagation procedure was conducted to obtain peak ground acceleration and spectral acceleration at ground surface and amplification factor. Peak ground acceleration and spectral acceleration for each borehole points was calculated based on the average value calculated from five different acceleration time histories.

investigations with minimum depth 30 m and maximum 60 m. Due to inadequate information of geotechnical parameters (shear wave velocity data) below borehole elevation, two different soil deposit models were performed. The first model (Model 1) of shear wave model as shown in Figure 7 was implemented using the real bedrock elevation calculated from seismometer measurement and by assuming the shear wave velocity at bedrock was 760 m/s. Shear wave profile below the bottom of borehole investigations for each borehole points was distributed linearly from the bottom of borehole elevation to bedrock elevation.

This study also proposed 30 m soil deposit model as an alternative model for site response analysis. The second model (Model 2) as shown in Figure 8 was implemented using 30 m soil deposit model or by assuming the bedrock elevation at 30 m below the ground surface. The geotechnical data were collected using 30 m boring data.

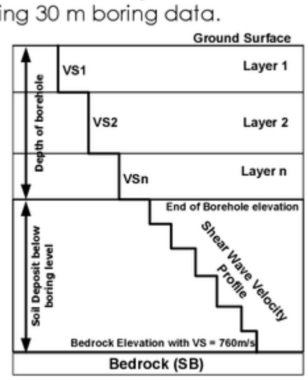


Figure 7 Model 1 for site response analysis

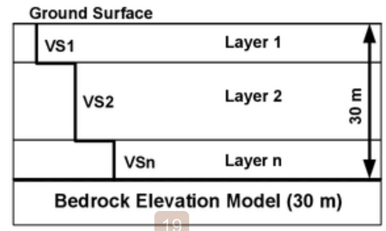


Figure 8 Model 2 for site response analysis

Site response analysis for Model 2 was implemented following the preliminary site response analysis for two different soil deposit model (clay and sand) by using five different bedrock elevations (30 m, 48 m, 60 m, 84 m and 120 m). Figure 9 shows the maximum acceleration profile for clay and sand for five different bedrock elevations. The red line represents the maximum PGA profile for 30 m soil deposit model. For clay (Figure 9a), the PGA at ground surface for five different bedrock models are almost the same and distributed between 0.2g to 0.45g except for 84 m soil deposit model. For sand (Figure 9b), PGA at ground surface for five different bedrock models are almost the same and distributed between 0.2g to 0.4g. Figure 10 shows spectral acceleration at the surface for clay and sand deposit for five different bedrock elevations. The red line represents the spectral acceleration for 30 m soil deposit model. Spectral acceleration for 30 m soil deposit model is almost the same with four other soil deposit models. For short period (T≤0.2s) the spectral acceleration for 30 m model is higher than four other models. However for long period (T≥ 0.2s) the spectral acceleration for 30 m model is lower than four other models.

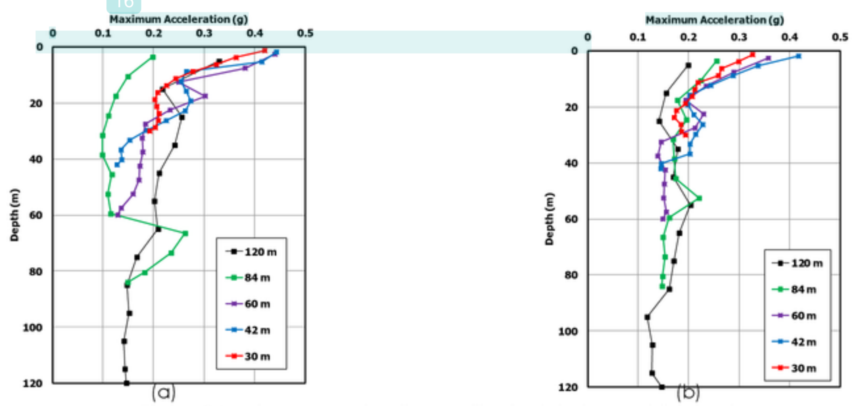


Figure 9 Maximum acceleration profiles for (a) clay and (b) sand

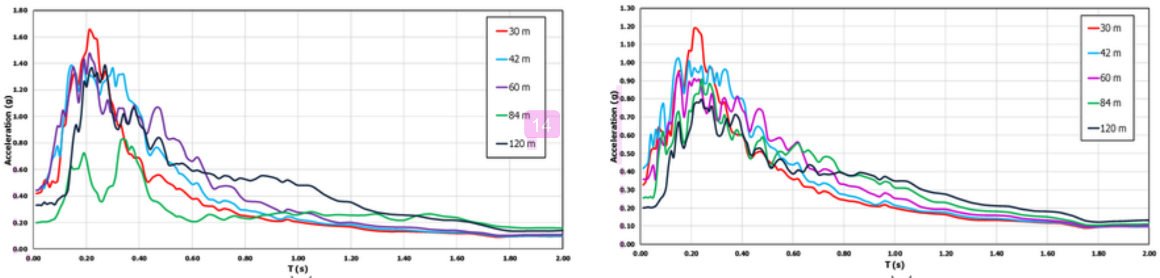


Figure 10 Spectral acceleration at ground surface for clay (a) and sand (b)

4.0 RESULTS AND DISCUSSION

Site response analysis was conducted to obtain the peak ground acceleration and spectral acceleration at the ground surface and amplification factor. Site response analysis for Semarang was carried out by selecting ground motion from worldwide historical earthquake records due to shallow crustal fault sources. The scenario for shallow crustal fault source was implemented using magnitude 6.5 Mw and maximum distance 20 km. The analysis was carryout using two different models of soil deposit, Model 1 was implemented using real bedrock elevation calculated from single station feedback seismometer measurements and Model 2 was implemented using 30 m bedrock elevation. PGA at ground surface and PGA amplification factor are presented in this paper.

Figure 11 shows two different maps of surface PGA for the study area calculated using site response analysis using Model 1 and Model 2. Surface PGA for the city are distributed between 0.1g to 0.5g. The maximum surface PGA for Model 1 are distributed at the South-Eastern part of the city and minimum surface PGA are distributed at the North-Western site of the city. However the maximum surface PGA for Model 2 are distributed at the Eastern part of the city and the minimum surface PGA are distributed at the North-Western site of the city. Figure 12 shows the comparison of two graphs of surface PGA in terms of V_S30 calculated from two different models. The red line represents the mean surface PGA calculated from 190 data using Model 2 and the black line represents the mean surface PGA calculated using Model 1. The mean surface PGA values calculated using Model 2 is higher than Model 1.

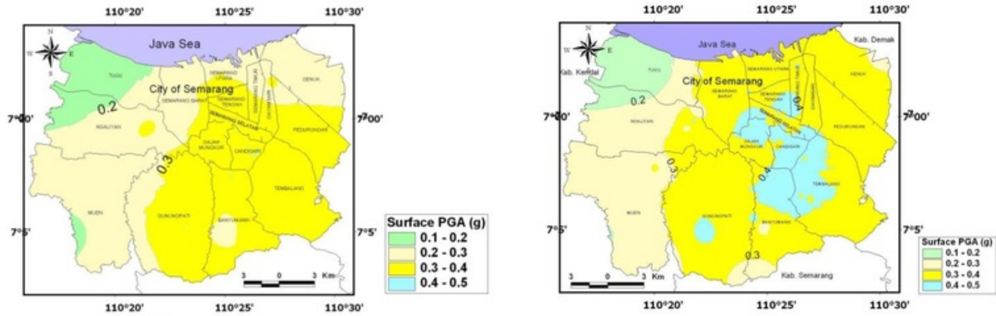
Figure 13 shows two different maps of amplification factor of PGA for the study area. The amplification factor for PGA values is distributed between 1 until 2.5. The maximum amplification factor for PGA is distributed at the South-Western part of the study area. However the minimum amplification factor is distributed at the North-Eastern part of the city. Figure 14 shows two different graphs of amplification factor PGA. The red line represents the mean amplification factor PGA calculated from 190 data using Model 2 and the black line using Model 1. Amplification factor of PGA calculated using Model 2 is higher than Model 1. Table 2 shows the ratio of surface PGA and amplification factor between Model 2 and Model 1 in terms of site class calculated from 190 data following the same method used by [1].

5.0 CONCLUSION

The surface PGA calculated from 190 data using Model 2 is greater than Model 1. For site class SE the surface PGA for Model 2 is 1.08 to 1.1 times greater than Model 1. The surface PGA for Model 2 is 1.12 to 1.32 and 1.33 to 1.49 times greater than Model 1 for site SD and SE, respectively.

The amplification factor of PGA calculated from 190 data using Model 2 is greater than Model 1. For site class SE the amplification factor of PGA for Model 2 is 1.17 to 1.18 times greater than Model 1. The PGA amplification factor for Model 2 is 1.18 to 1.21 and 1.21 to 1.22 times greater than Model 1 for site SD and SE, respectively.

It can be concluded that the site response analysis using 30 m soil deposit model can be used as an alternative model due to inadequate information of soil parameters and shear wave velocity for deep bedrock elevation. The 30 m soil deposit model (Model 2) can be used as an alternative model for an area with soil deposit thickness more than 30 m. Hence, this could reduce the budget for soil investigation works.



(a) (b)

Figure 11 Distribution of surface PGA for (a) Model 1 and (b) Model 2

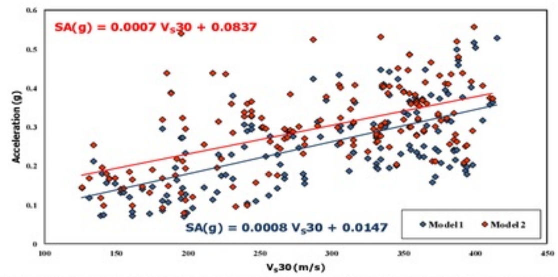
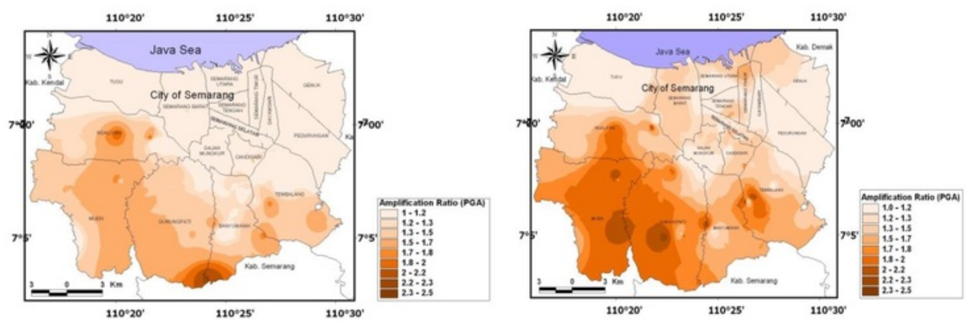


Figure 12 PGA at Ground Surface calculated at 190 points for Model 1 and Model 2



(a) (b)

Figure 13 Amplification factor of PGA for (a) Model 1 and (b) Model 2

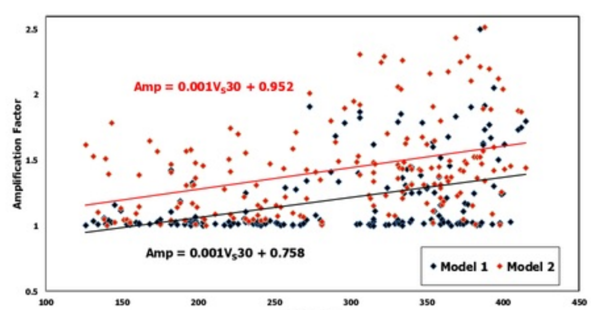


Figure 14 The amplification factor of PGA calculated at 190 points for Model 1 and Model 2

Table 2 The ratio of surface PGA and amplification factor between Model 2 and Model 1

Site Class	Surface PGA	Amplification Factor
SC	1.08 – 1.11	1.17 - 1.18
SD	1.12 – 1.32	1.18 - 1.21
SE	1.33 – 1.49	1.21 - 1.22

Acknowledgement

The authors express their sincere gratitude to the National Disaster Management Agency (BNPB) for the financial support in undertaking this research, Diponegoro University and the Team for Revision of Seismic Hazard Maps of Indonesia 2010 for providing seismic data and technical assistances.

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