

PEAK GROUND ACCELERATION AT SURFACE AND SPECTRAL ACCELERATION FOR MAKASSAR CITY BASED ON A PROBABILISTIC APPROACH

PERCEPATAN TANAH MAKSIMUM DI PERMUKAAN DAN PERCEPATAN SPEKTRA UNTUK KOTA MAKASSAR BERDASARKAN PENDEKATAN PROBABILISTIK

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ABSTRACT

The December 12, 2010 earthquakes (M 5.9) has drawn attention on the importance of knowledge of peak ground acceleration at surface (PGA_M) and spectral acceleration for Makassar City. The PGA_M and spectral acceleration play an important role in seismic design regulations. The purpose of this paper is to present the PGA_M and spectral acceleration for Makassar City based on a probabilistic approach. The analysis involved determination of peak ground acceleration at bedrock using Probabilistic Seismic Hazard Analysis (PSHA), the average shear wave velocity at 30 m depth ($Vs30$), and site classification. Results of the analysis showed that the values of PGA_M for Makassar City were varied from 0.177 – 0.21 g. Meanwhile, the spectral acceleration values at $T = 0.2$ and $T = 1$ second were varied from 0.459 – 0.541 g and 0.277 – 0.369 g respectively. From these results, the values of PGA_M and spectral acceleration are relatively higher at Tamalanrea and Biringkanaya districts and relatively lower at Tamalate district in comparison to other districts in Makassar City. This condition is associated with the location of those areas which are relatively closer to the earthquake source (Walanae fault), and is geologically dominated by stiff soil (SD).

Keywords: Peak ground acceleration at surface, spectral acceleration, PSHA, $Vs30$

ABSTRAK

Gempa 12 Desember 2010 (M5.9) menarik perhatian kita akan pentingnya pengetahuan tentang percepatan tanah maksimum di permukaan (PGA_M) dan spektra percepatan untuk Kota Makassar. PGA_M dan spektra percepatan memegang peranan penting dalam peraturan desain gempa. Tujuan dari penelitian ini adalah menentukan PGA_M dan percepatan spektra untuk Kota Makassar berdasarkan pendekatan probabilistik. Analisis yang dilakukan meliputi penentuan percepatan tanah maksimum di batuan dasar menggunakan Probabilistic Seismic Hazard Analysis (PSHA), rata-rata kecepatan gelombang geser pada kedalaman 30 m ($Vs30$), dan klasifikasi *site*. Hasil analisis menunjukkan bahwa nilai PGA_M untuk Kota Makassar bervariasi dari 0.177 – 0.21 g. Sementara itu, nilai spektra percepatan pada $T=0.2$ dan $T=1$ detik berturut-turut bervariasi dari 0.459 – 0.541 g dan 0.277 – 0.369 g. Nilai PGA_M dan spektra percepatan relatif lebih tinggi di Kecamatan Tamalanrea dan Biringkanaya serta relatif lebih rendah di Kecamatan Tamalate dibandingkan dengan Kecamatan lainnya di Kota Makassar. Hal tersebut dikarenakan lokasinya yang relatif lebih dekat dengan sumber gempa (patahan Walanae), dan secara geologi didominasi oleh jenis tanah sedang (SD).

Kata kunci: Percepatan tanah maksimum di permukaan, spektra percepatan, PSHA, $Vs30$

1. Introduction

BMKG and USGS historical earthquake archives from 1900 - 2014 showed no earthquake epicenter in Makassar City. Catalogue of significance and damaging earthquake from BMKG [1] showed that some earthquake events around Makassar City had

impacts to the city. One earthquake example that affects Makassar City was the December 12 th, 2010 Southwest Makassar earthquake (magnitude M 5.9) that occurred on 6.11° S and 117.55° E at 19 km depth. Although there was no report of any significant damage to buildings in the city, this earthquake caused panic among residents of Makassar City, as reported in various media [2, 3].

Makassar is the provincial capital of South Sulawesi, Indonesia. It is the largest city in Sulawesi Island in terms of population. The city has an area of 19,926 square kilometres and a population of around 1.6 million in 2013 [4]. Makassar City is also prone to earthquakes. There are active earthquake sources around Makassar City, i.e. Makassar thrust, Walanae, Palu Koro, Matano and Lawanopo faults. Seismotectonic conditions around Makassar which could trigger strong earthquakes that affect activities in this city.

There are some quite significant earthquake events felt in Makassar, of which occurred on February 23rd 1969 earthquake (Mw 6.1), and April 8th 1993 earthquake (Mw 5.5) with MMI values of III – IV MMI. Other earthquakes are on September 28th 1997 (Mw 5.9) with MMI values of III MMI [1], and December 12th 2010 earthquake (Mw 5.9) with MMI values of III-IV MMI [3]. Figure 1 shows earthquakes around Makassar City based on BMKG earthquake repository data [5] and USGS earthquake archive [6] from 1900–2014.

Makassar City is generally composed of three rock units, namely Alluvial, Basalt, and Breccia. The Alluvial dominated almost all Makassar City area. The Basalts mainly distributed in Tamalanrea and Biringkanaya districts. Tuffs and Breccias, could be found in Biringkanaya, Tamalanrea, Panakkukang, and Manggala districts [7]. Most of alluvial in Makassar City is dominated by stiff soil (SD), which will provide amplification effect in case of earthquake.

Thus, attentions must be paid to this vulnerable condition. One of the efforts to minimize the earthquake impacts is to provide the information of peak ground acceleration at surface (PGA_M) and spectral acceleration. Peak ground acceleration at surface (PGA_M) and spectral acceleration play an important role in seismic design regulations. The map of PGA_M and spectral acceleration is still not readily available for local scale in Indonesia, although, a study on seismic hazards had been conducted by Indonesian Seismic Hazard Map Revision Team in 2010 [8].

The main purpose of the paper is to present the peak ground acceleration at surface (PGA_M) and spectral acceleration for Makassar City based on a probabilistic approach. The study on PGA_M and spectral acceleration are believed to make a significant contribution in planning of the earthquake resistant buildings and infrastructures in Makassar City.

2. Methods

This research was conducted by collecting and analyzing earthquakes data, identifying and modeling earthquake sources, characterizing each earthquake sources, determining attenuation and logic tree, Probabilistic Seismic Hazard Analysis (PSHA), determining PGA_M and spectral acceleration. A brief description of the research method is summarized in the flow chart as shown in Figure 2.

All earthquakes data were processed using statistical principles to minimize the systematic error. The data processing steps included uniformity of magnitude, declustering and magnitude completeness analysis. Uniformity of magnitude refer to previous study [9, 10]. The relation between moment magnitude (Mw) and body wave magnitude (mb) also moment magnitude (Mw) and surface wave magnitude (Ms) is shown in Figure 3. The separation of main shock from foreshocks and aftershocks was conducted to obtain independent data using time and distance range based on Gardner and Knopoff empirical criteria [11] and performed with a software package to analyze seismicity (ZMAP) [12].

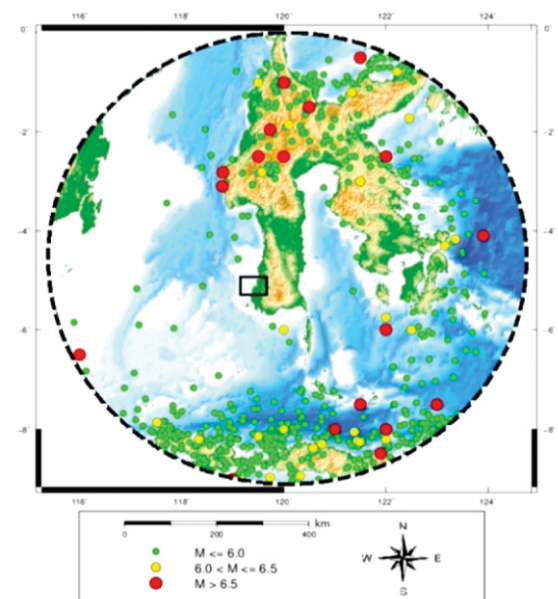


Figure 1. Earthquakes around Makassar from 1900 - 2014 ($M \geq 5$, depth ≤ 300 km and distance ≤ 500 km [5, 6].

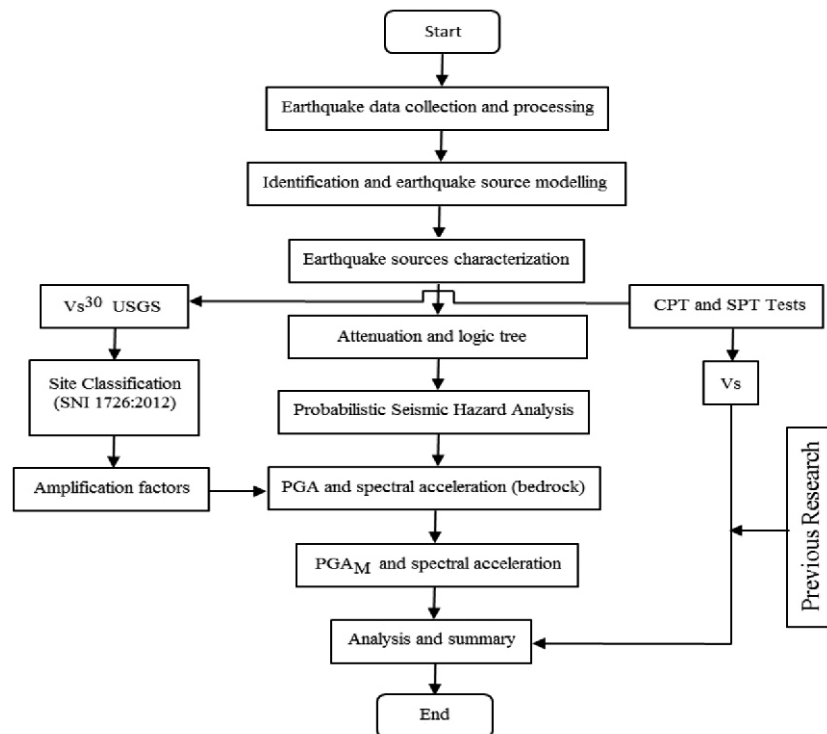


Figure 2. Flow chart of the analytical method used in this study.

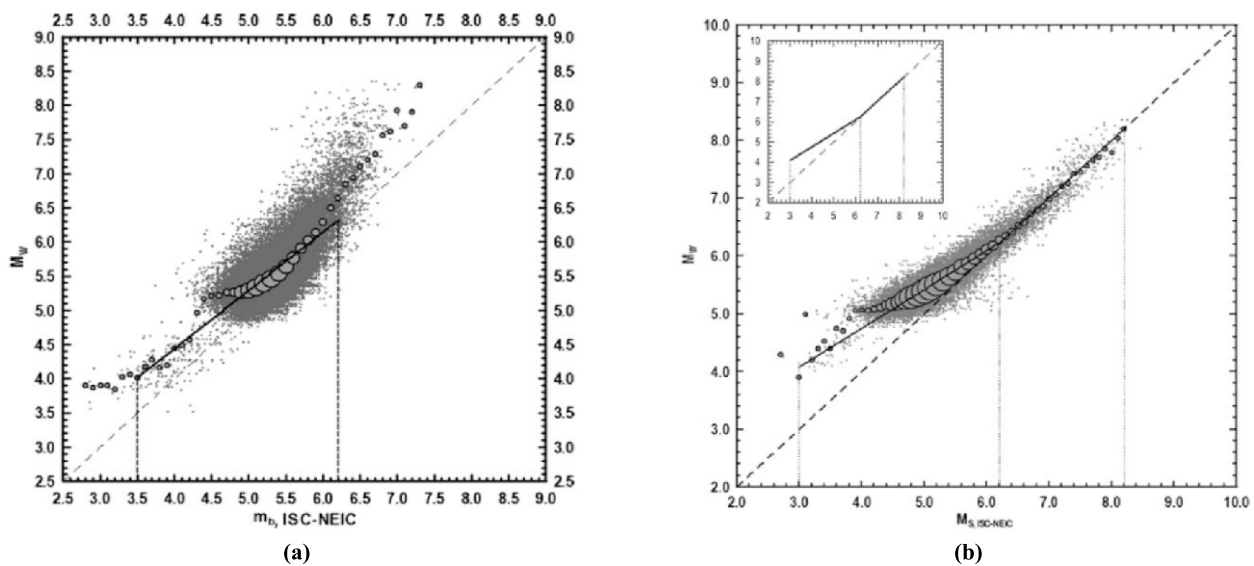


Figure 3. Relation between Mw vs mb (a), and Mw vs Ms (b) [10].

This study used BMKG and USGS earthquakes archive from 1900 to 2014 with 868 events having criterias: magnitude ($M_w \geq 5$), depth ≤ 300 km and distance ≤ 500 km from Makassar City (see Figure 1). Estimation of seismic hazard parameters requires magnitude completeness. Completeness of seismic data analysis method used in this study followed the Stepp procedure [13]. Completeness data was performed with Seismic Hazard Assessment Program (SHAP) [14]. Magnitude completeness data (Figure 4) show that earthquakes with magnitudes between 5 and 6 complete in the last 25 years, magnitude 6 - 7 complete in 45 years, while magnitude more than 7 complete in 80 years.

Identification and Earthquake Source Modeling.

Earthquake source modeling was made by interpreting geological conditions and seismotectonic around 500 km from Makassar City. In this study, earthquake sources were classified into subduction, fault, and background sources. Earthquake sources used in this study are Walanae fault, Makassar Thrust, Lawanopo fault, Matano fault, Poso fault, Palu Koro fault, Tolo Thrust, Sula fault and Batui Thrust as shown in Figure 5.

Earthquake Source Characterization.

Earthquake sources characteristics include the a-value, b-value, maximum magnitude, mechanism, dimension,

position, and slip rate. The a-value related to total number or annual rate of events [15]. The b-value is calculated from the slope of the log (number of earthquakes $\geq M$) vs earthquake magnitude plot [16], as shown in Figure 6.

Earthquake sources characteristics in this study were obtained from various previous study references [8, 17], as summarized in Table 1. Maximum magnitude, slip rate and fault position for global and local studies have the same values for each parameter because they used the same references. The a-value and b-value parameter are slightly different due to the differences in the use of seismic data interval. This study used earthquake data up to 2014 while the previous study [8] used up to 2009.

Attenuation Model. There is no specific attenuation model for Indonesia. Therefore, in this study we used attenuation model derived in other region, which is similar with tectonic and geology of Indonesia. Attenuation model selection is based on earthquake source model used. It was classified according to earthquake source model. Table 2 shows attenuation model used for subduction, fault / shallow crustal and background earthquake sources [18,19,20,21,22,23].

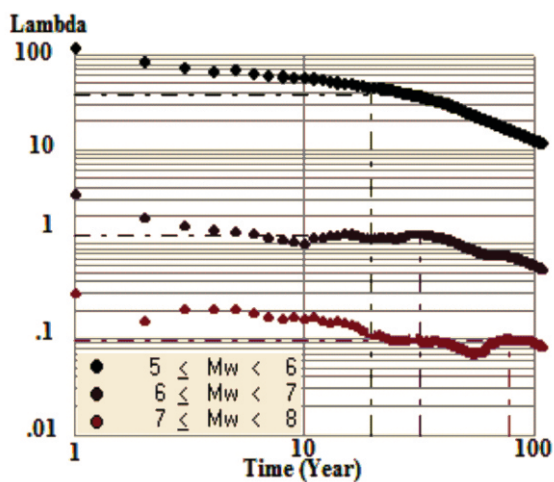


Figure 4. Magnitude completeness data.

Table 1. Earthquake source characteristics [8, 17].

Fault Name	Slip Rate	Mmax	Mechanism	Dip	Position	
					Top	Bottom
Palu Koro	35	7.94	Strike Slip	50	3	18
Poso	2	6.93	Strike Slip	90	3	18
Matano	37	7.9	Strike Slip	90	3	18
Batui Thrust	2	7.06	Reverse Slip	40	3	18
Sula Thrust	10	7.19	Reverse Slip	45	3	18
Makassar Thrust	4	7.46	Reverse Slip	25	3	20
Lawanopo	25	7.59	Strike Slip	70	3	15
Walanae	2	7.53	Strike Slip	90	3	18
Tolo Thrust	9	7.94	Reverse Slip	25	3	20

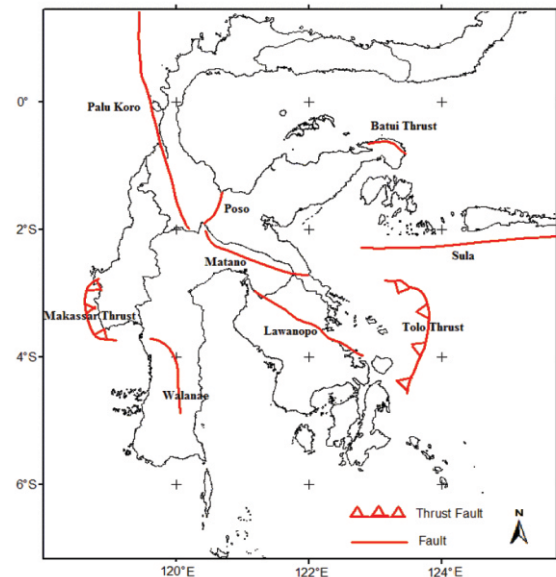


Figure 5. Earthquake sources modeling.

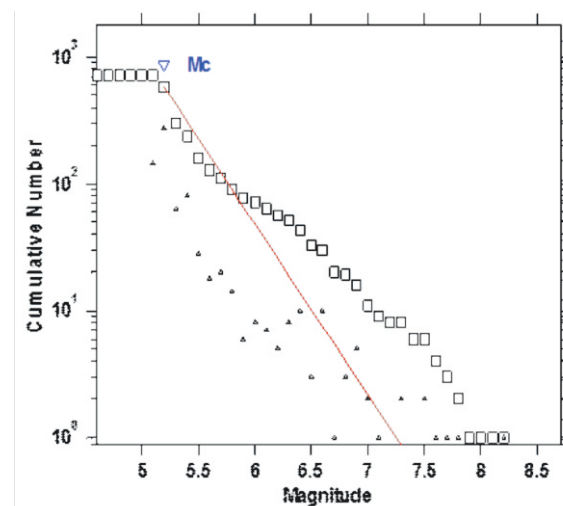


Figure 6. Frequency magnitude relationship for the study area.

Table 2. Attenuation model used in this study [18, 19, 20, 21, 22, 23].

No.	Earthquake Source	Attenuation Model
1	Subduction (Megathrust)	a. Zhao et al., 2006 [20] b. Youngs et al., SRL, 1997 [18] c. Atkinson danBoore, 2003 [19]
2	Shalow Crustal	a. ChioudanYoungs, 2008 [23] b. Booredan Atkinson, 2008 [21] c. Campbell danBozorgnia, 2008 [22]
3	Background (Deep)	a. Atkinson-Boore, Wordwide 2003 [19] b. Atkinson-Boore, Cascadia 2003 [19] c. Youngs et al., 1997 [18]

Uncertainty Management. Uncertainty in seismic hazard analysis such as recurrence model, maximum magnitude, and attenuation model were managed by logic tree approach. The use of logic tree was adjusted to each earthquake source models. Figure 7 is the logic tree model for fault earthquake source used in this study.

Probabilistic Seismic Hazard Analysis. Probabilistic Seismic Hazard Analysis (PSHA) is a commonly used tool to evaluate the hazard of seismic ground motion at a site by considering all possible earthquakes in the area. The analysis was commenced with calculated the probability of a particular value x will be exceeded a ground motion parameter X [24]. PSHA method was firstly developed by Cornell [25] and continued by Merz and Cornell [26] then further developed by McGuire [27]. Many researchers have adopted this methodology for evaluating hazard and recently this method has been adopted to determine seismic hazard map in Indonesia [8].

The Probabilistic Seismic Hazard Analysis (PSHA) is performed by using total probabilistic concept [25] as formulated in formula 1 below :

$$P_X(x) = \int_M \int_R P(X > x|m, r) f_M(m) f_R(r) dr dm \quad (1)$$

Where $P(X > x|m, r)$ is earthquake probability with magnitude m at distance r produced peaks $X > x$. $f_M(m)$ and $f_R(r)$ are probabilistic density functions for magnitude and distance respectively. In this research, PSHA was performed for 2% probability of exceedance (PE) in 50 years, as in NEHRP 1997, ASCE 7-98, IBC 2000 and SNI 1726:2012 which refers to ASCE 7-10 [28].

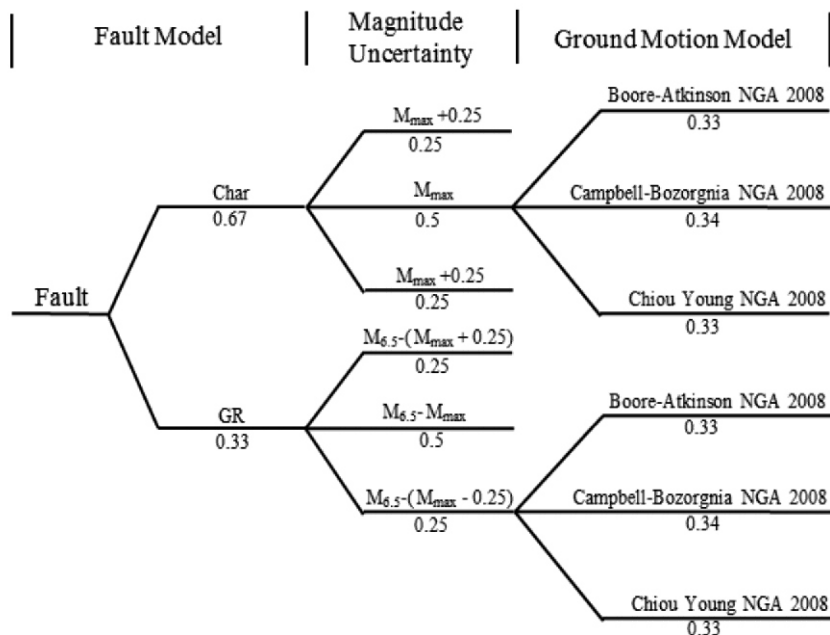


Figure 7. Logic tree for fault earthquake source.

Vs30 and Site Classification. Seismic hazard analysis at surface is influenced by soil layer conditions, including type, thickness, rigidity of soil layers, and ground water level. Soil layer conditions could be determined by performing soil investigation (boring) or other geophysics methods. In this study, soil layer condition was determined according to shear wave velocity for layer up to 30 m depth (Vs30) from the USGS global Vs30 [29].

Vs30 from USGS derived from topographic slope as a proxy. In order to verify Vs30 data and to support analysis results, this current study used Standard Penetration Test (SPT) and Cone Penetration Test (CPT) data. The Locations of CPT and SPT measurement point are shown in Figure 8, while Figures 9 and 10 show SPT and CPT data.

SPT data were converted into Vs30 by using the average of Ohta-Goto and Imai-Tonouchi equation [30, 31] as follow:

$$V_s = 85.3N^{0.341} \quad (2)$$

$$V_s = 96.9N^{0.314} \quad (3)$$

where Vs is shear wave velocity (m/s) and N is SPT values. Correlation between Vs and CPT for all soil types based on regression of a large dataset from various sites worldwide [32]. Equation (4) is presented Mayne formula [33] with Vs as a function of the logarithm of f_s , rather than the natural logarithm as originally [34].

$$V_s = 118.8 \log f_s + 18.5 \quad (4)$$

Where f_s is sleeve friction (kPa).

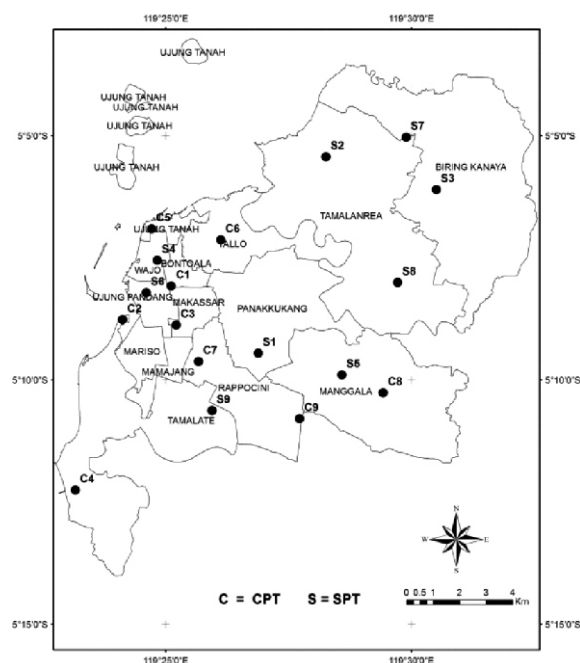


Figure 8. CPT and SPT measuring points.

In this study, site classification based on SNI 1726:2012 provision about procedure of earthquake resistance planning for building and non-building structures [35] as shown in Table 3.

Table 3. Site Classification [35].

Site Class	Vs (m/sec)
SA (Hard Rock)	>1500
SB (Rock)	750 - 1500
SC (Very Dense Soil and Soft Rock)	350 - 750
SD (Stiff Soil)	175 - 350
SE (Soft Soil)	< 175

Peak Ground Acceleration at Surface and Spectral Acceleration. Peak ground acceleration at surface was determined based on site classification by considering the amplification effect specifically (PGA_M). In order to obtain PGA_M , the provision in SNI 1726:2012 [35] can be used:

$$PGA_M = F_{PGA} = PGA \quad (5)$$

Where PGA_M is the peak ground acceleration adjusted for site classification effect. PGA is the peak ground acceleration at bedrock (g) and F_{PGA} is site coefficients factor for PGA. Like the, F_{PGA} coefficient also follows SNI 1726:2012 [35] as shown in Table 4.

Table 4. Site coefficient, F_{PGA} [35].

Site Class	$PGA \leq 0.1$	$PGA = 0.2$	$PGA = 0.3$	$PGA = 0.4$	$PGA \geq 0.5$
SA	0.8	0.8	0.8	0.8	0.8
SB	1.0	1.0	1.0	1.0	1.0
SC	1.2	1.2	1.1	1.0	1.0
SD	1.6	1.4	1.2	1.1	1.0
SE	2.5	1.7	1.2	0.9	0.9
SF	Specific Site				

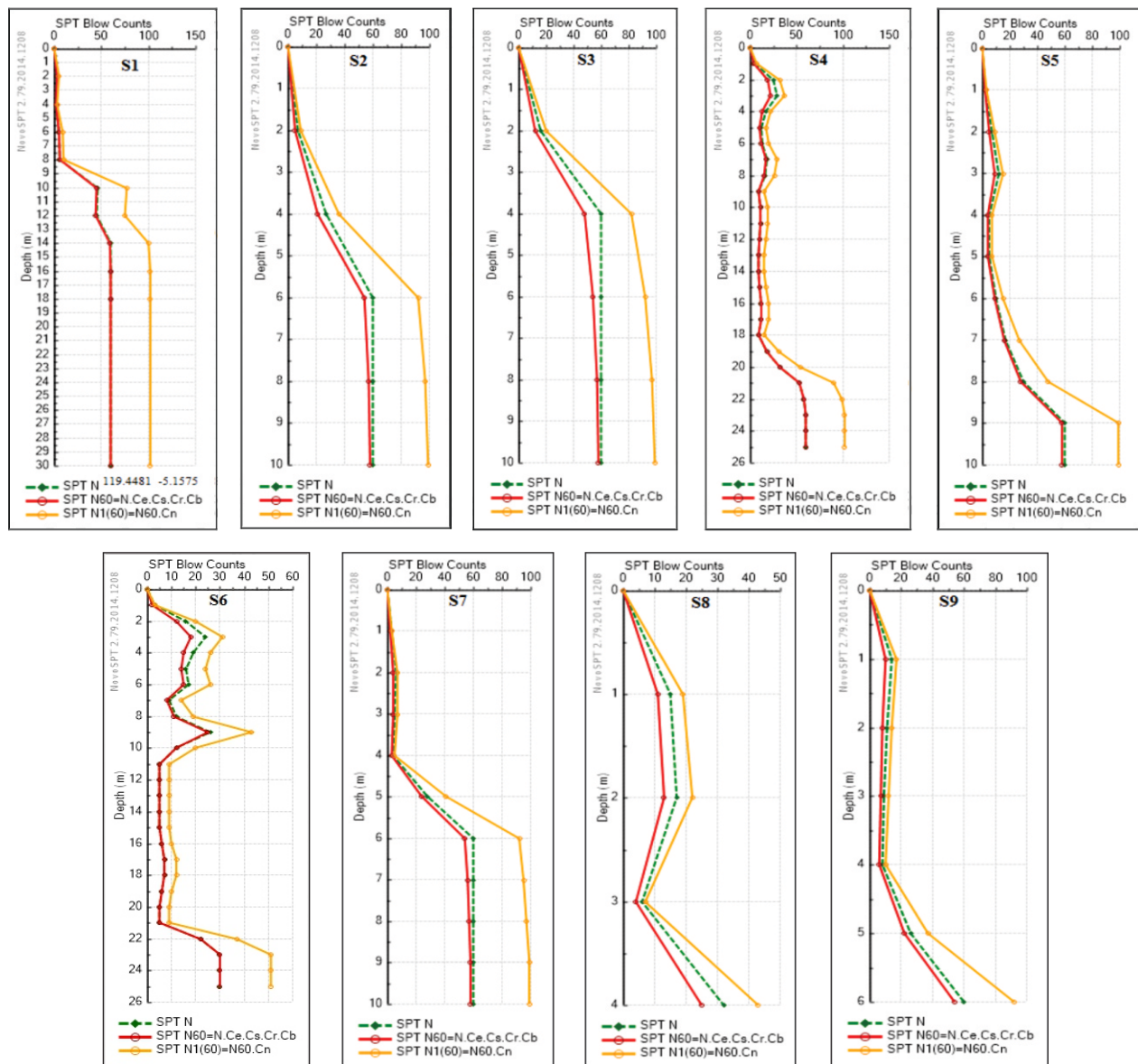


Figure 9. SPT data used in this study.

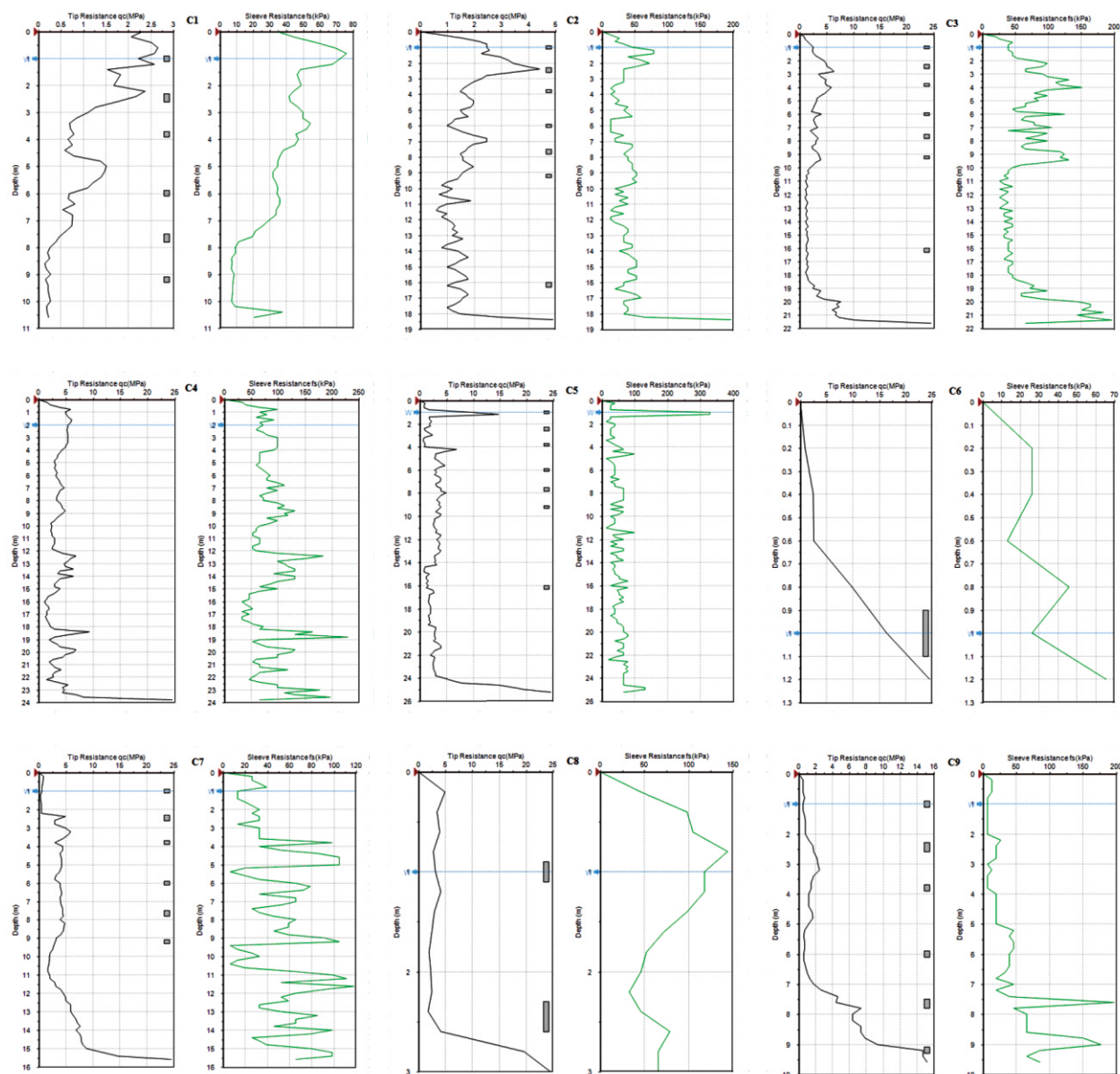


Figure 10. CPT data used in this study.

Seismic amplification factor at period (T) = 0.2 seconds and $T=1$ second was needed to determine spectral acceleration. Amplification factor includes vibration amplification factor related to acceleration at short period vibration $T = 0.2$ seconds (F_a) and $T = 1$ second (F_v). Spectral acceleration parameters at short period of $T = 0.2$ seconds (S_{MS}) and $T = 1$ second (S_{M1}) was adjusted to site classification effect, as stated in SNI 1726:2012 [35] provision:

$$S_{MS} = F_s \times S_s \quad (6)$$

$$S_{M1} = F_v \times S_1 \quad (7)$$

Where S_s is the bedrock spectral acceleration parameter mapped for short period of $T = 0.2$ seconds and S_1 is the bedrock spectral acceleration mapped for period $T = 1$ second. The F_a and F_v coefficients follow SNI 1726:2012 [35] as shown in Table 5 and 6.

3. Results and Discussion

Probabilistic Seismic Hazard Analysis (PSHA).

Figure 11 to 13 show the peak ground acceleration (PGA) and spectral acceleration at $T = 0.2$ seconds (short period), and $T = 1$ second (long period) at bedrock for the probability exceeded 2% in 50 year life of the building. The results indicate that the PGA value for Makassar City varies from 0.11 to 0.138 g. The spectral acceleration value at bedrock for $T = 0.2$ second ranges between 0.293 and 0.357 g while the spectral acceleration value for $T = 1$ second ranges between 0.135 to 0.152 g. This results are close to the previous study [8], which showed PGA values varies from 0.1 to 0.15 g. The spectral acceleration value at bedrock for $T = 0.2$ seconds ranges between 0.3 and 0.49 g while the spectral acceleration value at bedrock for $T = 1$ second ranges between 0.14 to 0.29 g.

Table 5. Site coefficient, F_a [35].

Site Class	$S_s \leq 0.25$	$S_s=0.5$	$S_s=0.75$	$S_s=1$	$S_s \geq 1.25$
SA	0.8	0.8	0.8	0.8	0.8
SB	1.0	1.0	1.0	1.0	1.0
SC	1.2	1.2	1.1	1.0	1.0
SD	1.6	1.4	1.2	1.1	1.0
SE	2.5	1.7	1.2	0.9	0.9
SF	SSb				

Table 6. Site coefficient, F_v [35].

Site Class	$S_1 \leq 0.1$	$S_1=0.2$	$S_1=0.3$	$S_1=0.4$	$S_1 \geq 0.5$
SA	0.8	0.8	0.8	0.8	0.8
SB	1.0	1.0	1.0	1.0	1.0
SC	1.7	1.6	1.5	1.4	1.3
SD	2.4	2.0	1.8	1.6	1.5
SE	3.5	3.2	2.8	2.4	2.4
SF	SSb				

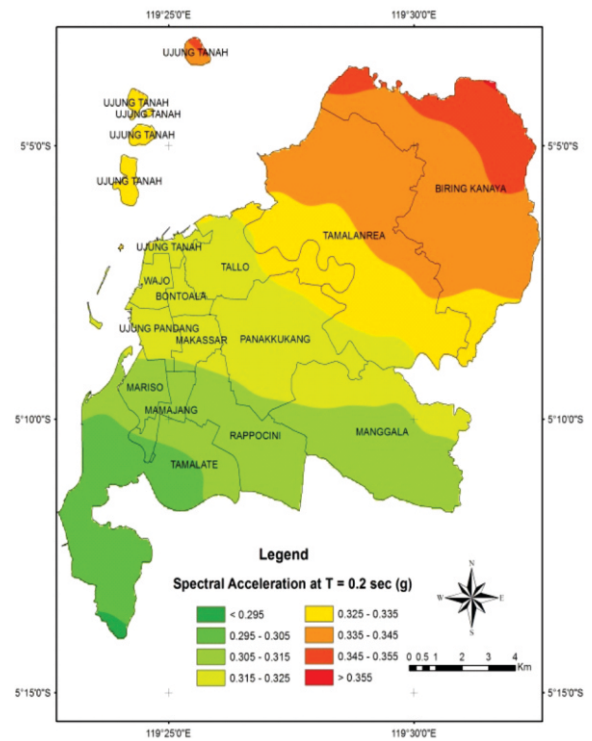


Figure 12. Spectral acceleration map at bedrock for $T=0.2$ seconds with 2% PE in 50 years.

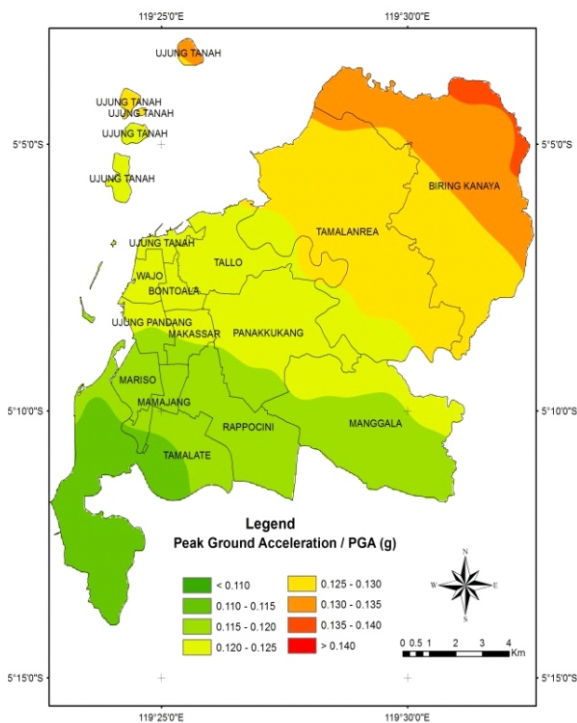


Figure 11. Peak ground acceleration (PGA) map at bedrock with 2% probability of exceedance (PE) in 50 years.

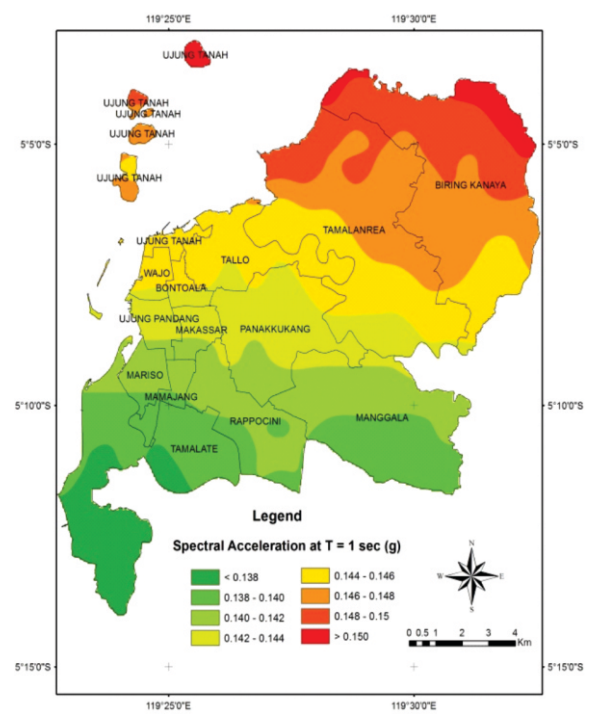


Figure 13. Spectral acceleration map at bedrock for $T=1$ second with 2% PE in 50 years.

Thus results indicate that PGA and spectral acceleration at $T = 0.2$ seconds and $T = 1$ second become higher in the northeast area (Biringkanaya and Tamalanrea districts) and relatively lower at Tamalate district in compare to other districts. This is associated with the Walanae fault, located about 90 km from Makassar City with a maximum magnitude about 7.53 (see Table 1).

Shear Wave Velocity (Vs30). Direct measurements of Vs30 can not be done in this study, but Vs30 from USGS were verified with indirect Vs estimation method from 18 points CPT and SPT tests in Makassar. The comparison of Vs30 values derived from USGS and estimated Vs values based on CPT and SPT tests is shown in Figure 14. It shows a good correlation between those parameters, which is about 0.73.

Figure 15 shows the values of shear wave velocity (Vs30) derived from USSG for Makassar City. The Vs30 value for Makassar City varies between 180 and 330 m/sec. In general, the Vs30 values variation of Makassar City are still in the same category or siteclass. Based on this figure, the site classification of Makassar City falls into stiff soil type / SD (see Table 3). However, most area of Tamalanrea district, northeast side of Biringkanaya district, most area of Tamalate, Rappocini, Mamajang and Makassar districts had Vs30 values smaller than other areas in Makassar City. Those lower Vs30 values area tend to be more vulnerable to the earthquake.

Peak Ground Acceleration at Surface. Peak ground acceleration at surface which is adjusted for site classification effect (PGA_M) for Makassar City is shown in Figure 16. The value of PGA_M for Makassar City varies from 0.177 to 0.21 g. The values of PGA_M are relatively higher at Tamalanrea and Biringkanaya districts and relatively lower at Tamalate district compared to other districts. This condition is associated with the locations which are relatively closer to earthquake source (Walanae fault) and the geological condition which were dominated by stiff soil (SD). The comparison of values between PGA_M and PGA imply amplification factor values around 1.5.

The PGA_M values obtained in this study are different from previous study [36] as shown in Figure 17. The figure shows two dominant clusters, the first located near the center of Makassar, which is dominated by acceleration values of 0.11 to 0.165 g. The second ones in eastern Makassar and west coast of Makassar, which were dominated by acceleration values less than 0.055 g. Thus, these results do not follow the typical patterns.

The results of this current study show relatively higher acceleration values than previous study [36]. The acceleration pattern increased towards the northeast

and slightly declined in the southern of Biringkanaya district. It was caused by the relatively higher Vs30 values in this area than the surroundings, which is therefore indicated that the amplification of acceleration from bedrock to surface is relatively lower. This decline of surface acceleration in southern Biringkanaya district also appeared in previous study [36].

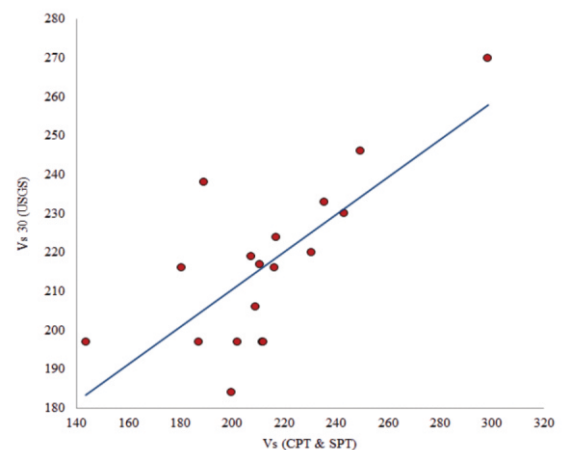


Figure 14. Correlation between Vs30 USGS [29] and estimated Vs from CPT and SPT test.

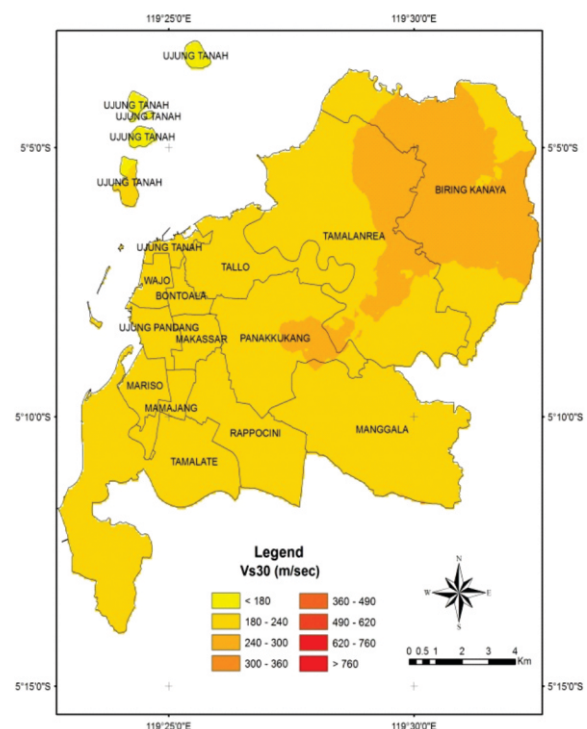


Figure 15. Vs30 map for Makasar City [29].

The difference between results of this study than previous ones [36] are in analytical method and the use of Determination Seismic Hazard Analysis (DSHA) to determine peak ground acceleration, while this current study used probabilistic approach (PSHA). The different attenuation function also contributes to the different results. The current result is more reliable because a previous study [36] assumed that bedrock acceleration for all area in Makassar had the same value is about 0.046 g, while this current study used 334 grid points with values varying from 0.11 to 0.21 g. Beside, probabilistic methods can be viewed as inclusive of all deterministic events with a finite probability of occurrence [37].

Spectral acceleration results at surface for period $T = 0.2$ seconds and $T = 1$ second are shown in Figures 18 and 19 respectively. From figure 18, the spectral acceleration values at period $T = 0.2$ seconds varies from 0.459 to 0.541 g. The spectral acceleration values are relatively higher at Tamalanrea and Biringkanaya districts, and relatively lower at Tamalate district compared to other districts. This figure also indicates amplification factor values about 1.54 when the spectral accelerations compared with spectral acceleration at bedrock values (0.293 g to 0.357 g).

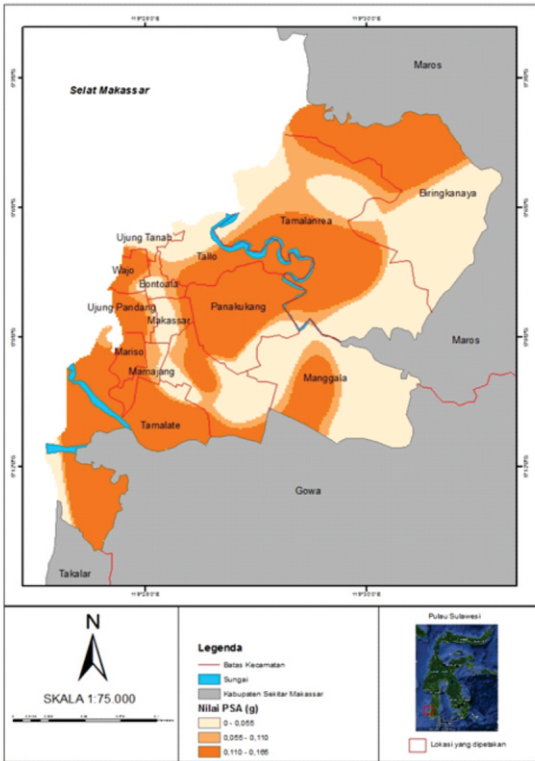


Figure 17. PGA map at surface for PGA (bedrock) value 0.046 g [36].

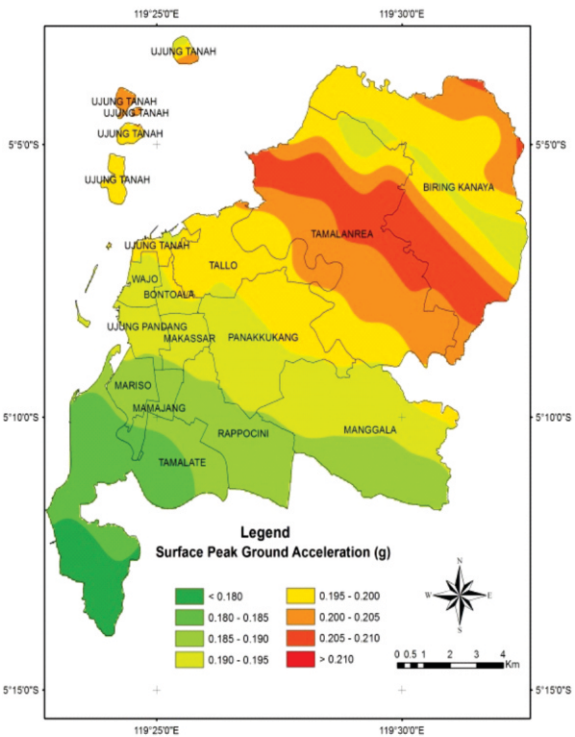


Figure 16. Peak ground acceleration map at surface (PGA_s) adjusted for site classification effect.

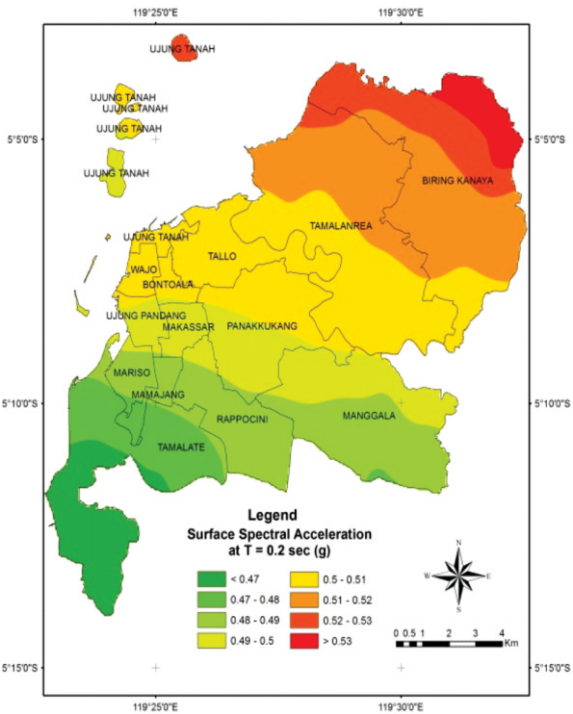


Figure 18. Spectral acceleration map at surface for period (T)=0.2 seconds.

As seen in figure 19, the spectral acceleration at surface for period $T = 1$ second varies from 0.277 to 0.369 g. Similar to the PGA_M and spectral acceleration at surface for $T = 0.2$ seconds, these spectral acceleration values were relatively higher at Tamalanrea and Biringkanaya district and relatively lower at Tamalate district compared to other districts. This figure also show amplification factor values about 2.24 when the spectral accelerations compared to spectral acceleration at bedrock values (0.135 g to 0.152 g).

In accordance with Table 6, except rock types (SA dan SB site classes), soil amplification is generally greater at longer periods than at the shorter periods. The natural vibration period of site (1D) would appears long period character. Meanwhile, when earthquake propagated in sufficient thickness site, the higher frequency (shorter periods) would be filtered. The frequency of earthquake would be closer to the natural vibration period of site and soil amplification would greater.

Strong motion data records from different geologic deposits during the Loma Prieta earthquake on October 17, 1989 provide important information. Figure 20 shows the average response spectra of ground motion recorded on soft clay and rock sites during the Loma Prieta earthquake [38]. The Peak acceleration values are approximately from 0.08 to 0.1 g at rock sites and were amplified of two to three times to 0.2 or 0.3 g at soft soil sites. The response spectral acceleration at short periods (~ 0.2 or 0.3 seconds) was also amplified an average of two to three times. At longer periods (between about 0.5 and 1.5 or 2 seconds), the amplification of the response spectra on the soft clay sites relative to the rock were also greater, ranging from about three to six times. Ground motion on stiff soil types relative to the rock also experienced amplification during the Loma Prieta earthquake, but the amplification value smaller than on soft soils [38]. This previous study gave the description that the amplification factors of long periods are greater than short periods.

This study results show that peak ground acceleration at surface (PGA_M) and spectral acceleration for $T = 0.2$ seconds and $T = 1$ second are relatively higher at Tamalanrea and Biringkanaya districts and relatively lower at Tamalate district compared to other districts. By considering most of Makassar City area have stiff soil (SD), the location factor which are relatively closer to the earthquake source (Walanae fault) cause the PGA_M and spectral acceleration for $T = 0.2$ seconds and $T = 1$ second to be relatively higher at Tamalanrea and Biringkanaya districts compared to other districts in Makassar City.

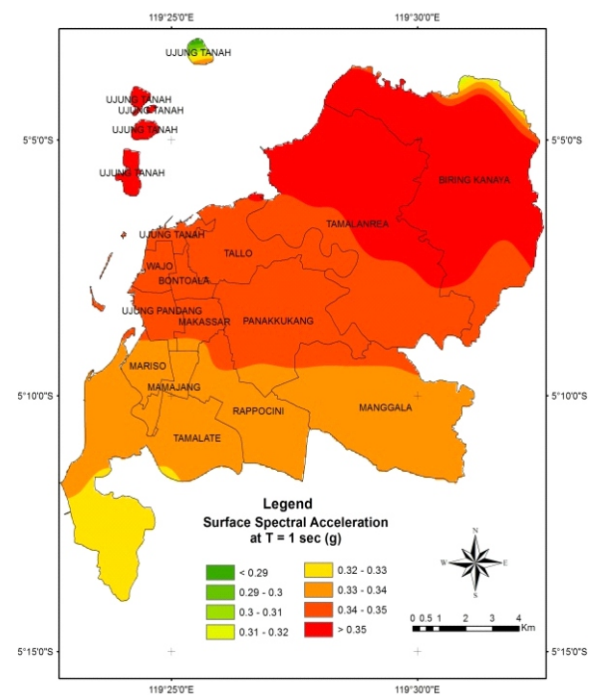


Figure 19. Spectral acceleration map at surface for period (T)=1 second.

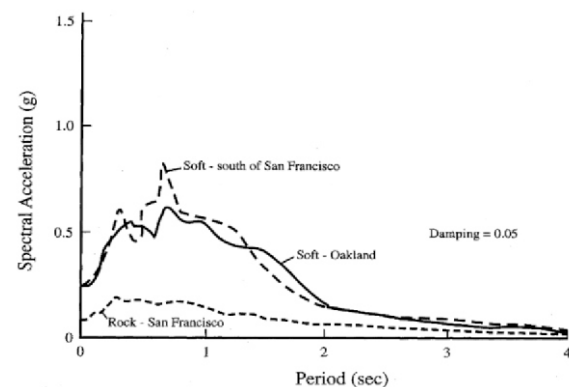


Figure 20. Average spectra recorded during the 1989 Loma Prieta earthquake at rock sites and soft soil sites [38].

4. Conclusion

Based on PSHA, peak ground acceleration (PGA) values at bedrock for Makassar City with 2% probability of exceedance in 50 years varies from 0.11 to 0.138 g, and spectral acceleration value for period $T = 0.2$ seconds varies from 0.293 to 0.357 g and for $T = 1$ second varies from 0.135 to 0.152 g.

Peak ground acceleration at surface adjusted to site classification effect (PGA_M) for Makassar City varies between 0.177 and 0.21 g. Spectral acceleration value for period $T = 0.2$ seconds varies from 0.459 to 0.541 g and for $T = 1$ second varies from 0.277 to 0.369 g.

Based on this current study, peak ground acceleration at surface values for Makassar City is relatively higher

at the Tamalanrea and Biringkanaya districts and relatively lower at Tamalate district compared to others districts. This condition is associated with relatively closer location of those areas to earthquake source (Walanae fault) and the geological condition as well which were dominated by stiff soil (SD).

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