Empirical Formulation of Natural Frequency vs Soil Thickness Based on Maximum Spectral Value H/V in Bandar Lampung, Indonesia

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Empirical Formulation of Natural Frequency vs Soil Thickness Based on Maximum Spectral Value H/V in Bandar Lampung, Indonesia

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Abstract

This paper presents an analysis of the natural frequency relationship of soil obtained by the H /V method and soil thickness based on the dispersion properties of surface waves with the MASW method approach so that empirical equations are obtained. This technique was adopted from several previous researchers who conducted studies on the relationship of natural frequency of soil to sediment thickness from boreholes. The empirical equation

obtained is used to map variations in the thickness of the soil layer of Bandar Lampung area and justified based on soil thickness conditions from geological data, especially related to gological formations in the research area. In addition, comparisons are made to test conformity with other empirical formulations of researchers with relatively similar soil layer characteristics. The importance of this study is that it will save more cost and time than by correlating the natural frequencies to the borehole data.

Keyword: natural frequency, surface waves, H/V ratio, multichannel analysis of surface wave, soil thickness.

1. Introduction

Land has a number of functions for the community including social, economic and environmental aspects, in the form of spaces for food production, environmental interaction, ecological habitat support and biodiversity, landscapes, cultural heritage protection, raw material providers, and of course for construction platforms. In addition to that are social and economic functions, such as provision of green open spaces, including gardens, playgrounds, and public open spaces. It provides cultural and social benefits that include improved well-being, physical and psychological health, and relationships with nature [1].

The construction space as one aspect of land use is sometimes not done wisely so that it often causes losses for the community and the environment. Hence, the zoning of the area based on soil characteristics becomes an aspect that must be done, such as planning and developing the region in the future. Mapping the thickness of the soil is needed to ensure the soil bearing capacity against the construction of infrastructure facilities and infrastructure, both for housing, bridges, buildings, roads, and bridges.

Along with the advancement in earthquake monitoring technology and facilities in recent years, it has become a good thing for researchers to map the condition of the soil layer in a region. The characteristics of the soil layer of a region based on seismological parameters become a topic of interest throughout. The soil layer characteristics study of a location aims to minimize infrastructure damage due to earthquake vibrations, especially in designing earthquake-resistant buildings.

The scientists observed that for earthquake events of the same magnitude had different levels of building damage for a relatively similar height building. Furthermore, they found an interesting fact that the natural frequency of buildings that have the same value as the natural frequency of soil layers will experience resonance. In addition, the amplification of earthquake waves is also influenced by the level of thickness of the soil layer. Therefore, the study of natural frequency and thickness of soil layers is very important to be known to prevent infrastructure damage in the future.

Various conventional techniques of determining the soil bearing capacity related to soil characteristics and thickness, namely standard penetration test (SPT) and cone penetration test (CPT) ([2]; [3]; [4]; [5]; [6]; [7]; [8]). Study of soil characteristics can also be done through coring analysis ([9]; [10]; [9]; [11]) but requires cost, energy and time. Soil characteristics research has developed very rapidly by utilizing the physical properties of soil, especially the ability of soil as a medium of propagation of earthquake waves and surface waves ([12]; [13]; [14]; [15]; [16]; [17]; [18]).

Measurement of microtremor data and calculation of natural frequency values based on maximum spectral values H /V is done to anticipate the impact of earthquakes and microtremor. This study refers to previous researchers, such as [19] developing numeric calculations HVSR methods. In addition, the implementation of HVSR is also carried out by [20], [21], [22], [23], [24], [25], [26]. Nakamura (2000) has introduced another method (the one-station method) to eliminate the effects of sources and pathways that measure ambient vibrations caused by man-made or natural sources in one location [27]. This method measures the ratio between the horizontal and vertical components of the noise and overcomes the weaknesses faced by previous methods Nakamura (1989) [28]. Here, it should be noted that usually the horizontal component of the microtremor measurement shows a greater peak compared to the vertical component. The contrast between these two components is due to the presence of a soil-rock interface. Thus, the peak of the horizontal to vertical spectral ratio (HVSR) of microtremor measurements at a given location is taken as a frequency corresponding to the natural frequency of the ground.

In general, microtremor microzoning is a process of estimating the response and behavior of soil layers or sediments to the presence of earthquakes. HVSR analysis refers to the technique of comparing the spectrum of horizontal components to the vertical components of microtremor. This technique is useful for demonstrating the dominant natural frequency (f_o) based on the spectral peak value of H/V which presents the dynamic characteristics of the sediment layer. Microtremor data is composed of several types of waves, but the main one is Rayleigh waves that propagate in the sedimentary layer above the bedrock. The effect of Rayleigh waves on microtremor recordings of the same magnitude for vertical and horizontal components when the frequency range is 0.2-20.0 *Hz*, so the spectrum ratio between horizontal and vertical components in bedrock is close to unity. Since the spectrum ratio between horizontal and vertical components in bedrock is close to unity, so there is only an influence caused by a local geological structure or *site effect* (*Tsite*), which is indicating the peak of amplification at the base frequency of a location.

Natural frequency is the value of frequencies that often appear so that it is recognized as the frequency value of the rock layers in the region. Lachet and Bard (1994) conducted a simulation test using six models of simple geological stsructures with a combination of contrast variations in the speed of shear waves and the thickness of sedimentary layers, and the results showed that the peak value of frequencies changed against variations in geological conditions [19]. In addition, surface wave measurements are carried out with the MASW method at several stations that overlap with microtremor measurements. Next, the inversion of the dispersion curve to get the value of surface wave speed and soil thickness at the measurement location is calculated. The MASW method is very popular in identifying earthquake vulnerable zones and is classified by site class which refers to the shear wave velocity value by the National Earthquake Hazard Reduction Program (NEHRP). The MASW application has been applied by many researchers including [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40].

Furthermore, a correlation of natural frequency values and soil thickness is conducted to obtain formulations of empirical equations that can be used to calculate soil thickness at other microtremor measurement stations. Some researchers have done the same and produced formulations of empirical equations, namely [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [23] dan [52]. This research aims to develop more efficient and precise techniques in mapping sediment thickness patterns in Bandar Lampung. Hence, it can be used for geotechnical analysis, especially in infrastructure development planning, buildings, residential residents, and all social and economic aspects related to aspects of space utilization.

2. Methods

2.1 Geological Setting

Geologically, Bandar Lampung is included in the geological map of Tanjung Karang sheet ([53], [54], [55], [56], [57]) which includes several rock formations including the Quarter-aged Lampung formation (QTl) with lithology of pumiceus tuff, rhyolitic tuff, welded tuff tuffit, tuffaceous claystone and tuffaceous sandstone. Lampung Formation stretches widely in the north and connects to the east of Bandar Lampung. In addition, it also occupies along the coast of Lampung Bay and becomes the bedrock of the islands around the coast of Lampung Bay. These formations interact with coastal sediment material (Qa) in the form of cobbles, pabble, sand, clay, and peats. Formation of young volcanic deposits Qhv(b) with intermediate lava lithology (andesite-basalt), breccia and tuff eruption results from Mount Betung. This formation occupies the middle and extends to the western part of Bandar Lampung. In the southwestern and northeastern parts of the research area there are Oligocene-Eocene-aged Tarahan Formations (Tpot) with lithology welded tuff, breccia with intercalacions of chert. On the surface, this formation is separated by the Lampung Bay. The oldest rock formations in this region are the unddifferentiated G. Kasih complex in the form of quartzite Sidodadi Pzg(k) and Way Galih Pzg(s) Paleozoic-aged bedrock. The existence of this rock is revealed in the eastern part of Bandar Lampung region. The faults that developed in this region is the Lampung-Panjang fault, which is the main fault of the northwest-southeast direction and several parallel minor faults in the western and eastern parts of the main fault.

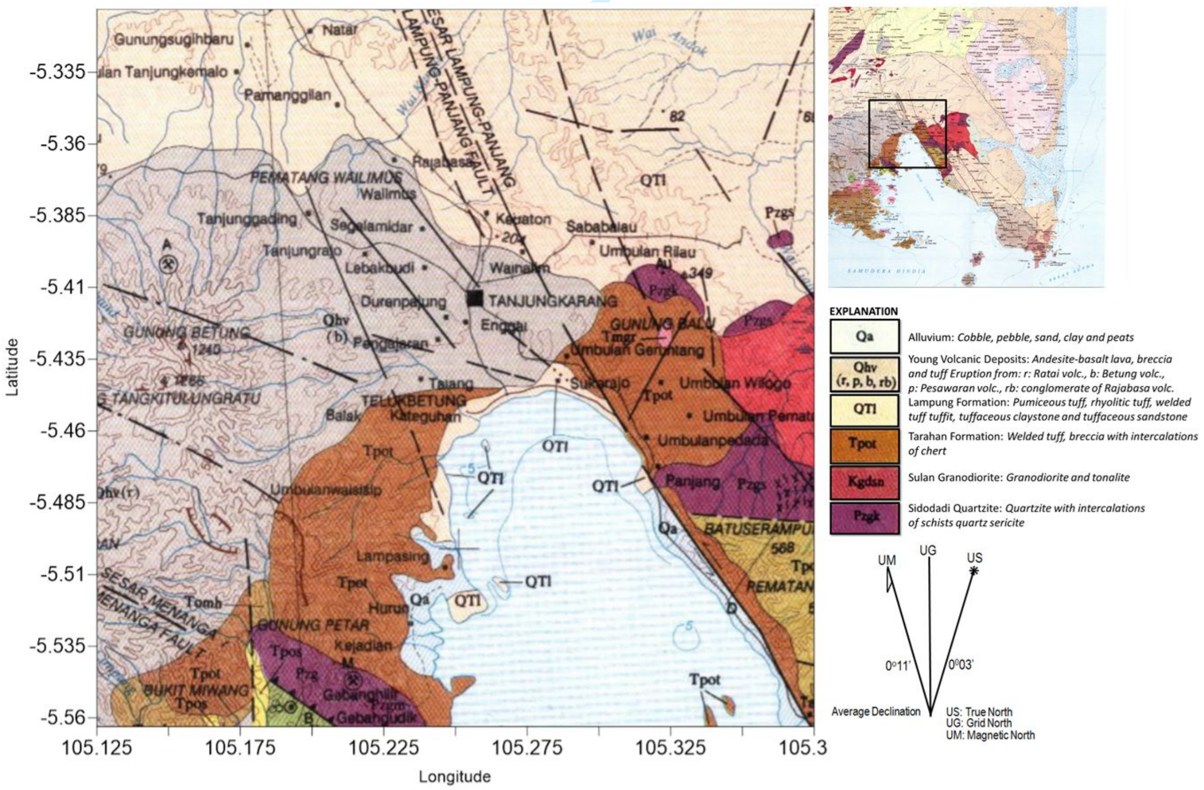

Figure 1. Geological map of Bandar Lampung [53].

2.1. Data Acquisition

Microtremor measurements were conducted at 139 station locations using the REFTEK 130-SMHR strong motion high resolution recorder, and natural frequency values were obtained from horizontal to vertical specral ratio (HVSR) calculations with reference to researches by [58], [35], (2012), [35], [59], [36]. Microtremor is defined as the natural harmonic vibration of soil that occurs continuously, trapped in the surface sediment layer, and reflected by the presence of a boundary plane of the layer with a fixed frequency. This phenomenon derived from human activity and natural vibrations of the soil [60]. Microtremor microzoning is a process of dividing areas based on certain parameters, including natural frequency, amplification factor and dominant period.

Surface wave measurements with the MASW method were carried out at seven station locations overlapping with micro tremor measurements. This measurement was done using the DMT Summit II Plus tool with 24 geophones with space of 2.5 meters, the source of the waves using a 12*lb* hammer. Furthermore, the MASW data processing was carried out with stages of [61], [32], [62], [63]; (i) raw data, (ii) geometric edit, (iii) Fourier transformation, (iv) disperse curve plotting, (v) picking, and (vi) calculation of inversion value of Vs versus thickness of soil/rock layer.

Figure 2. Distribution of microtremor and MASW measurement.

3. Result and Discussion

Some researchers have formulated empirical equations to derive soil thickness values from the natural frequency parameters of a region. The following table illustrates the development of soil thickness calculations based on the basic parameters of natural frequency values,

Table 1. Summary of the previous published equations (modified [53])

No.	Author	Empirical relationship	Study area	Comparison	Geology of the area	Sediment thickness covered
1.	Ibs-von Seht and Wohlenberg (1999)	$H = 96(f_o)^{-1.388}$	Western Lower Rhine Embayment in Germany	34 bore holes with data from 102 microtremor measurements	Sedimentary cover of approximate 1000 m thickness	15 to 1257 m
2.	Delgado et al. (2000)	$H = 55.64(f_o)^{-1.268}$	Bajo Segura Basin, Spain	33 microtremor surveys with 23 bore hole locations	Sedimentary	3.8 to 46.1 m
3.	Parolai et al. (2002)	$H = 108(f_o)^{-1.551}$	Cologne area, Germany	32 bore holes with 337 data from seismic stations	Sediment thickness varying from 100 to 500 m	10 to 401.6 m
4.	Hinzen et al. (2004)	$H = 137(f_o)^{-1.19}$	Lower Rhine Embayment, Germany	50 microtremor survey points with lithology data	Sedimentary cover with approximate1000 m thickness	60 to 1250 m (medium thickness of 600 m)
5.	Birgören et al. (2009)	$H = ¼151(f_o)^{-1.1531}$	Istanbul	15 microtremor (CMG-6T) survey at bore hole locations	Sedimentary	20 to 366 m
6.	Özalaybey et al. (2011)	$H = 141(f_o)^{-1.27}$	Izmit Bay area,Turkey	239 microtremo rsurveys with 405 points gravity measurements	Sedimentary cover ranging from thickness of 750 to 1200 m	60 to 1120 m

					thickness	
7.	Paudyal et al. (2013)	$H = 146(f_o)^{-1.2079}$	Kathmandu basin	172 microtremor surveys with 2 bore holes (taken from aprevious study)	Lacustrine sediments with varying sediment thickness within a few meters	Max. 357 m thickness
8.	Biswas et al. (2015)	$H = 160.9(f_o)^{-1.459}$	Shillong, Northeast India	70 microtremor surveys with available bore hole lithology data	Sedimentary	10 to 200 m
9.	Del Monaco et al. (2015)	$H = 129.3(f_o)^{-1.06}$	Western L'Aquila plain	790 microtremor surveys with available bore hole data	Sedimentary layer with 100 m thickness	10 to 200 m
10.	Sarfraz Khan and Asif khan (2016)	$H = 134(f_o)^{-1.23}$	Islamabad City, Pakistan	81 microtremor surveys in comparison with already published data	Sediment thickness up to 100 m	4 to 138 m
11.	Janarthana Boobalan Anthiraikili (2020)	$H = 198.35(f_o)^{-1.11}$	Indo-Gangetic Plain, India	31 microtremor measurements with available bore hole data	sedimentary basin (sedimentary cover ranging from 0.5 to 4 km)	52 to 1418 m

Some areas in the Bandar Lampung with high soil thickness are associated with sedimentation dynamics from intensive rock formations in this region with long periods. This is seen with a large enough rock age range including pre-Tertiary age in the form of exposed Mt. Kasih metamorphic rock collapses complex (schist, gneiss, marbles, carbonaceous schist, pelitic quartz and graphite, quartzite). In addition, other soil deposits are formed during Tertiary in the Tarahan Formations, sourced from sediments produced by continental arc volcanic rocks and sediments deposited at the edge of the volcanic arc that are deposited together widely. Contribution of the soil deposits in the Quarter is as fragmentation of Plistosen lava, breccia, and tuff and limestone deposits and alluvium sediments in the Holocene age.

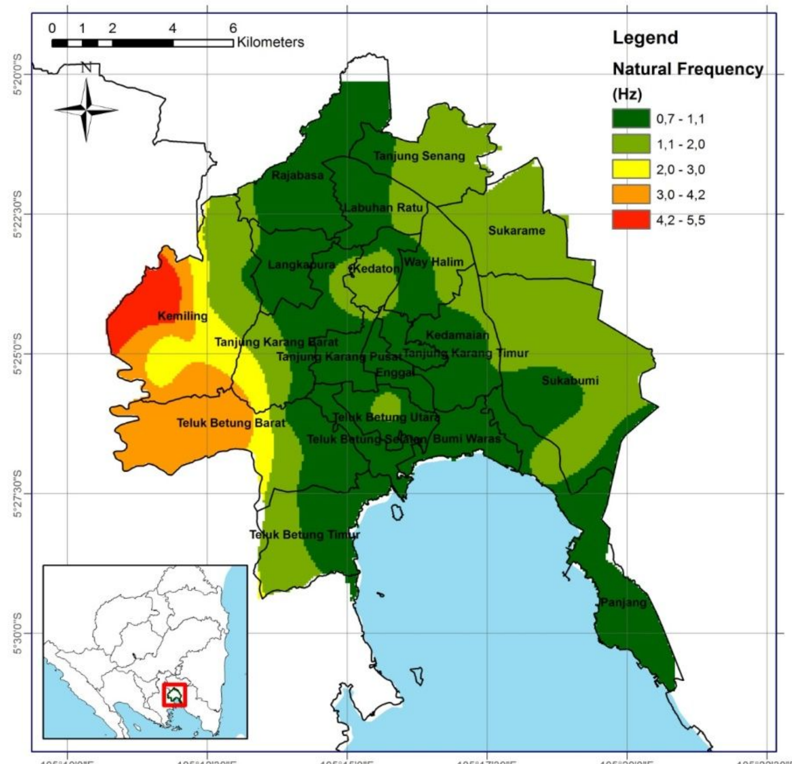

Figure 3. Map of natural frequency value f_o based on maximum spectral value H/V in Bandar Lampung.

The results of calculating natural frequency values based on the maximum spectral value of H/V in the study area describe variations in seismicity conditions that are directly related to the thickness of the sediment cover layer. Low natural frequency values occupy the middle and spread to the shores in the Lampung Bay area. While in the western part of the study area showed a high natural frequency value associated with the condition of a thin soil layer, where geologically the region is occupied by units of young mountain deposits of Mt. Betung as a product of andesitic-basaltic rock lava. In the eastern part of the study area is also influenced by the existence of Tarahan Formation consisting of compact tuff and breccia and the presence of Tanjung Bintang granite that spread widely in the region. Kanai (1983) classified the relationship of soil layers (sediment) with natural frequency values and gained the influence of soil layer thickness to the decreasing of the natural frequency values [60].

Table 2. Natural frequency value f_o based on maximum spectral H/V and soil depth based on estimated value Vs.

ID	Longitude	Latitude	f_o (Hz)	Z (m)
BDL-UL01	105.239306	-5.3635232	0.8	35
BDL-PJ16	105.315088	-5.4521342	1.3	11
BDL-TS12	105.247398	-5.4644418	0.7	37
BDL-KT02	105.263436	-5.4364093	1.1	16
BDL-WH02	105.250396	-5.4005006	1.3	12
BDL-TB19	105.246196	-5.4388953	0.9	26
BDL-KT06	105.296318	-5.4464355	0.8	33

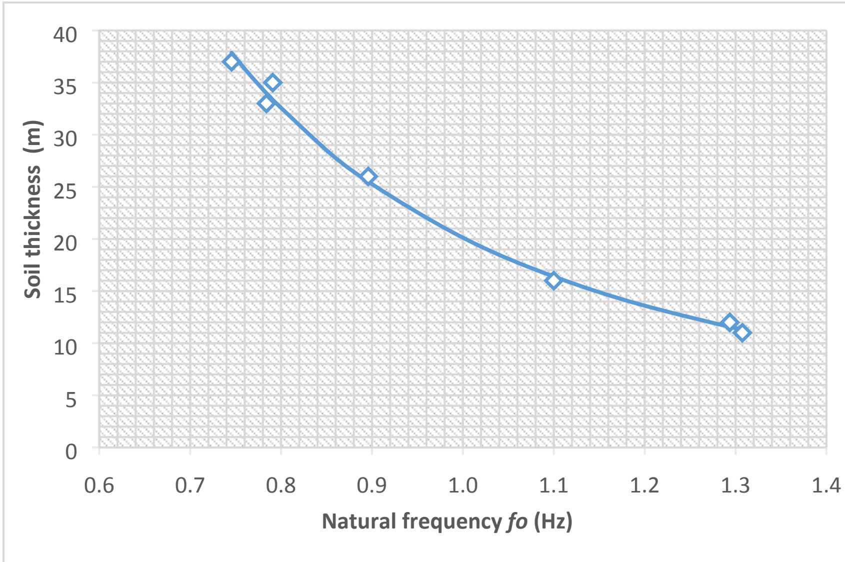

Figure 4. Natural frequency relationship curve based on maximum specral calculation H/V vs. soil thickness based on the MASW method.

The relationship of natural frequency and soil thickness shows a non-linear negative trend relationship. Several researchers have conducted correlation studies between the natural frequency of H/V and the sediment thickness based on the help of available borehole lithology data. [41], [48], [44] were the first to study the relationship between natural frequency and sediment thickness. Then, many other researchers did the same with the characteristics of different and distinctive regions, such as [50], [45], [42], [43], [47], [49], [46], and [52]. Empirical equations developed by researchers previously summarized in Table 1.

Empirical equations were previously developed for different regions with varying thicknesses of soil sediments. Most were developed taking into account of shallow basin data including [48], [47], [49] dan [46]. Meanwhile [41], [44], [50], [45], [43], [42] and [52] developed empirical equations for regions with sediment thicknesses of more than 500 m.

Based on the geological map of Tanjungkarang, Bandar Lampung area has a sediment cover of less than 200 m [53], so only the four empirical equations above can be considered appropriate to compare with the case of Bandar Lampung. Seht and Wohlenberg (1999) is the first to show the natural frequency (f_o) relationship of a layer of soil closely related to thickness $Z(f_o)$ through relationship,

$$Z(f_o) = a(f_o^{-b}) \tag{1}$$

Natural frequency values obtained based on maximum spectral H/V ratio and sediment thickness data from the MASW data calculations from seven measurement stations overlapped with the microtremor measurements (Figure 2), regression was conducted to obtain a curve fitting model based on equation (1) and obtained the following equation,

$$Z(f_o) = 20.129(f_o^{-2.151}) \tag{2}$$

The equation has an adequate R^2 value of 0.9958. The following are empirical equations presented by each researcher Delgado et al. (2000), Biswas et al. (2015), Del Monaco et al. (2015), Khan and Asif Khan (2016) in the form of,

$$Z(f_o) = 55.64(f_o^{-1.268}) \tag{3}$$

$$Z(f_o) = 160.9(f_o^{-1.459}) \tag{4}$$

$$Z(f_o) = 129.3(f_o^{-1.06}) \tag{5}$$

$$Z(f_o) = 134(f_o^{-1.23}) \tag{6}$$

respectively. The compatibility between the equations formulated in this study and the four equations put forward by previous researchers showed a highly correlated relationship. Where the pattern of the fitting curves formed is related to the condition of the sediment thickness in their respective research areas.

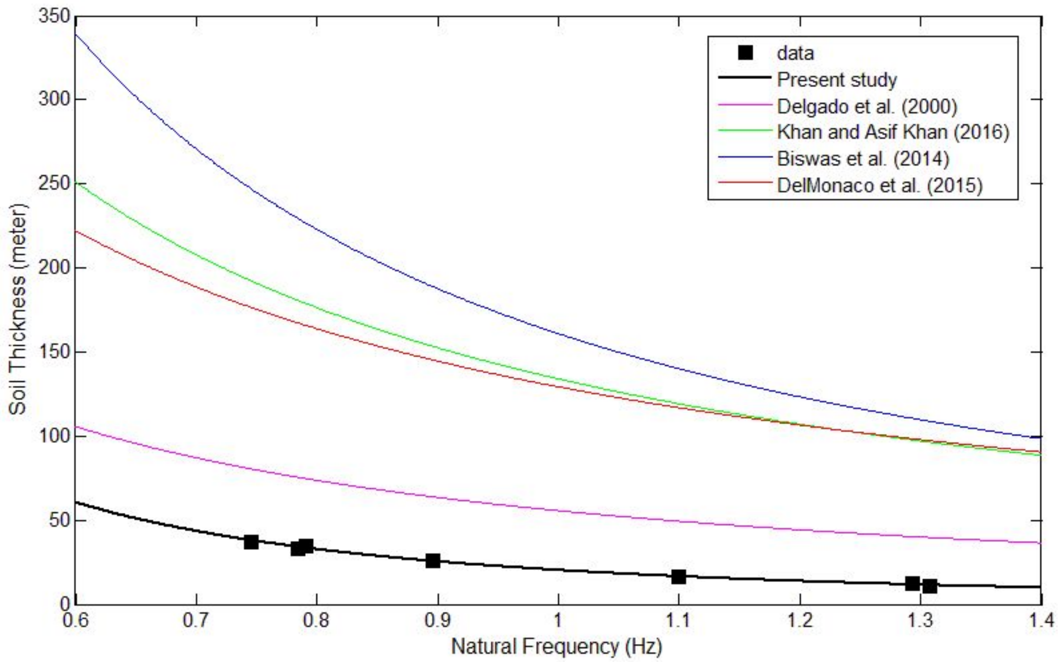

Figure 5. Comparison of natural frequency relationship curves and soil thickness calculated using various equations in Table 2 data.

Furthermore, the thickness of sediment for all the microtremor measurement stations is calculated using such empirical equations and presented as in Figure 6 below,

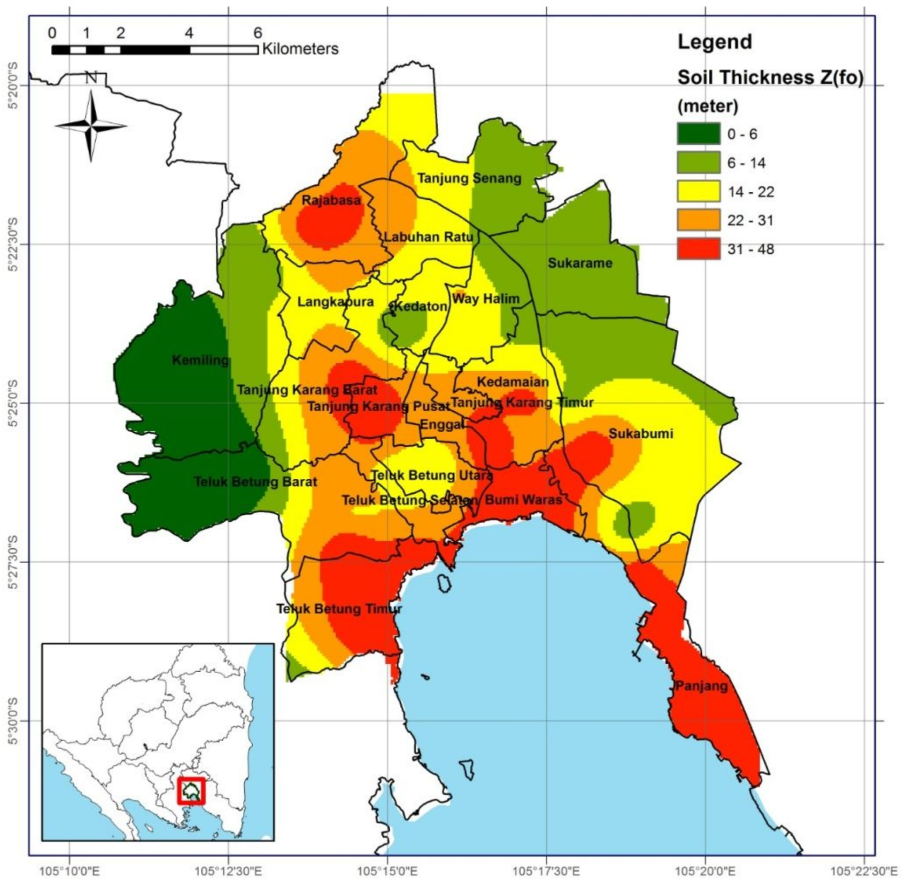

Figure 6. Map of the thickness of the soil layer of Bandar Lampung.

The results of the empirical calculations of the soil thickness in the study area showed the consistency of sediment with high thickness in the middle of the study area (base on eq. 2). This is certainly related to topographic conditions where the area is flanked by the height of Mt. Betung in the west and Tarahan in the east so that it becomes a supply area of rock and strong sedimentation deposits. In addition, along the coast in the Bay of Lampung area also showed high sediment cover conditions associated with the interaction of sea and land. Areas in the western part (Kemiling and West Teluk Betung) and east (part of Tanjung Senang, Sukarame and parts of Sukabumi) show a condition of thin soil thickness because it is related to geological conditions in the form of young mountain deposits of Mt. Betung Qhv(b) in the form of andesitic-basaltic lava formations and Tarahan Formations in the form of welded tuff and volcanic breccia rocks.

4. Conclusion

This article is an attempt to link the natural frequency value calculated based on the maximum spectral value of the H/V ratio method and soil thickness based on the shear wave speed value of the MASW method in the Bandar Lampung area. Natural frequencies are obtained based on measurements at 139 stations where seven locations are overlapped with the MASW measurements. The soil thickness also corresponds to the geological conditions of the study area and shows corresponding results. The results of soil thickness mapping based on empirical equations presented for Bandar Lampung by correlated the natural frequency obtained with the thickness of sediment available from the MASW method, showing a good correlation with the equations found by researchers from other regions. Although the empirical equation presented in this study shows conformity with the study area, it is still necessary to cross-check with rock bore data so that the accuracy of the equations-built biases is better.

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References

[1] Defra Soils Policy Team. (2009) *Construction Code of Practice for the Sustainable Use of Soils on Construction Sites*. Department for Environment, Food and Rural Affairs UK.

[2] Wazoh, H. N. and S. J. Mallo. (2004) Standard Penetration Test in Engineering Geological Site Investigations – A Review. *Int. J. Eng. Sci.*, 2319–1813, 2014.

[3] Cetin, K. O., R. B. Seed, A. Der Kiureghian, K. Tokimatsu, L. F. Harder, R. E. Kayen and R. E. S. Moss. (2004) Standard Penetration Test-Based Probabilistic and Deterministic Assessment of Seismic Soil Liquefaction Potential. *J. Geotech. Geoenvironmental Eng.* 130(12), 1314–1340.

[4] Osman, M. A. and E. O. Ahmed. (2003) Evaluation of Cone Penetration Test (CPT) Classification Methods for Some Local Soils. *Build. Road Res. J.* 5, 37-46.

[5] Lunne, T., P.K. Roberrson and J. Powel (2009) Cone-penetration testing in geotechnical practice. *Soil Mech. Found. Engineering* 46(6), 237-237.

[6] Robertson, P.K. (1990) Soil classification using the cone penetration test. *Can. Geotech. Journal* 27(1), 151-158.

[7] Baghdadi, Z. A., F. M. Ghazali and S. M. S. Al-ahmadi. (1993) Cone Penetration Testing for Field Density Prediction. *Eng. J. Qatar University* 6.

[8] Holmsgaard, R., L. B. Ibsen and B. N. Nelsen. (2016) Interpretation of Seismic Cone Penetration Testing in Silty Soil. *Electron. J. Geotech. Engineering* 21(15), 4759-4779.

[9] Carter, M. R. and E. G. Gregorich. (2008) *Soil Sampling and Methods of Analysis*. 2nd Canadian Society of Soil Science, vol. 44.

[10] Schroth, G. and D. Kolbe. (1994) A method of processing soil core samples for root studies by subsampling. *Biol. Fertil. Soils* 18(1), 60-62.

[11] Prior, S. A., G. B. Runion, H. A. Torbert and D. C. Erbach. (2004) A hydraulic coring system for soil-root studies. *Agron. J.* 96(4), 1202-1205.

[12] Socco, L. V., S. Foti and D. Boiero. (2010) Surface-wave analysis for building near-surface velocity models - Established approaches and new perspectives. *Geophysics* 75(5), 75A83-75A102.

[13] Chik, Z., T. Islam and M. R. Taha. (2011) The consistent performance in dispersion analysis for geotechnical surface wave investigations. *Tamkang J. Sci. Eng.* 14(2), 107-114.

[14] Dey, S. and P. K. De. (2010) Propagation of channel wave in an incompressible anisotropic initially stressed plate of finite thickness. *Tamkang J. Sci. Eng.* 13(2), 127-134.

[15] Chang, D. W. and S. M. Lee. (2013) EQWEAP analysis and its applications to seismic performance based design for pile foundations. *J. Appl. Sci. Eng.* 16(1), 29-40.

[16] Zandi, H. and H. Rahimi. (2020) 2-D surface wave tomography in the northwest part of the iranian plateau. *J. Earth Sp. Phys.* 45(4), 133-142.

[17] Matsuoka, M., K. Wakamatsu, K. Fujimoto and S. Midorikawa. (2006) Average shear-wave velocity mapping using Japan engineering geomorphologic classification map. *Struct. Eng. Eng.* 23(1), 57s-68s.

[18] Castellaro, S., R. B. Raykova and M. Tsekov (2016) Resonance Frequencies of Soil and Buildings - Some Measurements in Sofia and Its Vicinity. Proc. 3rd National Congress on Physical Sciences, Sofia, Bulgaria, 1-6.

[19] Lachet, C. and P. Y. Bard. (1994) Numerical and Theoretical Investigations on the Possibilities and Limitations of Nakamura's Technique. *J. Phys. Earth* 42(5), 377-397.

[20] Hasancebi, N. and R. Ulusay. (2006) Evaluation of site amplification and site period using different methods for an earthquake-prone settlement in Western Turkey. *Eng. Geol.* 87(1-2), 85-104.

[21] Langston, C.A., S. C. Chi Chiu, Z. Lawrence, P. Bodin and S. Horton. (2009) Array observations of microseismic noise and the nature of H/V in the mississippi embayment. *Bull. Seismol. Soc. Am.* 99(5), 2893-2911.

[22] Bour, M., D. Fouissac, P. Dominique and C. Martin. (1998) On the use of microtremor recordings in seismic microzonation. *Soil Dyn. Earthq. Eng.* 17(7-8), 465-474.

[23] Bignardi, S. (2017) The uncertainty of estimating the thickness of soft sediments with the HVSR method: A computational point of view on weak lateral variations. *J. Appl. Geophys.* 145, 28-38.

[24] Mucciarelli, M. (2011) Ambient noise measurements following the 2011 Christchurch earthquake: Relationships with previous microzonation studies, liquefaction, and nonlinearity. *Seismol. Res. Lett.* 82(6), 919-926.

[25] Tuladhar, R., F. Yamazaki, P. Warnitchai and J. Saita. (2004) Seismic microzonation of the greater Bangkok area using microtremor observations. *Earthq. Eng. Struct. Dyn.* 33(2), 211-225.

[26] Paudyal, Y.R., N. P. Bhandary and R. Yatabe. (2012) Seismic microzonation of densely populated area of kathmandu valley of nepal using microtremor observations. *J. Earthq. Eng.* 16(8), 1208-1229.

[27] Nakamura, Y. (2000) Clear identification of fundamental idea of Nakamura's technique and its applications. Proc. 12th World Conf. Earthq. Eng., Fujimidai, Kunitachi-shi, Tokyo, Japan, 1-8.

[28] Nakamura, Y. (1989) A method for dynamic characteristics estimation of subrurface using microtremor on the ground surface. *QR RTRI J.* 30(1), 25-33.

[29] Tokeshi, K., P. Harutoonian, C. J. Leo and S. Liyanapathirana. (2013) Use of surface waves for geotechnical engineering applications in Western Sydney. *Adv. Geosci.* 35(1), 37-44.

[30] Zeng, C., J. Xia, R. D. Miller, G. P. Tsoflias and Z. Wang. (2012) Numerical investigation

of MASW applications in presence of surface topography. *J. Appl. Geophys.* 84, 52-60.

[31] Mohamed, A. M. E., I. El-Hussain, A. Deif, K. Al-Jabri, Z. Al-Habsi and S. El-Hady (2015) Near-surface site characterization at Quriyat City, Sultanate of Oman using HVSR and MASW techniques. *Arab. J. Geosci.* 9(1), 1-18.

[32] Park, C. B. and R. D. Miller. (2008) Roadside passive multichannel analysis of surface waves (MASW). *J. Environ. Eng. Geophys.* 13(1), 1-11.

[33] Nolan, J. J., R. Miller, J. Ivanov, S. Peterie and E. Lindgren. (2013) Near-surface salt dissolution void identification using passive MASW. Proc. in SEG Houston 2013 Annual Meeting, Houston, USA, 2212-2217.

[34] Yordkayhun, S., C. Sujitapan and T. Chalermyanont. (2014) Joint analysis of shear wave velocity from SH-wave refraction and MASW techniques for SPT-N estimation. *Songklanakarin J. Sci. Technol.*, 36(3), 333-344.

[35] Albarello, D., R. Cakir and T. J. Walsh. (2011) Testing Joint Application Of HVSR Ambient Vibration Measurements And MASW Seismic Survey In The Puget Lowland And Coastal Area, Washington. *Nat. Resour.*

[36] Gorstein, M. and M. Ezersky. (2015) Combination of HVSR and MASW Methods to Obtain Shear Wave Velocity Model of Subsurface in Israel. *Int. J. geohazards Environ.* 1(1), 20-41.

[37] Devi, R., R. G. Sastry and N. K. Samadhiya. (2017) Assessment of soil-liquefaction potential based on geoelectrical imaging: A case study. *Geophysics* 82(6), B231-B243.

[38] Gouveia, F., R. C. Gomes and I. Lopes. (2019) Shallow and in depth seismic testing in urban environment: A case study in Lisbon Miocene stiff soils using joint inversion of active and passive Rayleigh wave measurements. *J. Appl. Geophys.* 169, 199-213.

[39] García-Jerez, A., H. Seivane, M. Navarro, M. Martínez-Segura and J. Piña-Flores. (2019) Joint analysis of Rayleigh-wave dispersion curves and diffuse-field HVSR for site characterization: The case of El Ejido town (SE Spain). *Soil Dyn. Earthq. Eng.* 121, 102-120.

[40] Bergamo, P. and L. V. Socco. (2016) P- and S-wave velocity models of shallow dry sand formations from surface wave multimodal inversion. *Geophysics* 81(4), R197–R209.

[41] Von Seht, M. I. and J. Wohlenberg. (1999) Microtremor Measurements Used to Map Thickness of Soft Sediments. *Bull. Seismol. Soc. Am.* 89(1), 250-259.

[42] Paudyal, Y. R., R. Yatabe, N. P. Bhandary and R. K. Dahal. (2012) Basement topography of the Kathmandu Basin using microtremor observation. *J. Asian Earth Sci.* 62, 627-637.

[43] Ozalaybey, S., E. Zor, S. Ergintav and M. C. Tapırdamaz. (2011) Investigation of 3-D basin structures in the ˙Izmit Bay area(Turkey) by single-station microtremor and gravimetric methods. *Geophys. J. Int.* 186. 883–894.

[44] Parolai, S., P. Bormann and C. Milkereit. (2002) New relationships between Vs, thickness of sediments, and resonance frequency calculated by the H/V ratio of seismic noise for the cologne area (Germany). *Bull. Seismol. Soc. Am.* 92(6), 2521-2527.

[45] Birgören, G., O. Özel and B. Siyahi. (2009) Bedrock depth mapping of the coast south of Istanbul: Comparison of analytical and experimental analyses. *Turkish J. Earth Sci.* 18(2), 315-329.

[46] Khan, S. and M. Asif Khan. (2016) Mapping sediment thickness of Islamabad city using empirical relationships: Implications for seismic hazard assessment. *J. Earth Syst. Sci.* 125(3), 623-644.

[47] Biswas, R., S. Baruah and D. K. Bora. (2015) Mapping Sediment Thickness in Shillong

City of Northeast India through Empirical Relationship. *J. Earthquakes* 2015, 1-8.

[48] Delgado, J., C. López Casado, A. Estévez, J. Giner, A. Cuenca and S. Molina. (2000) Mapping soft soils in the Segura river valley (SE Spain): A case study of microtremors as an exploration tool. *J. Appl. Geophys.* 45(1), 19-32.

[49] Del Monaco, F., F. Durante, L. Macerola and M. Tallini. (2015) Quaternary sedimentary cover thickness versus seismic noise resonance frequency in Western L'Aquila Plain," *GNGTS* 2(2), 81-86.

[50] Hinzen, L. G., B. Weber and F. Scherbaum. (2004) On the resolution of H/V measurements to determine sediment thickness, a case study across a normal fault in the Lower Rhine Embayment, Germany. *J. Earthq. Eng.* 8(6), 909-926.

[51] Ryanto, T. A., E. R. Iswanto, Y. Indrawati, A. B. Setiaji and H. Suntoko. (2020) Sediment Thickness Estimation in Serpong Experimental Power Reactor Site Using HVSR Method," *J. Pengemb. Energi Nukl.* 22(1), 29-31.

[52] Anthiraikili, J. B. (2020) Establishing empirical equation for resonant frequency vs sediment thickness using Nakamura or H/V ratio method in Indo-Gangetic Plain. *Arab. J. Geosci.* 13(6), 1-15.

[53] Mangga, S. A., Amirudin, T. Suwarti, S. Gafoer and Sidarto. (1993) *Geological Map Segment Tanjung Karang*. Geological Research and Development Center of Indonesia.

[54] Hamilton, W. (1979) *Tectonics of the Indonesian Region.* USGS, U.S. Goverment.

[55] Sieh, K. and D. Natawidjaja. (2000) Neotectonics of the Sumatran fault, Indonesia. *J. Geophys. Res. Solid Earth* 105(B12), 28295-28326.

[56] Silver, E. A., R. McCaffrey and R. B. Smith. (1983) Collision, rotation, and the initiation of subduction in the evolution of Sulawesi, Indonesia. *J. Geophys. Res.* 88(B11), 9407-

9418.

[57] McCaffrey, R. (2009) The Tectonic Framework of the Sumatran Subduction Zone. *Annu. Rev. Earth Planet. Sci.* 37(1), 345-366.

[58] Di Giacomo, D., M. R. Gallipoli, M. Mucciarelli, S. Parolai and S. M. Richwalski. (2005) Analysis and modeling of HVSR in the presence of a velocity inversion: The case of Venosa, Italy. *Bull. Seismol. Soc. Am.* 95(6), 2364-2372.

[59] Di Stefano, P., D. Luzio, P. Renda, R. Martorana, P. Capizzi, A. D'Alessandro, N. Messina, G. Napoli, S. Todaro and G. Zarcone. (2014) Integration of HVSR measures and stratigraphic constraints for seismic microzonation studies: the case of Oliveri (ME). *Nat. Hazards Earth Syst. Sci. Discuss.* 2(4), 2597-2637.

[60] Kanai, K. (1983) *Engineering Seismology*. University of Tokyo Press.

[61] Park, C. B. and R. D. Miller. (2007) Multichannel Analysis of Surface Waves (MASW). *Lead. Edge* 26(1), 60-64.

[62] Luo, Y., J. Xia, R. D. Miller, Y. Xu, J. Liu and Q. Liu. (2008) Rayleigh-wave dispersive energy imaging using a high-resolution linear radon transform. *Pure Appl. Geophys.* 165(5), 903-922.

[63] Wang, L., Y. Luo and Y. Xu. (2012) Numerical investigation of Rayleigh-wave propagation on topography surface. *J. Appl. Geophys.* 86, 88-97.