ISSN 0125-9849, e-ISSN 2354-6638
Ris.Geo.Tam Vol. 29, No.1, Juni 2019 (53-64)
DOI: 10.14203/risetgeotam2019.v29.978

RISET
Geologi dan Pertambangan

MICROZONATION OF SOIL AMPLIFICATION BASED ON MICROTREMOR, SPT and CPTU DATA IN BANDUNG BASIN

MIKROZONASI AMPLIFIKASI TANAH BERDASARKAN DATA MICROTREMOR, SPT DAN CPTU DI CEKUNGAN BANDUNG

Anggun Mayang Sari, Eko Soebowo, Afnindar Fakhrurrozi, Arifan Jaya Syahbana, dan Adrin Tohari

Pusat Penelitian Geoteknologi, LIPI, Jl. Sangkuriang, Bandung 40135

ABSTRACT Bandung Basin consists of Sunda-Tangkuban Perahu volcanic deposit that is made of lake sediment and an alluvial fan with fine to coarse-grained materials such as clay, silt and sand. The area is surrounded by several earthquake sources such as the Lembang, Cimandiri, and Baribis Faults. Therefore, it is important to understand soil dynamic problems with respect to seismic sources and soil properties. This research aims to investigate velocity amplification of the Bandung Basin using microtremor measurements and site classification based on the Standard Penetration Test (SPT) and Cone Penetrometer Test (CPTu). Velocity amplification was analyzed using the horizonal to vertical H/V spectral ratio, and site classification was determined using $\acute{N}$ and $\acute{V}_s$ values. Microzonation maps were developed using Geographical Information System (GIS) to determine the correlation between soil velocity amplification and site class. The results revealed that velocity amplification levels in the Bandung Basin vary with a range of 1.3 to 26.5. Site classification ranges from very dense soil and hard rock (class C), stiff soil (class D) to soft clay soil (class E). Site class E dominates the southeast part of the Bandung Basin with a high value of soil amplification. This scientific information is critical for further spatial planning focusing on infrastructure and residential building.

Keywords: Velocity amplification, H/V spectral ratio, Site class, GIS.

ABSTRAK *Cekungan Bandung berasal dari endapan vulkanik Sunda-Tangkuban Perahu yang terdiri dari sedimen danau dan kipas aluvial dengan material berbutir halus hingga kasar seperti lempung, lanau, dan pasir. Daerah ini juga dikelilingi oleh beberapa sumber gempa yakni sesar Lembang, Cimandiri, dan Baribis. Oleh karena itu masalah dinamika tanah yang dipengaruhi oleh sumber seismik dan sifat tanah perlu menjadi perhatian. Tujuan penelitian ini adalah untuk mengetahui amplifikasi kecepatan tanah di wilayah cekungan Bandung dengan menggunakan alat mikrotremor dan metode site classification berdasarkan uji SPT dan CPTu. Amplifikasi kecepatan dianalisis menggunakan perbandingan rasio spektral H/V dan site classification yang diperoleh dengan menggunakan nilai* $\acute{N}$ *dan* $\acute{V}_s$*. Peta mikrozonasi disusun menggunakan teknik Sistem Informasi Geografis (SIG) untuk menentukan korelasi amplifikasi tanah dan site class tanah. Hasil penelitian menunjukkan bahwa tingkat amplifikasi kecepatan di Cekungan Bandung bervariasi, berkisar 1,3 hingga 26,5. Site classification berkisar dari tanah yang sangat padat dan batuan keras (kelas C), tanah kaku (kelas D) hingga tanah lempung lunak (kelas E). Hasil penelitian menunjukkan site class E mendominasi bagian selatan Cekungan Bandung dengan nilai amplifikasi tanah yang tinggi. Informasi ilmiah ini diperlukan untuk perencanaan tata ruang kedepannya, dengan fokus pada infrastruktur dan bangunan tempat tinggal.*

Naskah masuk : 27 July 2018
Naskah direvisi : 15 October 2018
Naskah diterima : 14 January 2019

Anggun Mayang Sari
Pusat Penelitian Geoteknologi, LIPI, Jl. Sangkuriang
Bandung 40135
Email : angg021@lipi.go.id

***Kata kunci**: Amplifikasi kecepatan, rasio spektral H/V, site class, SIG.*

INTRODUCTION

Earthquake is one of natural hazards that frequently occurs in Indonesia especially in the recent years. According to the Meteorology, Climatology and Geophysical Agency (BMKG), there were 275 earthquake events with magnitudes larger than 5 SR in 2017 and the number increased to 382 seismic events in 2018. Almost every regions in Indonesia are affected by the natural disaster, including the Bandung Basin area. The geological condition of the Bandung Basin, which is surrounded by active faults, makes this area susceptible to seismic hazards that can cause damages to infrastructure and buildings, economic losses, and human fatalities.

Bandung is a large city in Indonesia with a population that reached 3,534,100 people in 2015 based on the Central Bureau of Statistics (BPS) of West Java. Its growth in population is accompanied by a high number of residential buildings and infrastructure development. Surrounded by active faults, the area is directly affected by the faults' movements. The National Board for Disaster Management (BNPB) of West Java recorded that 54,040 houses and 2,465 public facilities were damaged due to earthquake disasters between 2005 to 2018. There were 78,765 people affected and evacuated due to these events. In the last 15 years, 15 earthquakes occurred in the Bandung Basin area. The most destructive earthquake happened in the Bandung regency on September 2, 2009 (BNPB DIBI Data, West Java 2018). Topographic conditions of the area in the form of alluvial soil deposits, which consist mostly of soft clay and loose sand, make the area vulnerable to seismic hazards. Therefore, it is necessary to conduct soil vulnerability research in order to identify and reduce risks from earthquake events.

Soil vulnerability can be identified from several parameters, one of which is soil velocity on the ground surface. There are various methods to obtain soil velocity amplification, i.e. linear and non-linear equivalent modeling. For example, the Equivalent-linear Earthquake Site Response Analyzes (EERA) uses a 1-D linear model to calculate spectral relative velocity, amplification and stress-strain waves on the ground (Bardet et al., 2000). NERA stands for Nonlinear Earthquake site Response Analysis is a non-linear 1-D modeling that produces spectral relative velocity, amplification and stress-strain on the ground surface (Bardet et al., 2001) by calculating material models including viscoelastic models, equivalent linear models and material models of Iwan (1967) and Mroz (1967). These two methods require ground motion on the bedrock as the modeling input motion. Whereas, for a location that has no data on bedrock ground motion, the H/V spectral ratio analysis can be used as an alternative method to obtain velocity amplification.

The H/V spectral ratio is a method to estimate the ratio between the Fourier amplitude spectra of horizontal to vertical components of ambient noise vibrations recorded at a single microtremor station (Nogoshi and Igarashi, 1971). The amplitude-frequency relationship in earthquake motion was first observed by Kanai (1957). Aki (1957) showed the relationship between wave spectrum in space and time with reference on medium propagation of nature using microtremors at Hongo, Tokyo. In 1989, Nakamura popularized this method using analysis of strong motion records on various geological site conditions (Nakamura et al., 2008). The method is attractive because it provides the ease of data collection and can be adjusted in areas of no seismicity data, although the method does not predict seismic amplification accurately (Massa et al., 2012). Furthermore, this method had been carried out in many countries, such as in Japan (Liu et al., 1992), the U.S.A. (Seekins et al., 1996), Thailand (Tuladhar et al., 2004) and Nepal (Paudya et al., 2012).

Several studies on soil velocity amplification had been carried out in Indonesia. Tohari et al. (2016) mapped the thickness of soft soil layer in the Bandung Basin using microtremor data. They found that the soft soil layers in the center of the Bandung Basin range between 25-150 m. Cipta et al. (2018) observed seismic velocity structure using H/V spectral ratio measurements in Jakarta Basin. Their research showed low seismic velocities (<240 m/s) up to 100 m depth over the north to the central part of the city where alluvial fan material is deposited. Such geological condition influences seismic amplification and basin resonance of large earthquakes with epicenters close to Jakarta. With respect to the thickness of the sedimentary layer, the Bandung

Basin is similar to Jakarta. However, the risk is exacerbated in Bandung considering active seismicity and lack of soil amplification data; therefore, scientific investigation for soil amplification using seismic microzonation is highly needed. In this study, we conducted a microzonation study by correlating wave characteristics and soil site classification. The aim of this study is to investigate soil vulnerability to dynamic effects in the Bandung Basin to support regional infrastructure planning and development. Soil vulnerability to dynamic effects was investigated by combining velocity amplification values obtained from microtremor measurements and site classification derived from SPT and CPTu using GIS framework.

LOCATION AND GEOLOGICAL SETTING

The study was conducted in the Bandung Basin at 107°15’00” - 108°00’00” E and 6°45’00” - 7°15’00” S coordinates. Many areas in the Bandung Basin have been rapidly developed, particularly in the northwest and east areas where the demand for land use is high. Data acquisition consists of microtremor measurements, geotechnical borings with SPT and CPTu tests (Figure 1).

The Bandung municipality consists of the West Bandung regency, Bandung regency and Bandung city. The greater Bandung area comprises of a large intramontane basin surrounded by volcanic terrains (Dam, 1994). This basin area developed from the Sunda-Tangkuban Perahu eruption in 105 kyr B.P. and 50-35 kyr B.P. that caused sediment inflow in the northwestern basin (Dam, 1996). The Bandung Basin has a length of approximately 60 km starting from Padalarang - Nagrek and a width of 40 km from Lembang - South Soreang, with an elevation between 650 - 2200 m. The stratigraphy of the Bandung Basin (from older to younger order) consists of Tertiary sedimentary rocks of marl, claystone, sandstone, and limestone. According to Silitonga (1973), the formation is of the Late Miocene to Early Pliocene described as the Cikapundung Formation that consists of volcanic breccia, lava, and lahar of Pleistocene age. The Cikapundung Formation is more compact than the younger Cibereum Formation. The Cibereum Formation consists of breccia, pumice, tuff, obsidian, andesite and basalt of the Late Pleistocene to Holocene. The Kosambi Formation consists of Holocene tuffaceous clay, tuffaceous silt, and tuffaceous sand covering the middle part of the Bandung basin. The older rocks of Tertiary sedimentary and volcanic rocks, the Cikapundung Formation and intrusive rocks are considered as the bedrock of this area.

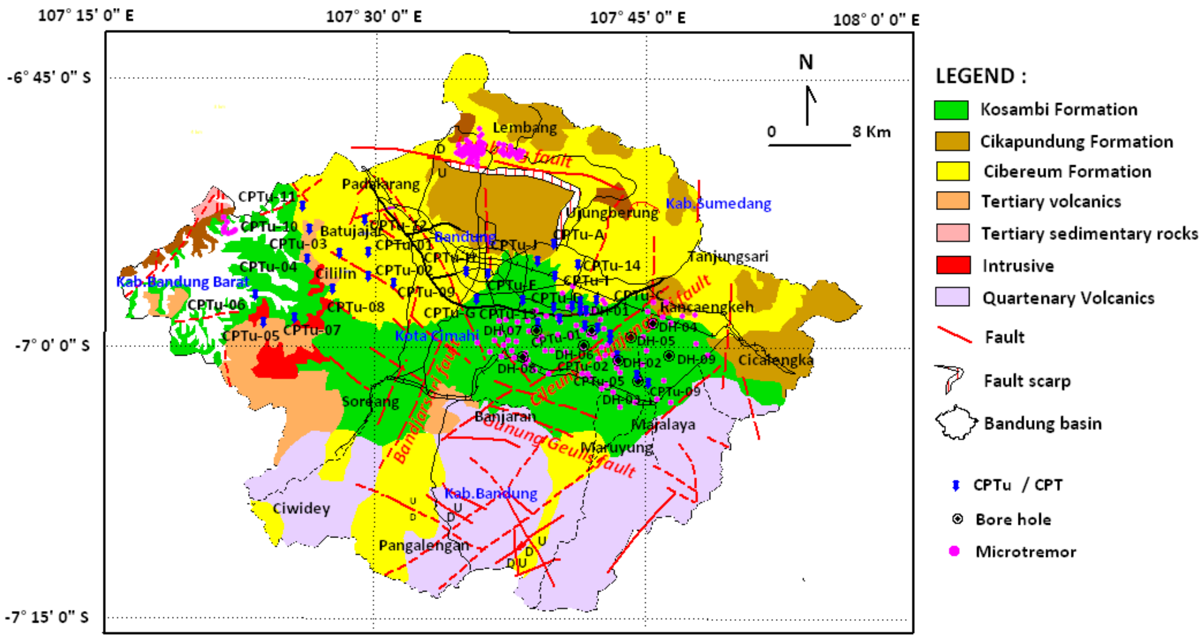

Figure 1. Geological map of the Bandung Basin shows the locations of engineering borehole, CPT/CPTu and microtremor. Compiled and modified from Silitonga (1973), Koesoemadinata and Hartono (1981), Alzwar et al. (1992), and Sudjatmiko (2003) from Hutasoit (2009) and Gumilar (2013).

Bandung Basin is surrounded by the active Lembang, Cimandiri, and Balibis Faults (Figure 2). There is a lack of earthquake record and sparse seismic station coverage in the area. Some of the recorded earthquake events were on July 22, 2011, with a magnitude of M. 2.9, followed by an earthquake event on August 28, 2011, with magnitude M of 3.3. The earthquakes caused minor damages to 103 buildings (Meilano et al., 2012). GPS observations have been installed at 14 stations since 1992, covering both the Lembang and Cimandiri Faults. The Cimandiri Fault has a left-lateral strike-slip motion with a N-S compression at ± 10 mm/year (Setydji et al., 1997). While the Lembang Fault has displacement rates that vary between 0.3 to 14 mm/year based on GPS surveys conducted in June 2006, August 2007 and August 2008 (Abidin et al., 2009).

METHODS

Determination of velocity amplification factor using H/V spectral ratio

Microtremor measurements had been carried out at as many as 84 points in the West Bandung regency, 98 points in the Bandung regency and 60 points in Bandung city (Figure 1). The measurements obtain the natural frequency value of soil (Nakamura., 2000; Hata et al., 2010). The H/V spectral ratios were calculated following the equation:

$$\left(\frac{H}{V}\right) = \sqrt{\frac{P_{NS}+P_{EW}}{P_{UD}}} \qquad (1)$$

where P_{UD} is Fourier power spectrum on vertical movement, while P_{NS} and P_{EW} are movements in the horizontal direction. The Fourier power spectrum was determined using the equation:

$$P_X = \frac{1}{L}\sum_{i=1}^{L} |S_{Xi}|^2 \qquad (2)$$

where L is the total of data that is not overlapping, and S_{Xi} is the Fast Fourier Transform on the i-data segment in the analyzed direction (Arai and Tokimatsu, 2004).

Velocity amplification values based on the H/V spectral ratio were processed using the Geonet software. It is is a single type of device that shows the number of velocity meter sensors. Time duration could be adjusted depending on the usage. Nakamura (1989) recorded more than 30 hours duration in Komonomiya substation for characterizing soil properties. Borgest et al. (2016)

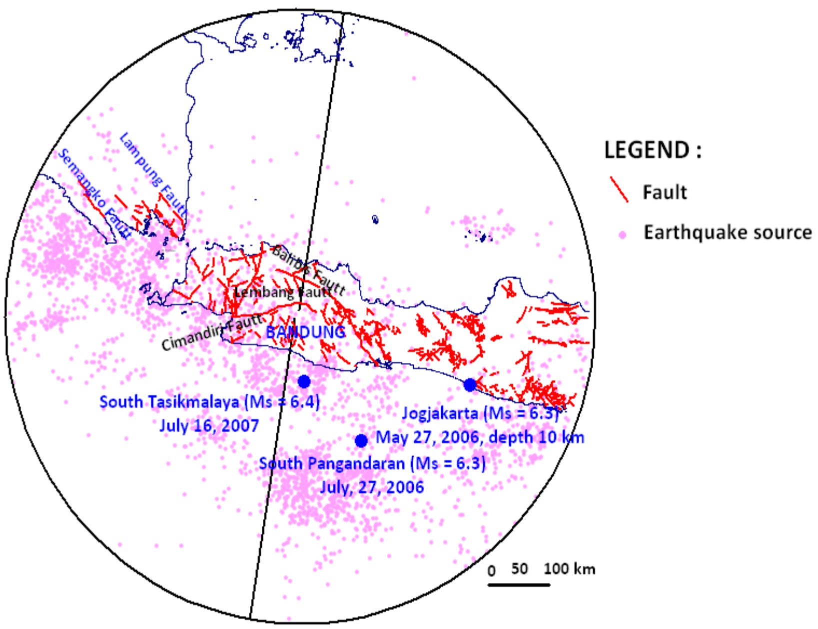

Figure 2. Bandung Earthquake Data from 1975 to 2017 at radius of 500 km (source Pusgen catalog, 2017).

eliminated the first 15 minutes of time series (from the beginning of the logging) to stabilize seismic registration. They used 660 seconds of data retrieval. After data recording, waves were picked to remove noise that would disturb the real site amplification value. To obtain amplification value, the natural frequency was converted into a

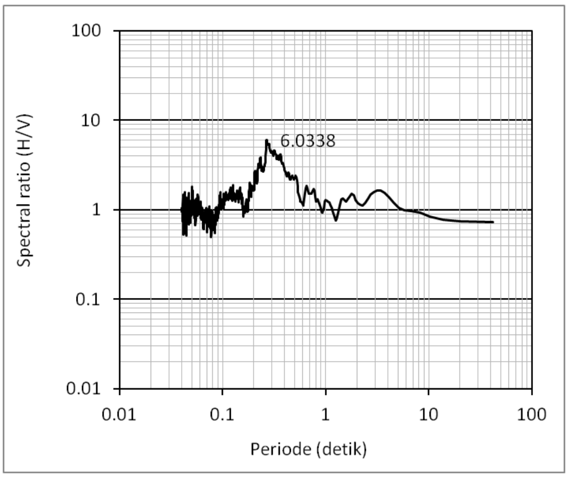

Figure 3. Velocity amplification from H/V spectral ratio against the predominant period.

predominant period. The velocity amplification is shown from the maximum value of H/V spectral ratio (Figure 3).

$\acute{N}$ and $\acute{V}_s$ value using SPT and CPTu data

Soil investigation was carried out using 9 SPT data from the Bandung regency, 14 CPTu data from the West Bandung regency, and 3 SPT and 10 CPTu data from Bandung city (Figure 1). $\acute{N}$ value was calculated based on ASCE 7.10 (2010):

$$\acute{N} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{N_i}} \quad (3)$$

where d_i is soil depth per layer above 30 meters, and N_i is the value of N-SPT per soil layer.

In the West Bandung regency, site class was analyzed using the correlation of CPT values to Vs value. Vs value was analyzed folowing Robertson (2009)'s equation for all types of soil:

$$V_s = \left[\left(10^{(0.55 I_c + 1.68)}\right)(q_t - \sigma_v)/p_a\right]^{0.5} \quad (4)$$

where I_c is the index of soil type behavior, q_t is cone resistance, σ_v is the total vertical volumetric weight of soil, and p_a is atmospheric pressure.

Site class determination from $\acute{V}_s$ values were derived from V_s, as calculated following ASCE 7.10 (2010):

$$\acute{V}_s = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{V_{si}}} \quad (5)$$

where d_i soil depth per layer above 30 meters, and V_{s_i} is the value of V_s per soil layer.

Site classification using $\acute{N}$ and $\acute{V}_s$ values

Site class analysis were determined based on ASCE 7-10 (2010) on 30 meters soil below the ground level. The soil profile was divided into several soil layers based on the types and depths of each layer. The soil layer was divided into layers of 1 to n - soil layer until reaching the total of n soil layer within 30 meters below the soil surface. Site class calculation in the Bandung Basin was performed using the $\acute{N}$ or $\acute{N}_{ch}$ values derived from N_SPT tests (Eq.3), and $\acute{V}_s$ derived from Vs values estimated from CPTu test data (Eq.4). The site classification was based on ASCE 7-10 (2010) (Table 1).

Microzonation of velocity amplification and site class using GIS

Microzonation of spectral amplification map was developed using GIS through interpolation. To perform the interpolation, $\acute{N}$ value was transformed into $\acute{V}_s$ value following Raju et al. (2010):

$$\acute{V}_s = 95.64\left(\acute{N}^{0.301}\right) \quad (6)$$

Inverse distance weighting (IDW) method was used to perform the prediction of unknown value points in the field of the study area. We used Vs distribution as an observation sample that scattered randomly across the study area and was assumed spatially autocorrelated as the observation sample. In other words, observation samples that are next to each other have strong relationship compared with further point location. Weighting has been assigned to each observation sample point to estimate the unknown points. The choice of weighting value (p-value) selection was determined using a visualization approach. Hence, distance coefficient power of three (p = 3) was selected after several attempts of interpolation process with a different value of weighting to search for excellent minimum and maximum value of observation samples. The extent of the

Table 1. Site Classification based on ASCE 7-10 (2010).

Site Class	$\acute{V}_s$	$\acute{N}$ **or** $\acute{N}_{ch}$	$\acute{S}_U$
A. Hard Rock	>5,000 ft/s	NA	NA
B. Rock	2,500 to 5,000 ft/s	NA	NA
C. Very dense soil and soft rock	1,200 to 2,500 ft/s	>50	>2,000 psf
D. Stiff soil	600 to 1,200 ft/s	15 to 50	1,000 to 2,000 psf
E. Soft clay soil	<600 ft/s	<15	<1,000 psf
	Any profile with more than 10 ft of soil having the following characteristics: - Plasticity index PI > 20, - Moisture content ω ≥ 40%, and - Undrained shear strength $\acute{S}_U$<500 psf		
F. Soils requiring site response analysis following Section 21.1	See Section 20.3.1		

For SI: 1 m/s = 3.28 ft/s and 1 lb/ft^2 = 0.0479 kN/m^2

study area has been used to define the search radius to make a robust estimation. As this method is very sensitive to outliers and noise, pre-processing datasets such as data cleaning was performed before interpolation.

RESULTS AND DISCUSSION

Results of spectral amplification analysis using microtremor spectral ratios

Analysis of microtremor data resulted in the H/V spectral ratio spectrum. The amplification is defined as the maximum amplitude of horizontal to vertical spectral ratio. Figure 4-left shows the spectral ratio in Desa Karangwangi of the West Bandung regency that results in spectral amplification of 6.7. Another location in Kampung Cibanteng shows a spectral amplification of 17.9 (Figure 4-right).

The results of amplification analysis range from 3.3 - 17.9 in the West Bandung regency, 1.3 - 26.5 in the Bandung regency, and 1.56 - 10.8 in the Bandung City. The differences in amplification values are influenced by soil characteristics. Soft clay soils show higher amplification compared to amplification values in stiff soils and very dense soils (soft rock) (Nakamura, 2008). The distribution of velocity amplification values in the Bandung Basin is shown in Figure 5.

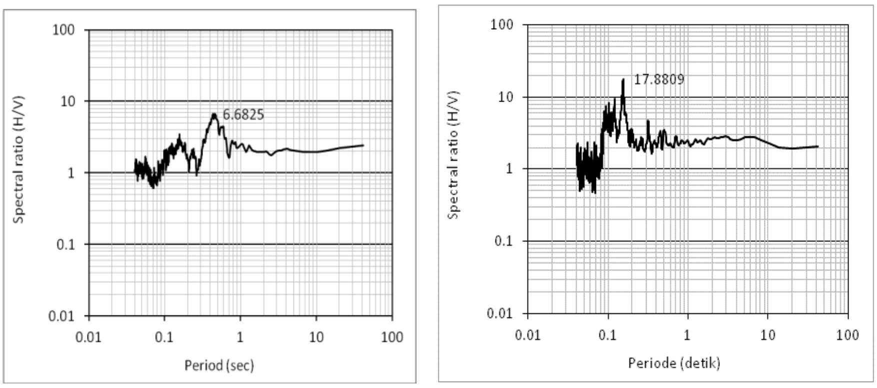

Figure 4. Spectral ratio of velocity amplification in Desa Karyawangi, Kecamatan Parongpong (left), and Kampung Cibanteng, Kecamatan Saguling (right).

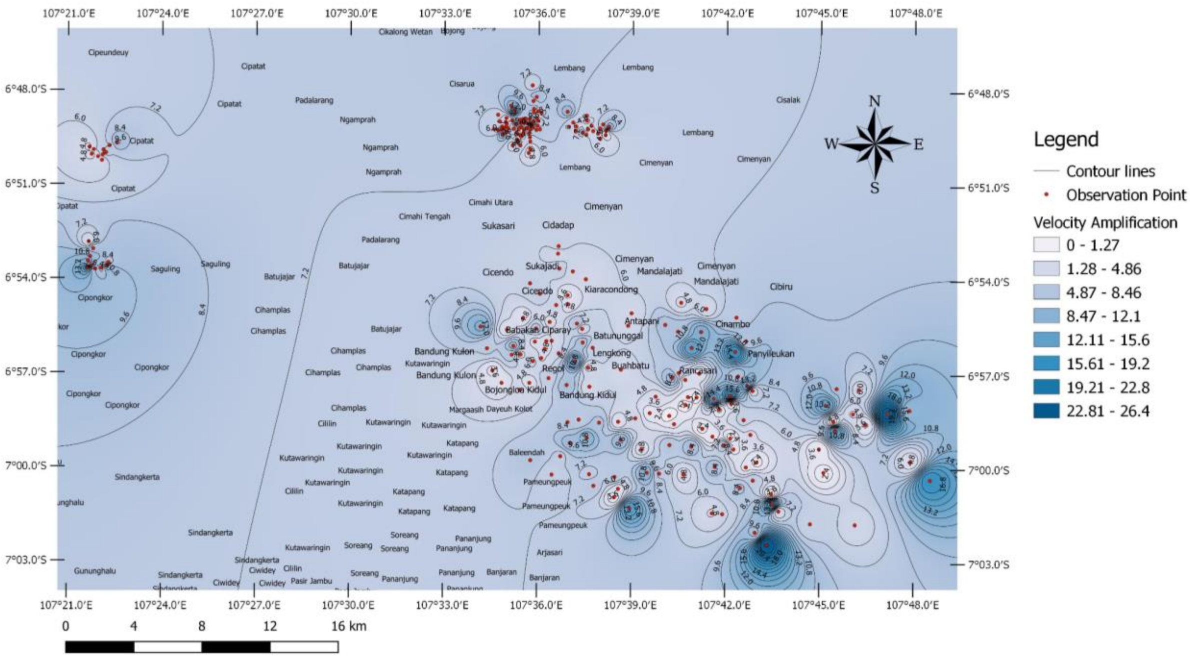

Figure 5. Microzonation of velocity amplification values in the Bandung Basin.

Site classification based on CPTu and SPT data

Site class analysis in Bandung basin resulted in 3 classes of soils, namely soft clay, stiff soil and dense to soft rock (Figure 6). The site class is derived from $\acute{V}_s$ and $\acute{N}$ values from SPT and CPTu tests as shown in Table 2.

Table 2 and Figure 6 show that the are around center and towards the east of the Bandung Basin is dominated by site class E (soft clay) with $\acute{V}_s$ values range from 87 ft/s to 558 ft/s and $\acute{N}$ values range from 1-12. The highest $\acute{V}_s$ value of 277 ft/s was found in CPTu I due to the cone penetration encountering desiccated stiff soil overlying the soft clay beneath. A similar case in DH-04 where stiff soil was found. The occurrence of site class E (soft clay) in the center of the Bandung Basin corresponds to the soft clays and silts of Kosambi Formation. Towards the west, site class D is identified in CPTu 02, 03, 04, 07 and 09. The stiff

Table 2. $\acute{V}_s$ and $\acute{N}$ values derived from CPTu and SPT test in Bandung basin

SPT test	$\acute{N}$	CPTu test	$\acute{V}_s$	CPTu test	$\acute{V}_s$
DH-01	8	CPTu-01	408 ft/s	CPTu-13	729 ft/s
DH-02	2	CPTu-02	635 ft/s	CPTu-14	87 ft/s
DH-03	6	CPTu-03	1010 ft/s	CPTu-A	146 ft/s
DH-04	12	CPTu-04	614 ft/s	CPTu-C	111 ft/s
DH-05	4	CPTu-05	511 ft/s	CPTu-D	142 ft/s
DH-06	7	CPTu-06	1366 ft/s	CPTu-E	155 ft/s
DH-07	4	CPTu-07	624 ft/s	CPTu-F	263 ft/s
DH-08	7	CPTu-08	426 ft/s	CPTu-Fa	123 ft/s
DH-10	1	CPTu-09	820 ft/s	CPTu-G	102 ft/s
BH-A	2	CPTu-10	515 ft/s	CPTu-H	153 ft/s
BH-B	2	CPTu-11	558 ft/s	CPTu-I	277 ft/s
BH-C	1	CPTu-12	551 ft/s	CPTu-J	123 ft/s

soils in CPTu 02 and 09 are derived from the weathering of the Cibereum Formation, where the $\acute{V}_s$ values are 635 ft/s and 820 ft/s, respectively. $\acute{V}_s$ values of 614 - 1010 ft/s in CPTu 03, 04 and 07 correspond to the stiff soils from the weathering of the volcanic formations.

Site class C is found in CPTu 06 that belongs to the weathered rock of Tertiary Volcanic Formation. Site class E is also found in the western part of the Bandung Basin as shown in CPTu 05, 08, 10 and 11 ($\acute{V}_s$ values of 511 - 558 ft/s) corresponds to the thin soft clay deposited at the upper part overlying the harder weathered Tertiary Volcanic Rock.

Microzonation of velocity amplification to $\acute{V}_s$ value in Bandung Basin

$\acute{V}_s$ values derived from SPT and CPTu data are compared to the velocity amplification values as shown in the microzonation map (Figure 7). Figure 7 shows that the lowest $\acute{V}_s$ values are within the high-velocity amplification area. Low $\acute{V}_s$ values (site class E) has velocity amplification of 8.47 to 26.4. This zone occupies the Kosambi Formation, covering the middle and the eastern part of the Bandung Basin. Site class D is identified in the western part of the Bandung Basin with $\acute{V}_s$ values range from 614 - 1010 ft/s. This site class is related to lower velocity amplification ranging from 4.87 to 8.46. The stiff clay soil occupies the Cibereum and Tertiary Volcanic Formations. The highest $\acute{V}_s$ value of >1200 ft/s corresponds to the lowest velocity amplification of 0 - 4.86 that belongs to the weathered hard Tertiary Volcanic rock.

High amplification is identified mostly in the eastern part of the Bandung Basin such as in Panyileukan, Cileunyi, Rancaekek, Solokan Jeruk and Majalaya. As these locations are dominated by soft clay, the vulnerability of soil to ground shaking becomes higher. The shaking impact triggered by the active faults (Cileunyi-Tanjung, Gunung Geulis and Bandjasari Faults) could cause severe damages to building and infrastructures. Likewise, Parongpong and Cipongkor areas that are close to the Lembang Fault could also face a similar hazard. The soft soil with high amplification value increases seismic risks that can cause failures to building and many collateral damages if not properly mitigated.

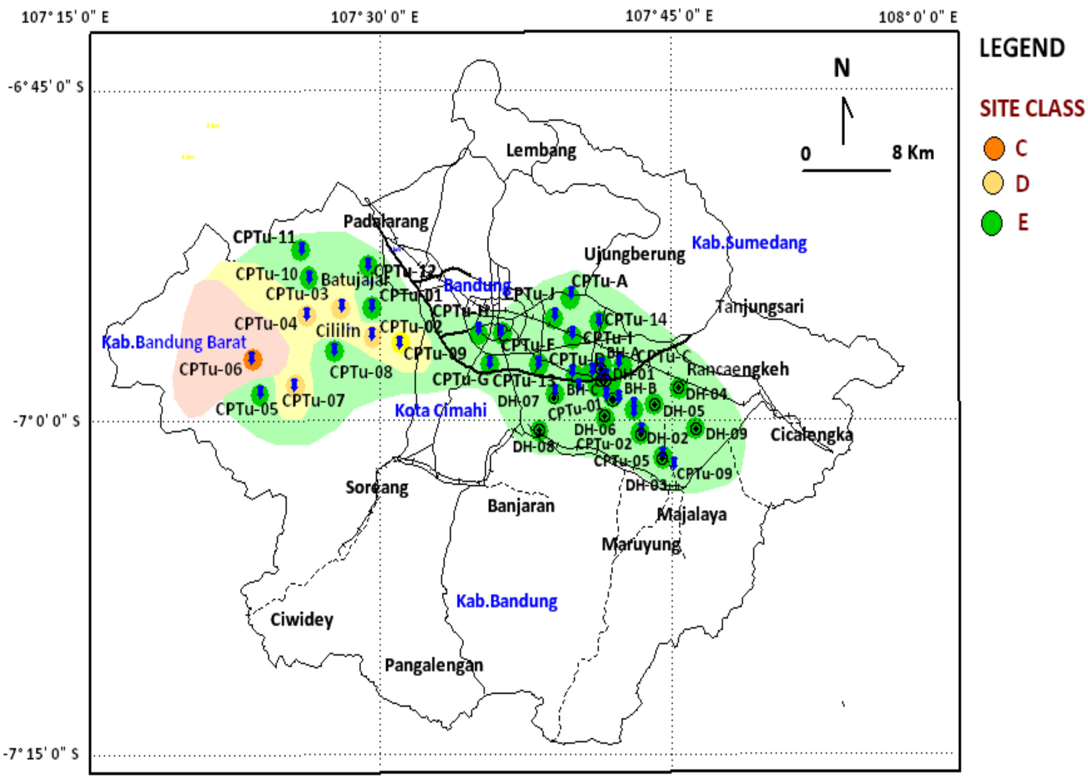

Figure 6. Map of site class in the Bandung Basin.

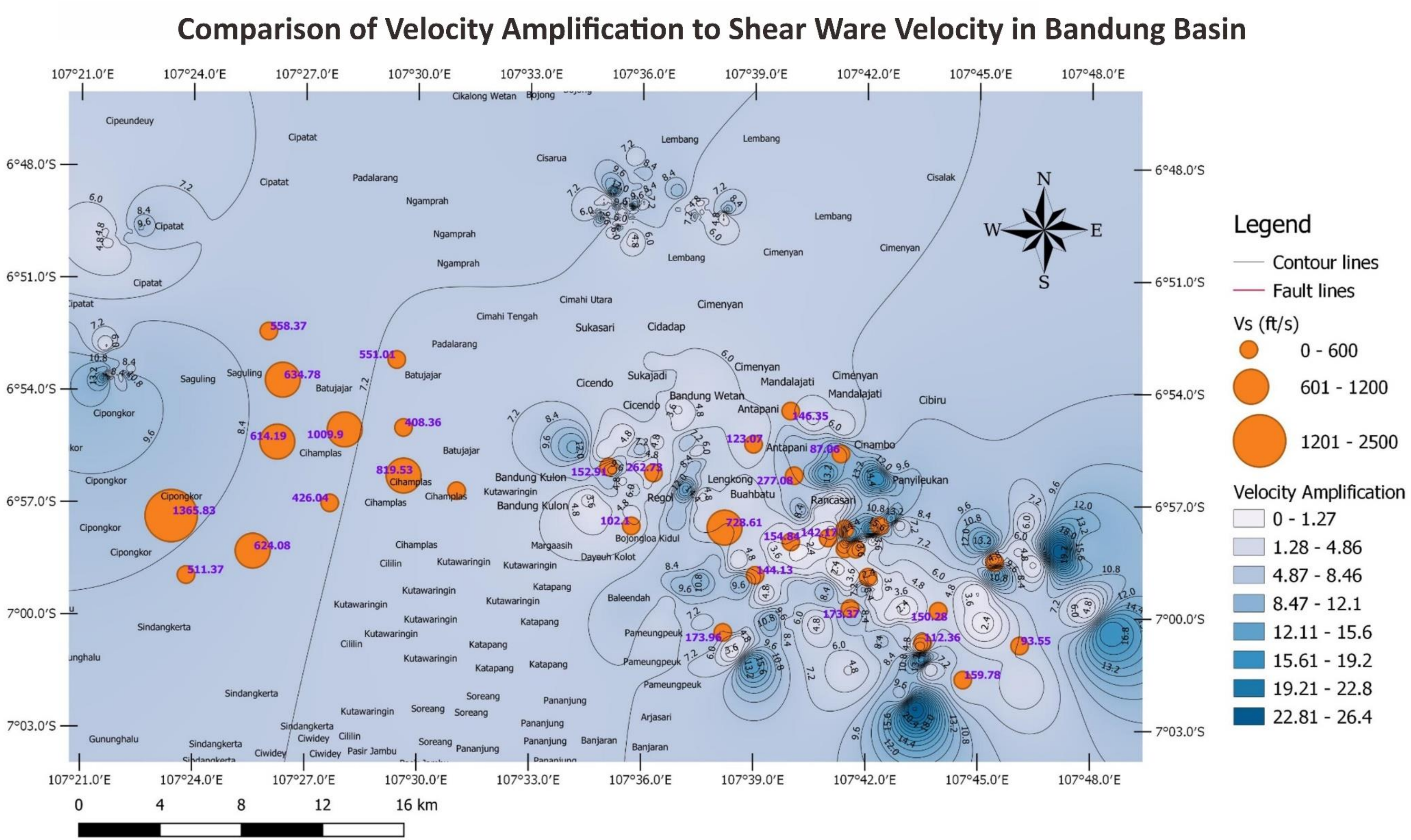

Figure.7. Comparison of site class analysis ($\acute{V}_S$ value based) to velocity amplification in the Bandung Basin.

CONCLUSION

Microzonation study of the Bandung Basin was conducted using microtremor, SPT and CPTu data to determine velocity amplification and site class of the soil profile. Based on the H/V spectral ratio analysis, our data show higher spectral amplification value in the central towards eastern part of the Bandung Basin. This area is identified as soft clay (E) based on the $\acute{V}_S$ calculation from the SPT and CPTu data. Meanwhile, the western part of the Bandung Basin shows low-velocity amplification values, where site classifications of these areas are stiff soil and very dense to soft rock. The geological formations influence the character of the subsurface soil as well as the spectral ratio of horizontal to vertical. The geological condition of the Bandung Basin shows adjacent sources of active faults coexist with a large part of soft clay in the subsurface. This condition is detrimental to the regional development of the Bandung metropolitan with high seismic risks to buildings and infrastructures. Mitigation measures must be taken by the government and community to minimize the hazard, for instance, by developing earthquake resistant building, reviewing the regional spatial planning as well community preparedness, among other measures.

ACKNOWLEDGMENT

The research was funded by the Research Center for Geotechnology - LIPI through DIPA during fiscal years of 2015 - 2017. We thank Dr. Cipta for his thorough and meticulous review, and Dwi Sarah for her useful insights and suggestions. We also thank the governments of Bandung regency, West Bandung regency and Bandung city for facilitating field survey activities.

REFERENCES

Abidin, H. Z., Andreas, H., Kato, T., Ito, T., Meilano, I., Kimata, F., Natawidjaja,, D. H., Harjono, H., 2009. Crustal Deformation Studies In Java (Indonesia) using GPS. Journal of Earthquake and Tsunamis, 3(2), 77-88.

Aki, K., 1957. Space and time spectra of stationary stochastic waves, with special reference to microtremors. Bull. Earthquake Res. Inst. University of Tokyo Earthquake Research Institute. ISSN: 00408972, 35(3), 415–457.

ASCE. 2010. ASCE 7-10. Minimum Design Loads for Buildings and Other Structures. Virginia: American Society of Civil Engineers. ISBN 978-0-7844-1115-5. USA.

Alzwar, M., Akbar, N., and Bachri, S., 1992. Peta Geologi Lembar Garut dan Pameungpeuk, Jawa Barat, Skala 1:100.000. Pusat Penelitian dan Pengembangan Geologi Bandung.

Badan Pusat Statistik Provinsi Jawa Barat. 2015. Jumlah Penduduk dan Jenis Kelamin Menurut Kabupaten/Kota di Provinsi Jawa Barat, 2015. https://jabar.bps.go.id/.

Bardet, J. P., Ichii, K., and Lin, C. H., 2000. A Computer Program for Euqivalent-linear Earthquake site Response Analyses of Layered Soil Deposits. Manual Program. University of Southern California. Department of Civil Engineering.

Bardet, J. P., and Tobita, T., 2001. A Computer Program for Nonlinear Earthquake site Response Analyses of Layered Soil Deposits. Manual Program. University of Southern California. Department of Civil Engineering.

Borges, J. F., Silva, H. G., Torres, R. J. G., Caldeira, B., Bezzeghoud, M., Furtado, J. A., and Carvalho, J., 2016. Inversion of ambient seismic noise HVSR to evaluate velocity and structural models of the Lower Tagus Basin, Portugal. Journal of Seismology, 20(3), 875-887.

Cipta, A., Cummins, P., Dettmer, J., Saygin, E., Irsyam, M., Rudyanto, A., and Murjaya, J., 2018. Seismic velocity structure of the Jakarta Basin, Indonesia, using trans-dimensional Bayesian inversion of horizontal-to-vertical spectral ratios. Geophysical Journal International (Vol. 215). https://doi.org/10.1093/gji/ggy289

Dam, M. A. C., 1994. The Late Quaternary Evolution of the Bandung Basin, West-Java, Indonesia, Thesis Vrije Universiteit, Amsterdam, 252.

Dam, M. A. C., Suparan, P., Nossin, J. J., Voskuil, R. P. G. A., and Group, G. T. L. 1996. Chronology For Geomorphological Developments In The Greater Bandung Area, West-Java, Indonesia. Journal of Southeast Asian Earth Sciences, 14, 101-115.

Data DIBI BNPB. 2018. http://bnpb.cloud/dibi/ xdibi_list.

Data BMKG 2017-2018. https://inatews.bmkg. go.id/new/query_gempa_isu.php.

Gumilar, I., 2013. Pemetaan Karakteristik Penurunan Muka Tanah (land Subsidence) Berdasarkan Integrase Metode GPS dan Insar serta Estimasi Kerugian Keekonomian Akibat Dampak Penurunan Muka Tanah (Wilayah Studi : Cekungan Bandung), Desertasi, ITB.

Hata, Y., Susumu, N., Atshusi, N., Susumu, S., Yohei, M., and Koji, I., 2010. Microtremor H/V Spectrum Ratio and Site Amplification Factor in the Seismic Observation Stations for 2008 Iwate-Miyagi Nairiku Earthquake. Bull of Graduate School of Engineering Hiroshima University, 59(10).

Hutasoit, L. M., 2009. Kondisi Muka Airtanah Dengan dan Tanpa Peresapan Buatan Daerah Bandung: Hasil Simulasi Numerik. Jurnal Geologi Indonesia, 4(3), 177-188.

Iwan W. D., 1967. On A Class Of Models For The Yielding Behaviour Of Continues and Composite System. J. App. Mech., 34, 612-617.

Kanai, K., 1957. Semi-empirical formula for the seismic characteristics of the ground. Bull. of the ERI. 35, 309–325.

Koesoemadinata, R. P., and Hartono, D., 1981. Stratigrafi dan Sedimentasi Daerah Bandung. Proceedings PIT X Ikatan Ahli Geologi Indonesia, Bandung, 318-336.

Lu, L., Yamazaki, F., and Katayama, T., 1992. Soil Amplification Based On Seismometer Array And Microtremor Observations In Chiba, Japan. Earthquake Engineering And Structural Dynamics, 21(955108),1592.

Massa, M., and S, Lovati., 2012. Seismic amplification in presence of topography and their consequences for ground motion predictions and seismic code for building: the case of Italy. 15th World Conference on Earthquake Engineering, Lisbon Potugal.

Meilano, I., Abidin, H. Z., Andreas, H., Gumelar, I., Sarsito, E., Hanifa, N. R., Rino., Harjono, H., Kato, T., Kimata, F., Fukuda, Y., 2012. Slip Rate Estimation of the Lembang Fault West Java from Geodetic Observation. Journal of Disaster Research., 7(1), 12-18.

Mroz, Z., 1967. On The Description Of Anisotropic Work Hardening. J. Mech. Phys. Solids, 15, 163-175.

Nakamura, Y., 1989. A Method for Dynamic Characteristics Estimation Of Subsurface Using Microtremor on the Ground Surface. Quarterly Reports of the Railway Technical Research Institute, Tokyo, 30, 25-33.

Nakamura, Y., 2000. Clear Identification Of Fundamental Idea Of Nakamura's Technique And Its Applications. Proc XII World Conf. Earthquake Engineering, 8.

Nakamura, Y., 2008. On The H/V Spectrum. The 14th World Conference on Earthquake Engineering. Beijing, China.

Nogoshi, M., and Igarashi, T., 1971. On The Amplitude Characteristics Of Microtremor (Part 2). Jour. seism. Soc. Japan, 24, 26-40.

Paudya, Y. R., Yatabe, R., Bhandary, N. R., and Dahal, R. K., 2012. A study of local amplification effect of soil layers on ground motion in the Kathmandu Valley using microtremor analysis. arthq Eng & Eng Vib Journal, 11, 257-268.

Pusat Studi Gempa Nasional, 2017. Peta Sumber dan Bahaya Gempa Indonesia tahun 2017, Pusat Litbang Perumahan dan Permukiman, Badan Penelitian dan Pengembangan, Kementerian

Pekerjaaan Umum dan Perumahan Rakyat.ISBN 978-602-5489-01-3.376.

Raju, U. M., Boominathan, A., and Dodagoudar, G. R., 2010. Use of Surface Waves in Statistical Correlations of Shear Wave Velocity and Penetration Resistance of Chennai Soils. Geotech Geol Eng, 28, 119–137.

Robertson, P. K., 2009. Interpretation of Cone Penetration Tests, a Unified Approach. Canadian Geotechnical Journal, 46 (11), 1337–1355.

Seekins, L. C., Wennerberg, L., Margheriti, L., and Liu, H. P., 1996. Site Amplification at Five Locations in San Francisco, California: A Comparison of S Waves, Codas, and Microtremors. Bulletin of the Seismological Society of America, 86(3), 627-635.

Setydji, B., Murata, I., Kahar, J., Suparka, S., and Tanaka, T., 1997. Analysis of GPS measurementin West-Java, Indonesia. Ann. Disas. Prev. Res. Inst. Kyoto Univ., 40(B-1), 27-33.

Silitonga, P. H., 1973. Peta Geologi Lembar Bandung Skala 1 : 100.000. Pusat Penelitian dan Pengembangan Geologi, Bandung.

Sudjatmiko. 1972. Peta Geologi Lembar Cianjur, Jawa Skala 1 : 100.000. Pusat Penelitian dan Pengembangan Geologi, Bandung.

Tohari, A., Sari, A. M., and Syahbana, A. J., 2016. Ketebalan Lapisan Tanah Lunak Di Wilayah Cekungan Bandung Berdasarkan Metode Mikrotremor. Prosiding Geoteknologi LIPI. 84-93.

Tuladhar, R., Yamazaki, F., Warnitchai, P., and Saita, J., 2004. Seismic Microzonation Of The Greater Bangkok Area Using Microtremor Observations. Earthquake Engng Struct. Dyn, 33, 211–225.