DEVELOPMENT OF SEISMIC MICROZONATION MAPS OF SEMARANG, INDONESIA

by Windu Partono

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DEVELOPMENT OF SEISMIC MICROZONATION MAPS OF SEMARANG, INDONESIA

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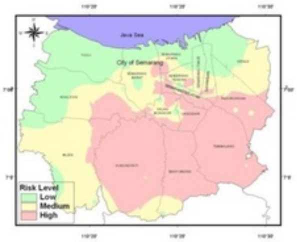
Graphical abstract



1.0 INTRODUCTION

Semarang is the capital city and located at the center of the Northern part of Central Java Province. The city has an area of about 374 square kilometers. The city extends for 22 km in length and 22 km in width and is elongated in both North-South and East-West directions. The city can be separated into two different regions based on topographic relief, a coastal plain area in the northern part with maximum slope of 5% and the hilly area in the center and southern parts with maximum slope of 33%.

Seismic microzonation study is generally recognized as one of the effective method to perform seismic hazard assessment and risk evaluation which is defined as the zone with respect to ground motion characteristics taking into account source and site conditions [3]. This paper presents several aspects in seismic microzonation in Semarang city including the seismotectonic condition, geological condition and seismic hazard microzonation.

The microzonation level graded based on the scale of investigation and method of ground motion assessment. The seismic microzonation methodology and level of study for Semarang city is performed according to [3] and [4] but not including building vulnerability analysis. Seismic microzonation study in Semarang city requires input parameters regarding the seismic hazard in Semarang, depth of engineering bedrock, geotechnical condition and parameters, ground water level and ground response analysis. The site specific ground response analysis is performed based on the influencing of Lasem fault seismotectonic data. The seismic microzonation in Semarang city is divided into 3 steps:

a. Evaluation of the input motion at bedrock elevation
b. Site specific response analysis
c. Seismic hazard microzonation

2.0 SEISMIC SOURCES INFLUENCING SEMARANG CITY

Seismic sources that significantly influence Semarang are the Java subduction zone and shallow crustal faults ([5], [6] and [7]). Three large earthquakes due to the subduction zone were reported by [8] including 7.9 Ms (1903), 7.2 Ms (1937) and 7.9 Ms (1977) events. The tectonic environment for Semarang is quite similar to that of Yogyakarta, in that there is an active fault near both cities. The 2006 Yogyakarta earthquake of 6.3 Mw caused by Yogyakarta fault was an earthquake that caused thousands of casualties in Yogyakarta [9]. Learning from the Yogyakarta earthquake, the city of Semarang with adjacent Lasem fault requires a comprehensive seismic microzonation studies for hazard mitigation and disaster preparedness. Figure 1 shows a map with seismic epicenter data within a radius 500 km which influences the seismic hazard in Semarang. Seismotectonic map showing fault locations within a radius 500 km and the position of Lasem fault. The nearest fault which has been proven as an active shallow crustal fault is Lasem fault.

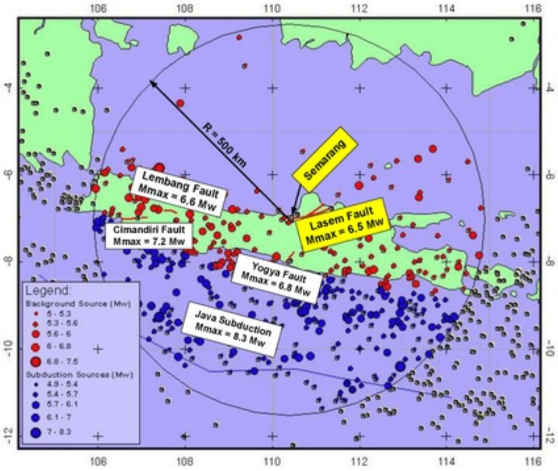


Figure 1 Seismotectonic map of Java Island in a radius of 500 km from Semarang City and the position of Lasem Fault

Following the work conducted by the Team for Revision of Seismic Hazard Maps of Indonesia 2010 (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 extends from 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 [6]. 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 [6].

Development of a risk map was performed using the following procedures: 1) conducting literature review on geology, geophysics and seismology to identify activity of seismic sources in and around the Indonesian region, 2) collecting and processing recorded earthquake data for the entire Indonesian region, 3) collecting and processing geotechnical data for site class and shear wave velocity profile calculation 4) developing seismic risk map following the same concept used by [1], 5) collecting and processing acceleration time histories of ground motion due to shallow crustal fault seismic sources for input motion in shear wave propagation analysis, 6) developing shear wave propagation analysis by implementing engineering bedrock elevation based on seismometer measurement, 7) developing PGA and spectral acceleration at ground surface distribution map based on shear wave propagation analysis, 8) developing risk map by categorizing risk level into three different zones.

3.0 SEISMIC HAZARD ANALYSIS OF SEMARANG

Probability Seismic Hazard Analysis (PSHA) and Deterministic Seismic hazard Analysis (DSHA) were conducted to obtain peak ground acceleration (PGA) and spectral acceleration at bedrock elevation for short periods (0.2 seconds) and 1.0 second period. DSHA was performed using 84% percentile (150% median). Both probabilistic and deterministic analysis is required for building design.

PSHA and DSHA are implemented using similar concepts used by [1] and TRSHMI 2010 ([7] and [10]). Seismic sources are divided into subduction, shallow crustal fault and background sources. Faults that have been well identified within 500 km of Semarang are Cimandiri, Lembang, Lasem, Pati and Yogya faults. Earthquake parameters are then derived based on earthquake catalog, geological and seismological information. Table 1 shows required seismic parameters for PSHA for subduction, shallow crustal fault and background sources. Fault parameters required as input for PSHA included fault traces, focal mechanism, slip-rate, dip, length of fault and maximum magnitude. Location of each fault was determined based on the previous study conducted by [7].

PSHA was conducted based on the total probability theorem proposed by [11] by using a three-dimensional seismic source model and geological and seismological data used by [7]. According to [11], the average annual frequency that a particular level of strong ground motion will be exceeded is calculated by the Equation (1). Where λa^* is the total average exceedance rate of earthquake source with acceleration greater than a*, $P(a>a^*|m,r)$ comes from the ground motion model, $P_m(m)$ and $P_R(r)$ are probability distribution function (PDF) for magnitude and distance and ν is the mean rate of exceedance.

DSHA was performed using 84% percentile (150% median). Both probabilistic and deterministic analysis is required for building design. It has been decided that [1] adopt [2] that uses Risk-Targeted Maximum Considered Earthquake (MCE_R) map integrating deterministic and probabilistic hazard as well as fragility curves of buildings. DSHA was undertaken using the largest magnitude and the closest distance to Semarang. The Lasem fault, an active fault near Semarang, is considered as the main shallow crustal that can significantly influence the hazard of the city. The size of the largest possible earthquake is estimated using the same maximum magnitude used for the PSHA.

$$\lambda a^* = \nu \int_M \int_R P(a > a^* | m.r) P_m(m) P_R(r) dr dm \qquad (1)$$

Other important step in seismic hazard analysis is selection of attenuation relationships. Due to inadequate ground motion records to develop attenuation function in Indonesia, attenuation functions used in this study were adopted from other countries following the work by [7]. The attenuation functions were selected considering the source types. Attenuation function from [12], [13] and [14] were used for shallow crustal faults and shallow background sources. Attenuation function from [15], [16] and [17] were used for subduction megathrust source. Attenuation function from [16] and [15] were used for deep background source. The risk targeted ground motions (RTGM) for Semarang were calculated as spectral response accelerations that result in 1% probability of building failure in 50 years through numerical integration and an iterative process as conducted by [18].

In order to get the spectral response accelerations at ground surface, the response accelerations at bedrock elevation from seismic hazard analysis are then mutiplyed by the amplification factor. The amplification factor is interpreted using the same methods used by [1]. Figure 2-4 show the distribution of PGA and spectral acceleration on the ground surface for Semarang city.

Table 1 Parameters of seismic sources in a radius of 500 km from Semarang city

Sources	**Name**	**Mechanism**	**Mmax (Mw)**	**Length (km)**	**Slip Rate (mm/year)**	**GR Parameter**	
						a	**b**
Fault	Cimandiri	Strike-slip	7.2	62.2	4	-	-
	Lembang	Strike-slip	6.6	34.4	1.5	-	-
	Yogya	Strike-slip	6.8	31.6	2.4	-	-
	Lasem	Strike-slip	6.5	114.9	0.5	-	-
	Pati	Strike-slip	6.8	51.4	0.5	-	-
Subduction	Java Megathrust	Reverse	8.3	-	-	5.36	1.0307
Background	Shallow (0-50km)	-	6.8	-	-	7.04	1.3549
	Deep1 (50-100km)	-	8.3	-	-	7.62	1.4116
	Deep2 (100-150km)	-	6.6	-	-	5.73	1.0608
	Deep3 (150-500km)	-	7.5	-	-	7.27	1.3974

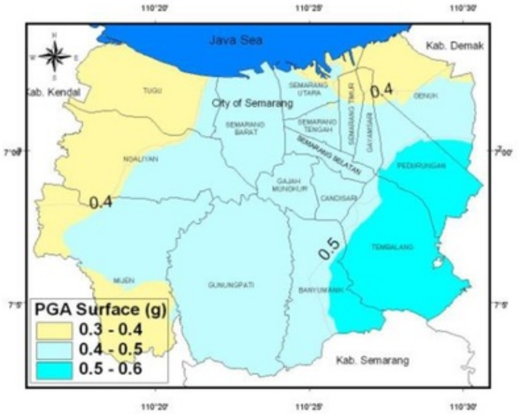


Figure 2 Contour of PGA at surface elevation based on [1]

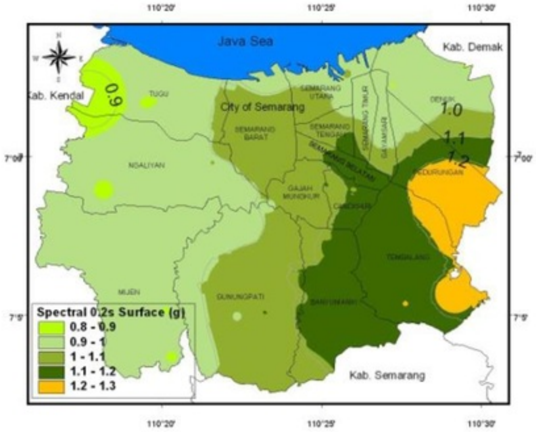


Figure 3 Contour of spectral 0.2s at surface elevation based on [1]

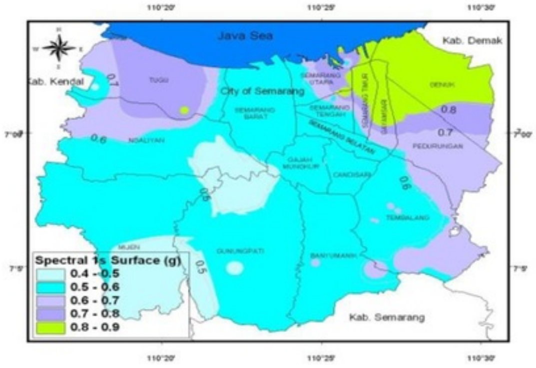


Figure 4 Contour of spectra 1s at surface elevation based on [1]

4.0 GEOLOGICAL AND GEOTECHNICAL CONDITION OF SEMARANG

The Depth of engineering bedrock is one of the required parameters used to perform the site response analysis. Identification of bedrock elevation is required because the elevation of bedrock is not well identified until now. 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 of three component ambient vibrations (NS, EW and V) ([19], [20] and [21]). Peak frequency of HVSR result (Fo) can be used to estimate the elevation of bedrock. According to [22] and [23], the depth of bedrock (Z) can be predicted using the Equation (2). Figure 5 shows the distribution of single station seismometer test points for HVSR analysis and Figure 6 shows the distribution of bedrock depth of Semarang city.

$$Z = a(Fo)^b \tag{2}$$

Table 2 a and b parameters for depth of bedrock prediction

Fitting Parameters		References
a (m)	b	
96	-1.388	[22]
108	-1.551	[23]

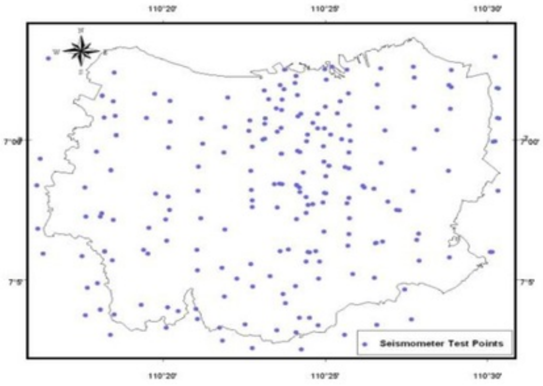


Figure 5 Distribution of single station feedback seismometer test points for HVSR analysis

Reflecting to the depth of engineering bedrock (Figure 6) and geological condition in Semarang (Figure 7), the soil deposit layers thickness increase to the North. Site characterization is carried out by interpreting the results of field measurements including in-situ testing standard penetration test (SPT), laboratory tests including shear wave velocity test for rock sample. To develop seismic microzonation 190 boreholes investigation with 30 m depth was performed in all part of Semarang city [24]. Figure 8 shows the distribution of borehole points used for the development of seismic microzonation maps. The borehole points are not well distributed within the study area. Most of the deep boring investigations with minimum 30 meter depth were performed between 2009 to 2013 using machine equipment and part of technical and engineering requirements for commercial building and high rise building constructions. Most of those buildings are constructed in the center part of the city. However most of the Western part and North-eastern part of the city consist of villages, farm area and resident area and the soil investigation for building constructions within these area are usually performed using auger boor with maximum 5 meter depth. Few deep boring investigations as part of the seismic microzonation study were performed during 2014 and distributed at the western, North-eastern and Southern part of the study area.

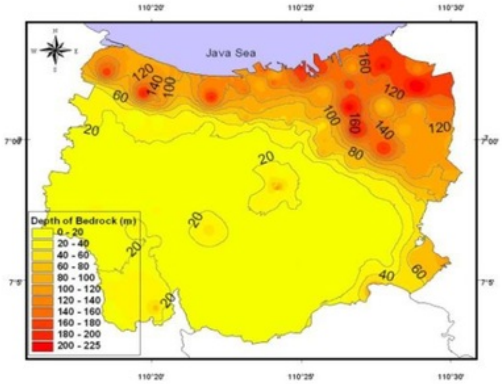


Figure 6 Contour map of depth of engineering bedrock identified by single station feedback seismometer

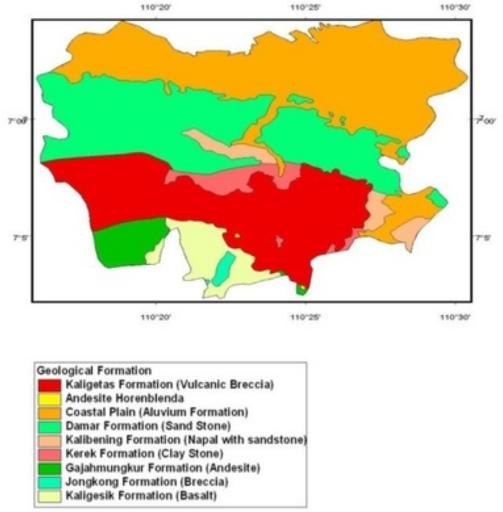


Figure 7 Geological map of Semarang (after [25])

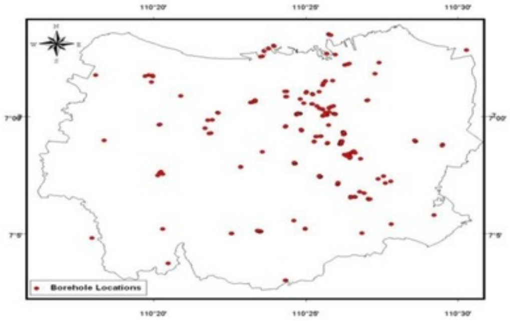


Figure 8 Distribution of borehole points for site response analysis

Site classification study for Semarang is performed based on the VS30 according to the [1] site classification standard as shown on Figure 9. The dynamic soil property is also conducted to encounter limited data of shear wave velocity profiles in Semarang. The shear wave velocity profile is estimated based on empirical equations proposed by [26], [27] and [28]. The study shows that the northern part of Semarang is classified as the soft soil site (SE) with VS30 value less than 175 m/s. Most of the center and southern part of Semarang is classified as the medium (SD) to hard soil site (SC) with VS30 value ranging from 175 to 350 m/s and greater than 350 m/s, respectively.

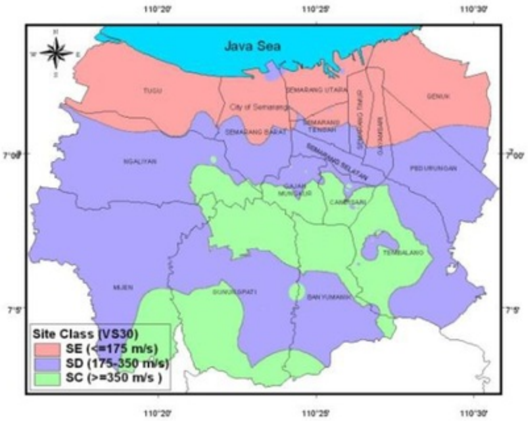


Figure 9 Site classification of Semarang using VS30 value

5.0 SITE RESPONSE ANALYSIS

In addition to PSHA and DSA site response analysis is also performed in the development of seismic microzonation maps of Semarang. Site response analysis for Semarang is carried out by selecting ground motion from worldwide historical earthquake records due to shallow crustal fault sources. The scenario for shallow crustal fault source is implemented using magnitude 6.5 Mw and maximum distance 20 km. 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 are collected for shallow crustal fault. Each ground motion with certain magnitude and distance is represented by appropriate time-histories of ground motion records for input motion in shear wave propagation analysis. Modified acceleration time histories are then generated using the selected time histories and estimated target spectrum at bedrock by implementing spectral matching method proposed by [29]. Table 3 summaries the selecting ground motion collected from worldwide historical earthquake and used for site response analysis for Semarang.

Table 3 Earthquake records used as input motion for site response analysis

No	Seismic Sources	Station	M (Mw)	R (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 Sta	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

Site response analysis was undertaken using the largest magnitude and the closest distance to Semarang. The Lasem fault, an active fault near Semarang, is considered as the main shallow crustal that can significantly influence the hazard of the city. The size of the largest possible earthquake is estimated using the same maximum magnitude used for the PSHA. Due to the position of borehole points against fault trace, all borehole points are then distributed into four different distances to the fault trace (0-5 km, 5-10 km, 10-15 km and 15-20 km). Figure 10 shows the distribution of borehole points against fault trace. Site response analysis for each borehole points is conducted by using five different earthquake records (6.2 Mw, 6.33 Mw, 6.53 Mw, 6.54 Mw and 6.9 Mw). Site response analysis is conducted to obtain peak ground acceleration and spectral acceleration at ground surface. Peak ground acceleration and spectral acceleration for each borehole points is calculated based on the average value calculated from five different acceleration time histories.

Site response analysis using 1-D shear wave propagation procedure is then conducted once the input motions corresponding to a specific magnitude and distance. 1-D shear wave propagation method is 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. Although the soil layers are sometimes inclined or bent, they are regarded as horizontal in most cases. Refer to the depth of engineering bedrock and the depth of borehole investigation not all boreholes can reach the elevation of bedrock. Due to the limited information of shear wave velocity profile, a model of shear wave velocity profile is then implemented for site response analysis. Figure 11 shows the model of shear wave velocity profile used for site response analysis. The site response analysis is performed using the constitutive model proposed by [30] and [31] and by utilizing the free software NERA [32].

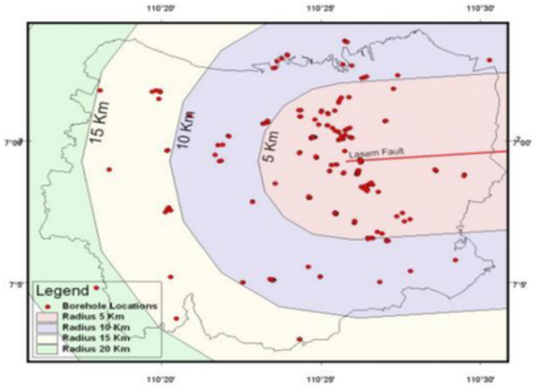


Figure 10 Distribution of borehole distance to fault trace

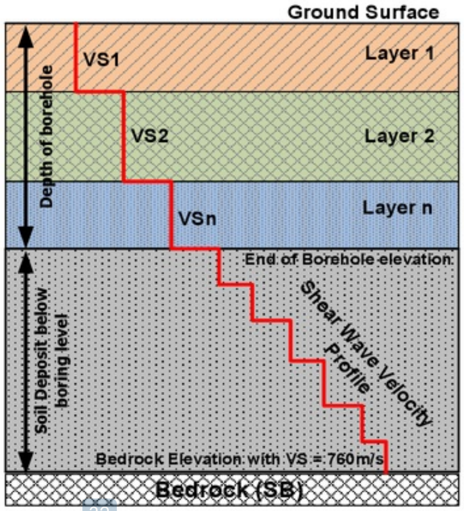


Figure 11 Soil profile model for site response analysis

The general response analysis should consider the non-linearity of soil behavior to provide reasonable results. 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 nonlinear and hysteretic stress-strain behavior of soils is approximated during cyclic loadings. Shear wave propagation analysis were performed for all existing soil data for all borehole locations in Semarang to obtain peak acceleration and spectral acceleration at the ground surface. The results of site response analysis at several points were used to develop response spectra at the surface and microzonation maps. Figure 10-12 show the distribution of peak ground acceleration and spectral acceleration at the ground surface.

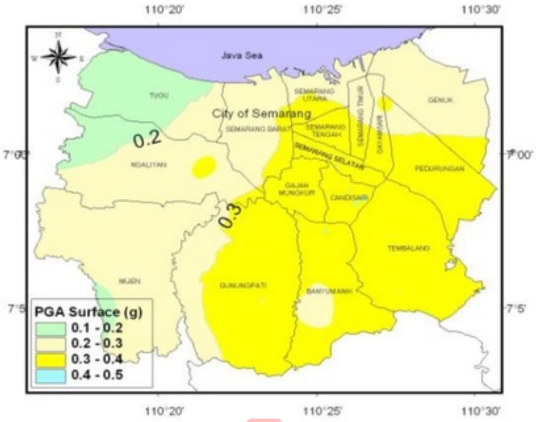


Figure 12 Contour map of Peak Ground Acceleration at surface due to shallow crustal fault source (Lasem Fault) with magnitude 6.5 Mw

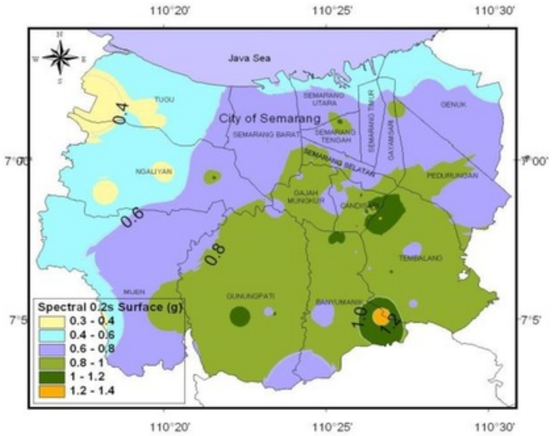


Figure 13 Spectral acceleration (T=0.2s) map at ground surface due to shallow crustal fault source (Lasem Fault) with magnitude 6.5 Mw

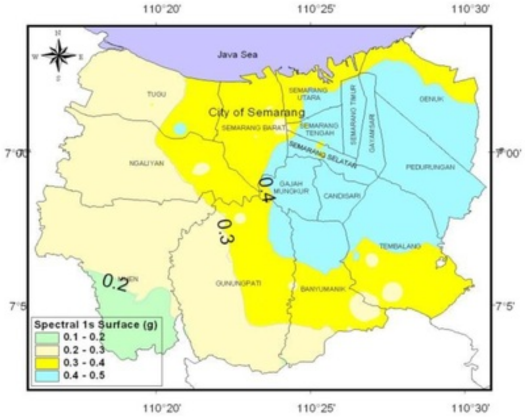


Figure 14 Spectral acceleration (T=1s) map at ground surface due to shallow crustal fault source (Lasem Fault) with magnitude 6.5 Mw

6.0 RESULTS AND DISCUSSION

The Results of the seismic microzonation study of Semarang include the combination of probabilistic and deterministic hazard analysis to obtain peak acceleration and spectral acceleration for short periods (0.2 seconds) and for 1.0 second period at bedrock level. Both probabilistic and deterministic analysis is required for building design. PSHA was conducted based on the total probability theorem using a three-dimensional seismic source model. DSHA was undertaken using the largest magnitude and the closest distance to Semarang. Lasem fault, an active fault near Semarang, is considered as the main shallow crustal that can significantly influence the hazard of the city. Ground shaking intensity at the ground surface can be implemented by multiplying the values of PGA and spectral acceleration at bedrock elevation with amplification factor.

Site response analysis is also conducted to obtain the peak ground acceleration and spectral acceleration at the ground surface. Site response analysis for Semarang is carried out by selecting ground motion from worldwide historical earthquake records due to shallow crustal fault sources. The scenario for shallow crustal fault source is implemented using magnitude 6.5 Mw and maximum distance 20 km.

Figure 15-17 show peak ground acceleration and spectral acceleration at ground surface calculated from both seismic hazard analysis (combination of PSHA and DSHA) and site response analysis. Peak ground acceleration and spectral acceleration at 190 points calculated using site response analysis are less than peak ground acceleration and spectral acceleration calculated using similar concepts used by [1].

In seismic microzonation with respect to ground shaking intensity, the values PGA and spectral acceleration at ground surface are used to differentiate three different zones with relatively equal levels [3]. For spectral zoning evaluation, the peak ground acceleration and spectral acceleration values of this study area are divided into three different zones which represent low, medium and high levels of spectral values. Table 4 shows the values of spectral accelerations that were used to distinguish the three different zones: low, medium and high spectral level. Figure 18 shows the distribution of risk level of Semarang based on the value of peak ground acceleration at ground surface.

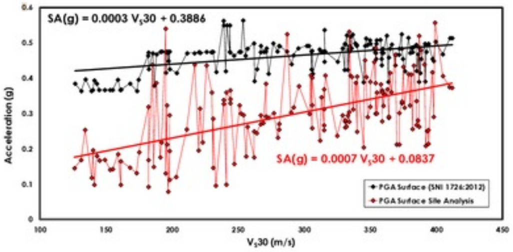


Figure 15 PGA at ground surface based on [1] and site response analysis

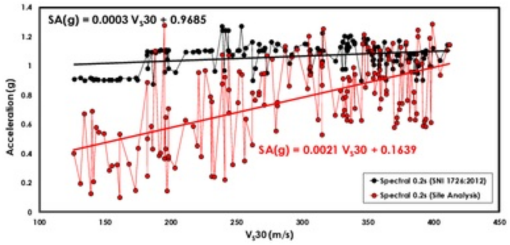


Figure 16 Spectral acceleration (T=0.2s) at ground surface based on [1] and site response analysis

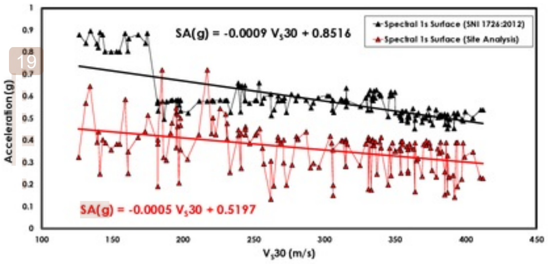


Figure 17 Spectral Acceleration (T=1s) at ground surface based on [1] and site response analysis

Table 4 Zoning Criteria for Seismic Risk according to PGA and spectral acceleration value at ground surface

	Surface Acceleration		
	PGA (g)	**0.2s (g)**	**1s (g)**
Low	0.15 – 0.32	0.43 – 0.72	0.14 – 0.31
Medium	0.32 – 0.47	0.72 – 1.00	0.31 – 0.37
High	0.47 – 0.64	1.00 – 1.29	0.37 – 0.64

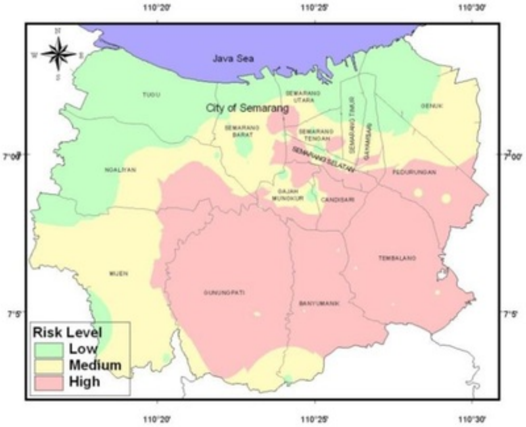


Figure 18 Seismic Risk map for Semarang City according to the PGA value at ground surface due to shallow crustal fault source (Lasem Fault) with magnitude 6.5 Mw and maximum distance 20 km

7.0 CONCLUSIONS

Seismic microzonation hazard and risk map have been carried out for Semarang city. The study includes the identification of all seismic sources influencing Semarang city, seismic hazard analysis based on [1], the identification of engineering bedrock using single station feedback seismometer, five acceleration time histories development based on shallow crustal fault source, site characterization, shear wave profile development using empirical equations and ground response analysis using 1-D shear wave propagation analysis.

The seismic risk map developed from this study is expected as basic information for disaster preparedness in planning and development of infrastructures of Semarang city.

Acknowledgement

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

DEVELOPMENT OF SEISMIC MICROZONATION MAPS OF SEMARANG, INDONESIA

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