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Analysis of Seismic Ground Response in Makassar using Geotechnical In-situ Tests

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Abstract. This paper presents the analysis of seismic ground response of Makassar, the capital city of South Sulawesi Province in Indonesia, by employing an equivalent linear approximation of non-linear response technique. In this way, in-situ geotechnical tests were undertaken to obtain soil mechanics properties and establish shear wave velocity profiles by using CPT and SPT based empirical correlation formulas. Acceleration time histories model, which is considered to be able to propagate similar maximum credible earthquake, was used for input motion in computing seismic ground response of typical deep sediment in Makassar. Our findings suggested that seismic wave travels from bedrock to surface would be amplified at range of 0.124g to 0.349g with amplification factor of 1.14 to 5.54. Response spectral acceleration is found at range of 0.315g to 1.501g with the frequency of 7.69 Hz to 20 Hz. The southern areas of the city would propagate a high seismic amplification, while the eastern areas would yield low amplification. This is due to typical deep sediment seated on the southern areas is a thick clay overlying stiff sand. This would create impedance contrast, leading to reverberating a trapped seismic wave in between those two layers, and then producing high resonance at surface level. Deep sediment with interbedded clay and sand or interbedded sand and clay above bedrock would yield a larger seismic amplification than deep sediment with only clay dominated or sand dominated soil.

Introduction

Damaged structure associated with earthquake is generally caused by strong ground motion. To mitigate severe impact of earthquake, seismic hazard microzonation should be conducted. Microzonation is a tool of assessing seismic hazard and evaluating seismic risk on an area. The product of microzonation is the characteristics of ground motion, which is much controlled by seismic sources at relatively closed distance to the area as well as site specific geotechnical conditions [1]. Microzonation comprises the following activities such as modelling earthquake mechanism, evaluating the propagation of seismic waves from bed rock to the surface, and then developing a hazard map to indicate the vulnerability due to potential seismic hazard [2]. It is very urgent to conduct such assessment of ground motion hazard propagated by earthquake in one of the most populated city in Indonesia. Makassar is a capital city of South Sulawesi Province where around 1.3 million people residing on 175.8 km^2 area. The city is located at a relatively low seismic area and its peak ground acceleration (PGA) is probabilistically at range of 0.05g to 0.1g [3]. However, since Makassar is seated on a deep sedimentary deposit, the low seismic magnitude could be propagated to a high seismic ground motion. Therefore, we endeavour to investigate how large the seismic propagation in ground surface with typical Makassar deep sediment deposits. Seismic ground response analysis was undertaken by using an equivalent linear approximation of non-linear response technique. Makassar is located in southern arm of Sulawesi (Figure 1). Geomorphology of the city is relatively flat in South-West to North-West, around 1 to 2 meters above mean sea level (MSL). In the East-North to East-South of the city, the ground surface is contouring with slope about 5°. Quaternary sedimentation from Jeneberang River and Tallo River has formed alluvial sediment where the city seating on, covering about 85% of total area with more than 60% of total population.

Figure 1. Satellite image of Makassar.

PGA Based on DSHA

Deterministic seismic hazard analysis (DSHA) was implemented to assess peak ground acceleration (PGA) at bedrock level. A number of earthquake events, which is considered to have impact on Makassar was collected, and then employed as seismic sources. The data is totally from historical seismic record published by US Geological Survey. DSHA consists of identification of seismic sources, their distance to Makassar, and selection of the controlling earthquake by using attenuation equation [4]. Several faults and thrusts affecting the seismicity of Makassar were analysed, such as Palu-Koro Fault, Poso Fault, Matano Fault, Walanae Fault, Makassar Thrust, Lawanopo Fault, and Flores Back Arc. It is around 837 earthquake events in the period of 1900 – 2015. The largest magnitude of the earthquake events is Flores Sea earthquake in 1990, with M 7.1, located at around 270 km from Makassar. The second largest is the Mamuju 1984 earthquake with M 7.0, 266 km from Makassar, then the Majene 1969 earthquake with M 7.0, 225 km from Makassar. The closest distance of earthquake events to Makassar is the Matango 2014 earthquake, with M 4.3, at 77 km north of Makassar. After seismic sources data was collected, empirical attenuation relationships of their PGAs and distances were analysed in order to obtain a controlling earthquake. The attenuation relationships used in this study are Crouse [5], Donovan and Bornstein [6], Joyner et al [7], and Fukushima and Tanaka [8] formulas. It was found that controlling earthquake for Makassar is 0.034g at 222.95 km in the north of Makassar, closed to Majene.

Shear Wave Velocity and In-Situ Geotechnical Tests

To investigate Makassar's specific seismic ground response, in-situ geotechnical tests were conducted, consisting of 32 CPTs and 24 SPT-boreholes. The quantity seems to be less, yet they are still considered to be sufficient for this study as they are more representative of major parts in the city. Empirical correlations between skin friction of CPT and shear wave velocity (V_s), as well as its relation to unit weight of soil (Eq.2) were employed, based on Mayne approximation [9] [10].

$$V_s = 118.8 \log f_s + 18.5 \tag{1}$$

$$\gamma = (8.32 \cdot \log(V_S)) - (1.61 \cdot \log(z)) \tag{2}$$

where γ_{soil} is soil mass density, kN/m^3, V_S is shear wave velocity, in m/s and z *is* depth, in metres, d f_s is skin friction (kPa).

On the basis of SPTs data, shear wave velocity was estimated by using Wair et al formula [11], as follow:

$$V_s = 30 \cdot N_{60}^{0.215} \cdot \sigma'_v{}^{0.275} \tag{3}$$

where N_{60} is N-SPT with uniform reference energy ratio of 60%, and σ'_v is effective vertical stress (KPa).

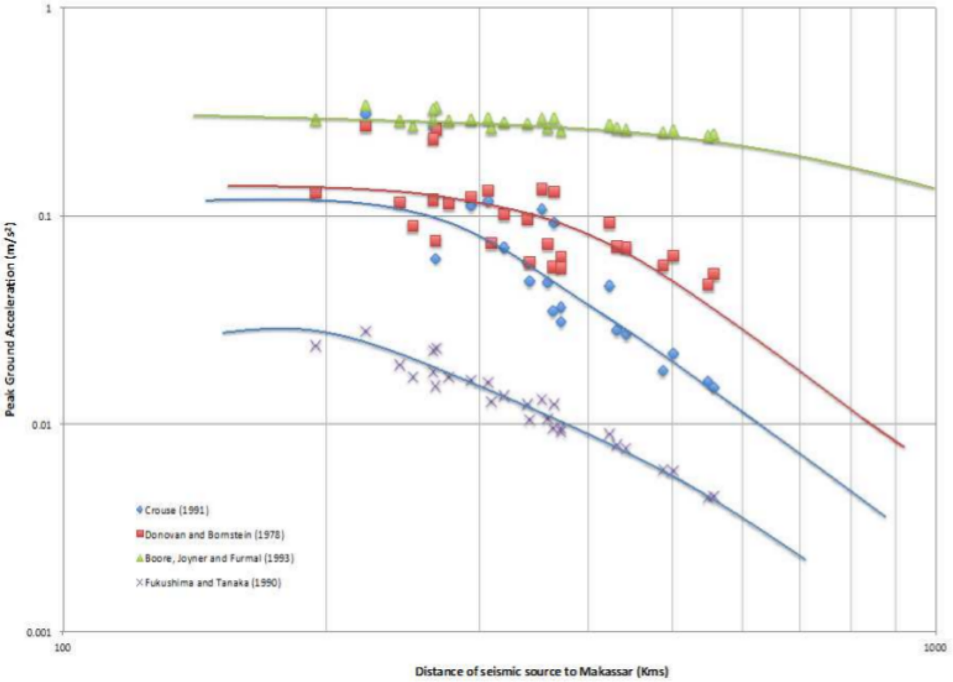

Figure 2. Attenuation PGA vs distance of seismic sources to Makassar.

Once th CPTs and SPTs data were collected, shear wave velocity profiles can be empirically imated. As shown in Figure 3, the shear wave velocity profiles are much related to thickness and type of soil in the sediment. By using site classification of International Building Code (IBC) 2003, typical soil re ed to share wave velocity can be identified. Most of soil is categorized as stiff to soft soil since the shear wave velocity values are about 200 m/s. In the north coastal area such as Ujung Tana, bedrock was found at -24.8 m, underlying a stiff sand and a bit clay. Similarly, in the South coastal area, such as Barombong, bedrock was found at -23.8 m overlaid by stiff sand. In the Centre Point of Indonesia (CPI) located at the mid-west, bedrock was found at -18.8 m, underlying 14 metres marine clay and 4 metres stiff sand. In contrast, as it moves eastward, sediment is shallowed at 3 m deep, mostly dominated by sand and a bit clay. As a result, central area has such transition from deep to shallow sediment deposits. For instance, in the central north, bedrock was found at about -11.6 m, underlying stiff soil, whereas in central-south the bedrock was detected at -6 m, underlying clay and stiff sand. Shallow sediment was also found at Tamalanrea, with about 1.6 meters thick, mostly stiff sand. The results confirmed that typical sediment in the southern and western areas is deep sediment with clay or sand dominated soils and interbedded sand and clay. In contrast, in eastern area, the sediment is shallow sediment with stiff sand.

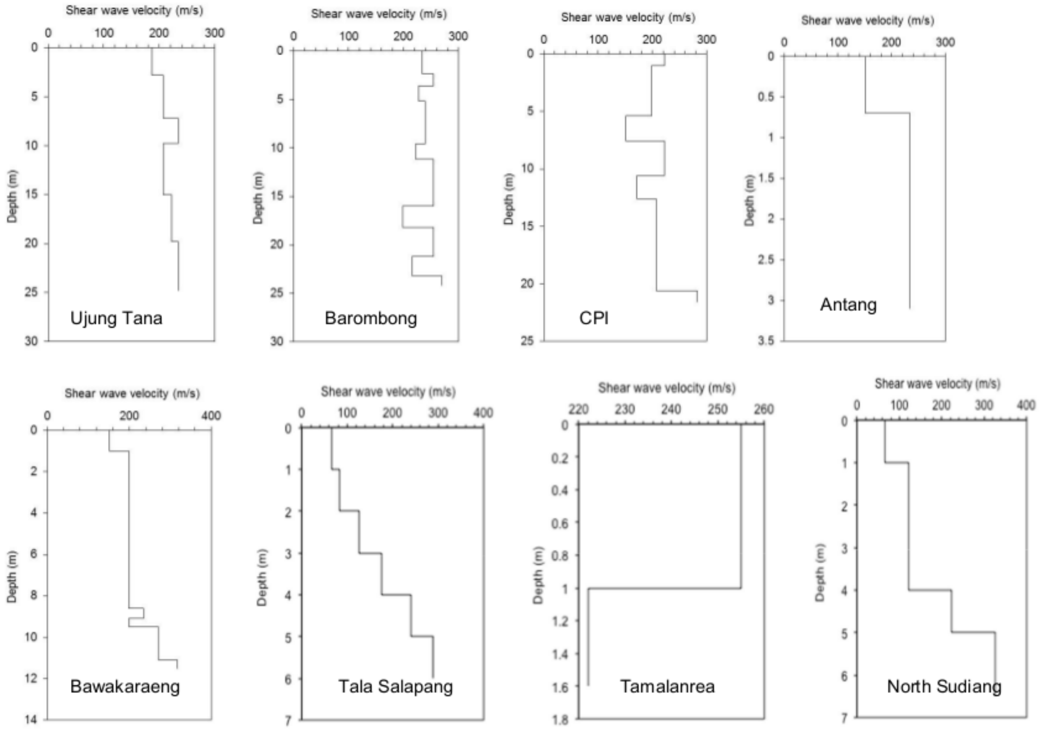

Figure 3. Shear wave velocity profiles of designated sites.

Acceleration Time Histories Model

Acceleration time histories model was derived from Sumatera earthquake 2007 model, available from Sikuai Island station of Caltech Tectonics Observatory. There are available three components of acceleration data (NS, WE, and Vertical), however the acceleration NS was selected since it has largest PGA values among the others. The model was scaled and filtered to get realistic model, conforming the PSHA based maximum PGA of Makassar at 0.1g (Figure 4). Time for peak acceleration is 12.5 sec and mean square frequency is 6.445 Hz.

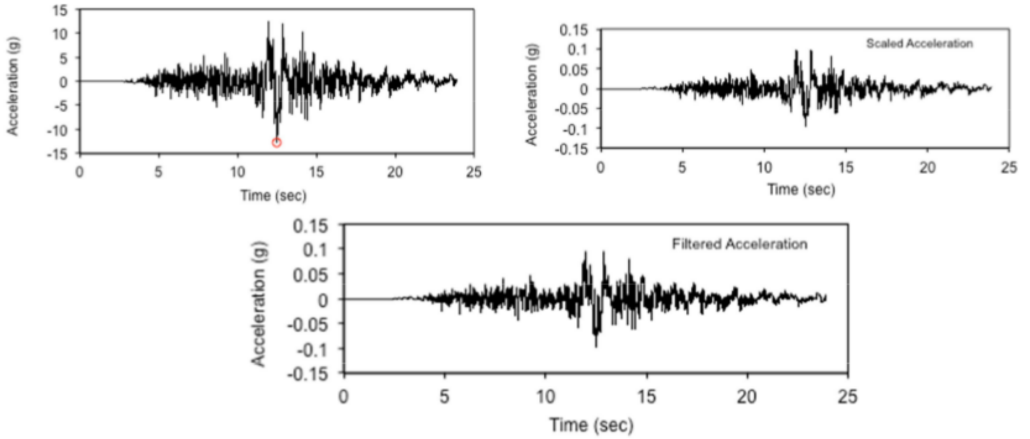

Figure 4. Acceleration time histories model of Sumatera Earthquake with 7.9 M was employed in this study.

Seismic Ground Response Analysis

Site specific ground response analysis was undertaken to simulate the behaviour of soil during seismic loading. Therefore, we utilized equivalent linear approximation of nonlinear response technique, such as EERA [12], later development of SHAKE [13]. EERA is add-on program embedded in Microsoft Excel, suitable for use in conducting a site-specific ground response analysis [12]. As shown in Figure 5, several steps were conducted as following: site characterization by utilizing CPT and SPT data, producing a simplified shear wave velocity profile. Meanwhile, acceleration time histories of an earthquake from strong motion virtual data centre of Consortium of Organization for Strong Motion Observation Systems (COSMOS) was analysed. The acceleration time histories model of Sumatera 2007 (Figure 4) was used as input motion for computing seismic ground response of the city.

Ground motion and geotechnical site characterization were used as input on EERA, computing ground response of horizontally soil layered deposits subjected to transient and horizontal propagating shear waves through a single soil column. It was assumed that soil layer is homogeneous, visco-elastic, and infinite horizontal extended. Soil's shears modulus and damping values are a function of shear strain amplitude, determined from iterative process of effective strain induced in each sub layer [12][14]. The process is repeated until strain compatible with shear modulus and damping values, with 1% error in converging. Initial step is processing earthquake data. In this study, default shear modulus-strain and damping ratio – strain curves in SHAKE91 and EERA was used as its upper bound for soil type of sand [15], clay [16] and rocks [17].

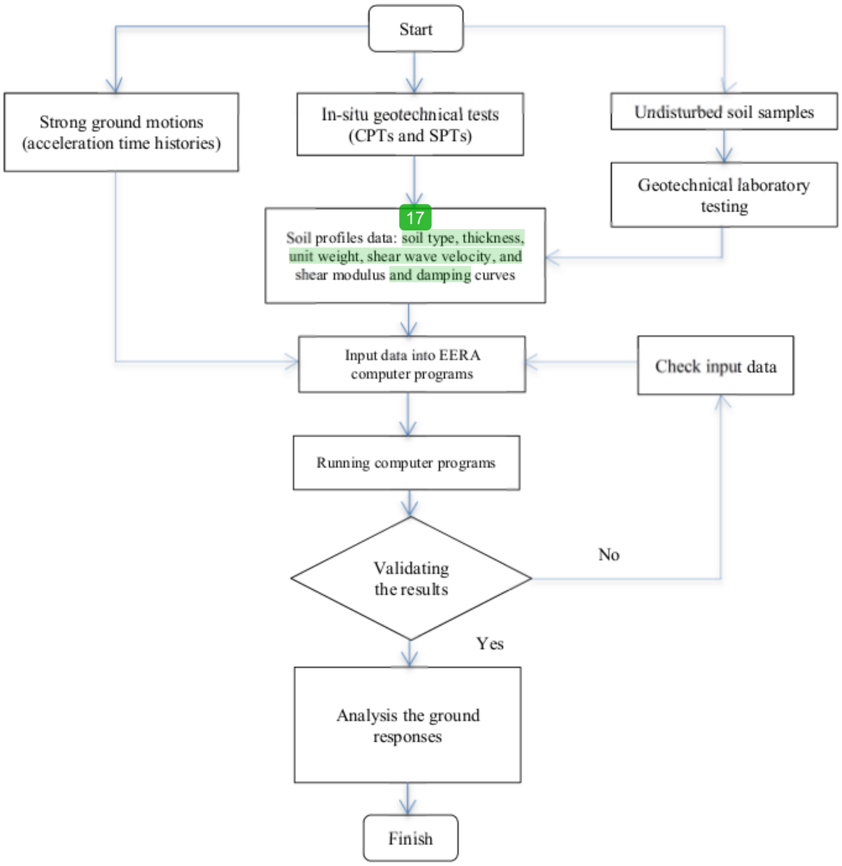

Figure 5. Method of computing site-specific ground response analysis (Adapted from Setiawan [18]).

Seismic Ground Response

Site-specific ground response analysis through equivalent linear approximation of nonlinear response technique was undertaken based a number of in-situ tests data and acceleration time histories model. The results show that, ground acceleration at bedrock level would be amplified during the seismic wave travel through the sediment. Hence, the ground acceleration increases from 0.1g at bedrock level, to be minimum 0.124g and maximum 0.349g at surface level. It can be seen in Figure 6, the maximum ground acceleration at surface level was found at Tala Salapang of Rappocini District with 0.349g, while the minimum one is 0.124g at Tamalanrea. In average, ground acceleration at surface level is 0.213g ± 0.0417g, and the data can be modelled as normal distribution probabilistic model (Figure 7).

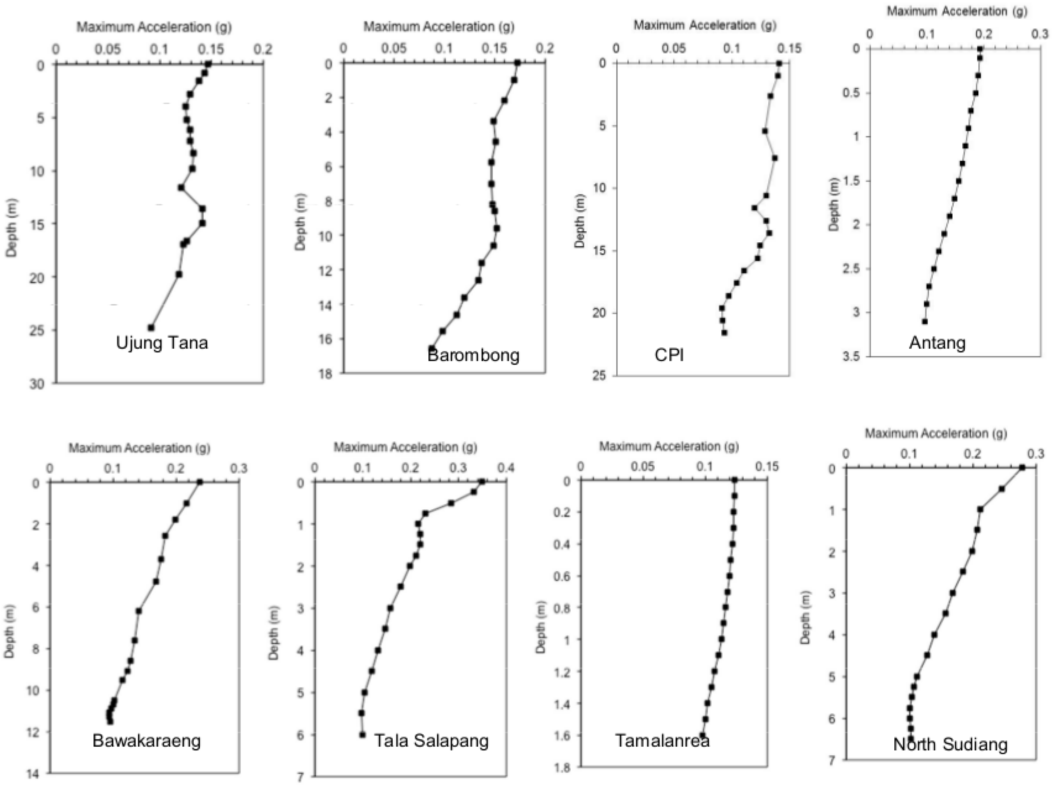

Figure 6. Maximum of ground acceleration vs depth in designated sites.

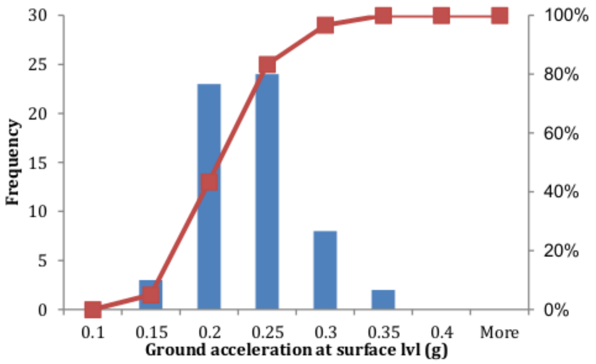

Figure 7. Statistical distribution of ground acceleration at surface level.

Tabel 1 Summary of the results of site specific seismic ground response of designates sites.

No	Parameter	Designated sites							
		UT	BRB	CPI	ATG	TML	TLS	BW	NSDG
1	Maximum acceleration at surface level (g)	0.146	0.197	0.173	0.195	0.124	0.349	0.237	0.279
2	Time of maximum acceleration (sec)	12.50	13.03	12.61	12.88	12.87	14.18	12.93	12.56
3	Mean square frequency (Hz)	4.00	5.59	4.41	12.58	11.68	8.87	7.15	9.34
4	Maximum acceleration at bedrock level (g)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
5	PGA amplification factor	1.81	2.84	2.06	2.84	1.141	5.54	2.55	4.44
6	Maximum strain (%)	0.0016	0.0043	0.0016	0.0004	0.0001	0.0101	0.005	0.016
7	Maximum stress (kPa)	1.142	4.605	1.681	0.398	0.1214	0.803	2.179	1.27
8	Frequency of maximum amplification (Hz)	5.55	7.142	2.44	16.66	20	7.69	4.54	6.67
9	Fundamental frequency of Fourier Spectrum (Hz)	1.098	1.99	2.487	17.24	1.096	6.485	4.288	6.485
8	Maximum spectral acceleration (g)	0.490	0.5192	0.557	0.7625	0.315	1.501	0.690	1.202
9	Maximum spectral velocity (cm/s)	53.02	49.71	41.227	32.46	31.665	36.753	36.69	34.25

UT = Ujung Tana, BRB = Barombong, CPI = Central Point of Indonesia, ATG = Antang, TML = Tamalanrea, TLS = Tala Salapang, BW = Bawakaraeng, NSDG = North Sudiang

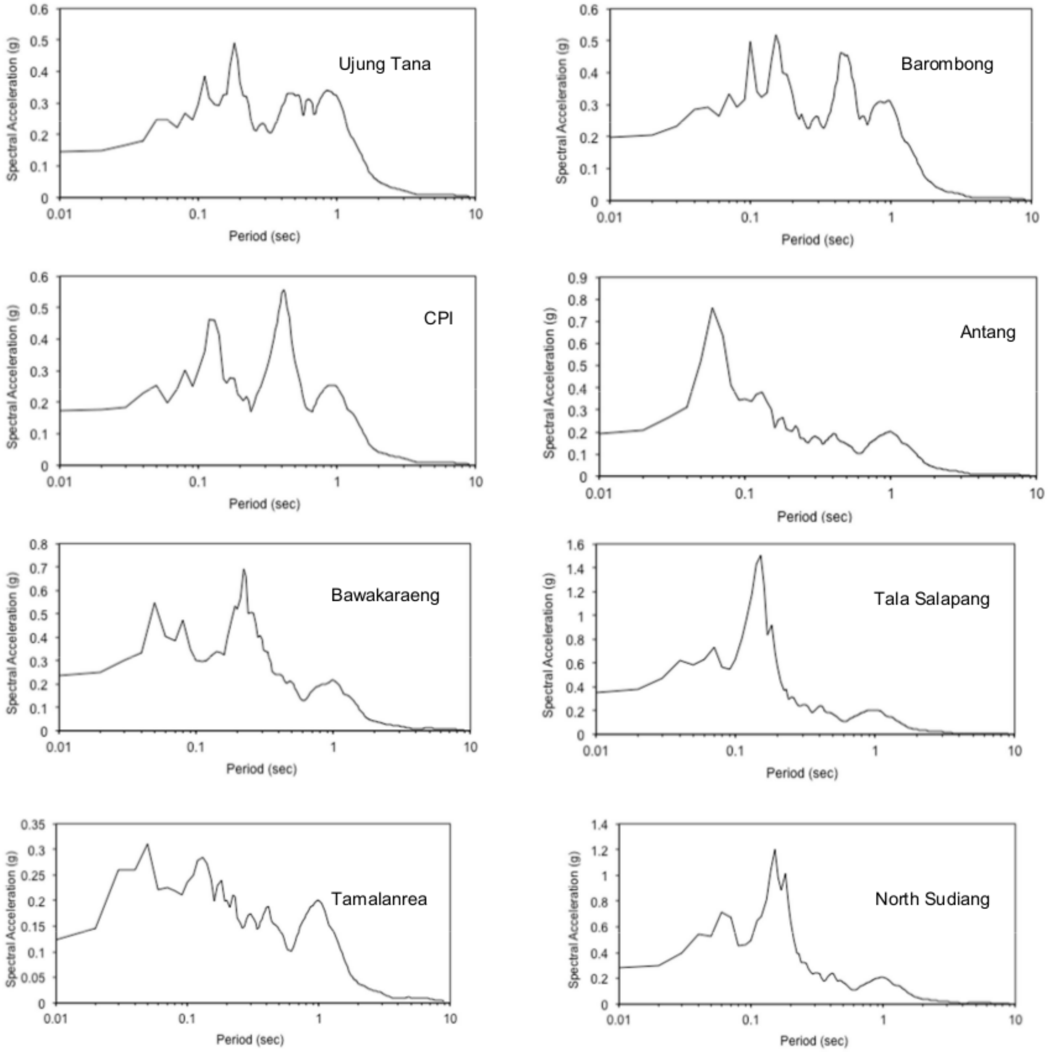

Figure 8. Response spectral acceleration of designated sites in Makassar.

Table 1 presents several ground response characteristics in designated sites across Makassar. The area with highest amplification factor was found at around Tala Salapang, with 5.54 factor and 7.69 Hz frequency. The area with lowest amplification factor was found at around Tamalanrea, with 1.14

factor at 20 Hz frequency. Maximum strain in the topsoil layer resulted from amplified seismic wave would be in the range of 0.0001% to 0.01%. In addition, the highest maximum stress would be yielded at around Barombong with 4.605 kPa and the lowest one would be around Tamalanrea with 0.121 kPa. Fourier spectrum indicates the fundamental frequency due to seismic events would be at the range of 1.096 Hz to 17.26 Hz.

Response spectrum analyses on several designated sites were obtained in which a critical damping ratio of 5% applied. The results reveal a maximum response spectral acceleration at surface level would be in the range of 0.315g with a 0.05 sec period to 1.501g with a 0.15 sec period. Mostly areas where deep sediment located have similar response spectral acceleration profiles (Figure 8). Barombong and Ujung Tana have identical broader profiles of response spectral acceleration with broader; however Tala Salapang and North Sudiang show a bit different profiles with more focused profiles. Antang with uni-modal response spectral at early period confirmed its stiffness soil sediment. On the other hand, other areas with multi-modal response spectral indicate the depth and type of sediment.

Zonation of Ground Acceleration at Surface Level

The zonation of ground acceleration at surface level employed a natural neighbour technique, which is a spatial interpolation based on Voronoi tessellation using a discrete set of spatial CPTs and SPTs data. The zonation of ground acceleration at surface level can be seen in Figure 9. In southern area, such as the districts of Rappocini, and Panakkukang, and eastern part of Tamalate district, it was found that high ground acceleration at surface level would be propagated. In addition, in the districts of Makassar, and Ujungpandang, the propagated ground acceleration would be a bit lower than that in the southern area. It was also found that the districts of Manggala, and Tamalanrea would yield the lowest ground acceleration. This is due to the characteristics of sediment in the southern areas becoming the primary contributing factor to very high ground acceleration yielded. In southern areas, typical sediment is deep sediment consisting of very thick clay overlying stiff sand. The sediment could be up to 14 meters thick, where its upper layer is clay at about 8 meters thick, and the bottom layer is sand with 6 meters thick. In similar trend, in the eastern area of Tamalate district, the sediment is also very deep, at about 25 meter thick, in which 6 meters thick clay overlying 19 meters thick sand. Similar type of sediment was also found at Tala Salapang where the sediment is only 6 meters thick, but its upper layer is dominated by 4 metres thick clay overlying a 2 meters thick sand. Such condition has created large impedance contrast between the upper layer of clay and the bottom layer of sand. As seismic wave travels from bedrock to the surface, it moves through the sediment material from stiff sand with large impedance to clay with small impedance capacity. As a result, seismic waves get trapped in between clay layer and sand layer, and they begin to reverberate, leading to high resonance at surface level.

Figure 9 also indicates that although coastal areas are seated in very deep sediment, they would not yield a high ground surface acceleration similar to the southern areas. The sediment is clay dominated or sand dominated soil which has different ground response to seismic motion. In this area, no impedance contrast was found since material is more homogeneous clay or sand. Nonetheless, the coastal areas adjacent to the centre of the city would yield moderate ground surface acceleration since their sediment is interbedded underlying a 7 meters thick clay and 17 meters thick sand. By comparing ground acceleration in southern areas and coastal areas, it can suggested that typical soil sediment in which underlying sand interbedded with clay is more vulnerable to be amplified than the sediment where more homogeneous sand or clay deposited. In addition, the sediment with underlying clay interbedded with sand would yield a bit lower ground acceleration than the sediment with reverse interbedded, underlying sand to clay. Clay soil has larger damping capacity for seismic wave than sandy soil. This means clay soil would act as absorber when seismic wave travels through. As it is absorbed, the increase in amplitude of seismic wave due to resonance can be mitigated. This implies the impedance contrast is small for the case of clay overlaid by sand, leading to lower amplification.

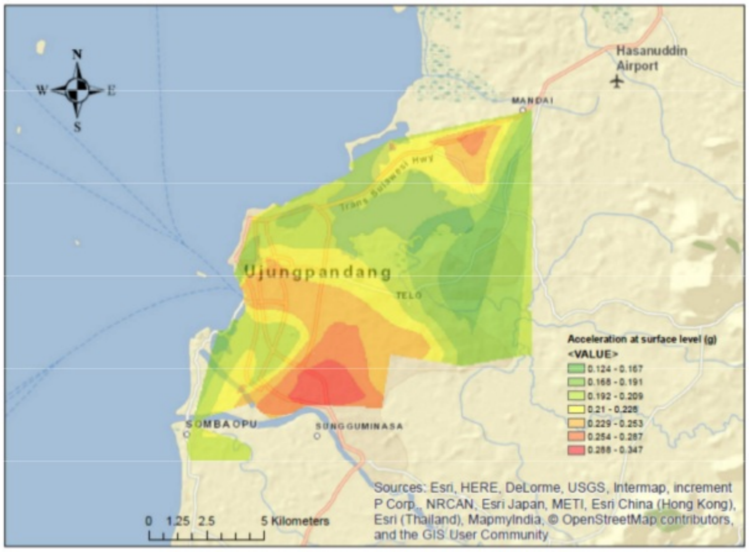

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Figure 9**.** Zonation of ground acceleration at surface level in Makassar.

Summary

This paper has presented seismic ground response in Makassar by using equivalent linear approximation of non-linear response technique. A number of findings can be derived as follow:

1. In the case of 0.1g considered as possible PGA at bedrock level, deep sediment would amplify seismic wave. Ground acceleration at surface level is found in the range of 0.124g to 0.349, and the amplification factor varies from 1.14 to 5.54. In average, ground acceleration at surface level in Makassar is accounted for 0.213g ± 0.0417g.
2. Response spectral acceleration at surface level is found in the range of 0.315g to 1.501g at frequency from 7.69 Hz to 20 Hz.
3. High ground acceleration at surface level is found at southern area of the city such as Rappocini District, and Panakkukang District, while low ground acceleration is found at eastern areas.
4. Typical deep sediment with interbedded underlying sand with clay would propagate larger amplification factor, than the sediment with more homogeneous soil deposits.

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