International Journal of GEOMATE, Sept. 2022, Vol.23, Issue 97, pp.211-219
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2022.97.j2357
Geotechnique, Construction Materials, and Environment

STUDY OF THE SUBSURFACE STRUCTURE BASED ON MICROSEISMIC DATA IN THE HERITAGE AREA OF KOTA LAMA SEMARANG, INDONESIA

*Supriyadi[1], Khumaedi[2], Sugiyanto[3], Akhmad Riki Fadilah[4], Wahyu Humam Muttaqin[5]

[1,2,3,4,5] Faculty of Mathematics and Natural Sciences, Universitas Negeri Semarang, Indonesia

*Corresponding Author, Received: 10 Oct. 2021, Revised: 22 June 2022, Accepted: 02 Aug. 2022

ABSTRACT: Microseismic measurements are popularly applied to investigate local seismic responses based on the dominant frequency and amplification factor. Understanding the resonance frequency of heritage sites and their buildings is essential in spatial and regional planning in Kota Lama Semarang. The problem to be solved in this research is that there are no subsurface data available, especially the vulnerability index. The method that is applied to solve the problem is the HVSR method and the data obtained are Kg (vulnerability index), PGA (peak ground acceleration), and GSS (ground shear strain). This study aims to describe the subsurface structure in Kota Lama in 2 dimensions based on Kg, PGA, and GSS data. Data analysis of microtremors showed that the predominant frequency (f_0) values range from 5.36-17.86 Hz, the amplification (A_0) values range from 0.25-0.87, the Kg values range from 0.62-5.8 x 10^{-2} cm/s^2, the PGA values range from 3.9-7.5 x 10^{-2} gal, and the GSS values range from 0.6-12.58 x 10^{-6}. The subsurface structure was assessed using the Vs value, which was determined by a 2D profile consisting of 5 slices at a depth of 100 m depth. Slice 1 has Vs values ranging from 100-1300 m/s, slice 2 has values ranging from 100-1600 m/s, slice 3 has values ranging from 100-800 m/s, slice 4 has values ranging from 100-800 m/s, and slice 5 has values ranging from 100-1200 m/s. According to the values of Vs > 1500 m/s, the subsurface area of Kota Lama Semarang is dominated by soft rocks.

Keywords: Microseismic, HVSR method, Subsurface structure, Kota Lama

1. INTRODUCTION

Over the last three decades, microtremor measurements have been popularly used to identify local seismic responses [1]. Measuring microtremors is classified as a passive geophysical method. A microtremor is defined as a low-amplitude continuous ground vibration due to human-made factors, e.g., manufacturing activities, traffic, mining, etc., as well as natural factors, e.g., rain and wind [2]. One of the methods used for processing microtremors is horizontal to the vertical spectral ratio (HVSR), which was introduced by Nogoshi and Igarashi in 1970 [3] and then popularized by Nakamura in 1989 [4]. The HVSR works by comparing the horizontal and vertical component spectra of the microtremor wave [5] to obtain the dynamic parameters (predominant frequency and amplification). Microtremor measurements and HVSR techniques are commonly used for site effect studies, deal with wave amplification mechanisms in shallow geological layers and determine the thickness of the sediment layer [6]. Understanding the resonance frequencies of heritage sites and their buildings is essential in spatial and regional planning to prevent the resonant effect of the soil structure, which can affect the amplification of seismic waves with identical frequencies [7]. Kang et al. [8] reported the use of the HVSR method to identify resonance frequencies, describe the bedrock depth, and assess seismic susceptibility. Moreover, microtremor measurements can also be applied for monitoring volcanic activities, supporting geothermal exploration, supporting microzonation, and studying geophysical and geotechnical processes [9]. This method is suitable for application in urban areas due to its low cost and simple data collection without any drilling or active seismic surveys [10].

Kota Lama Semarang is a preserved colonial city that used to be a central economy, military, and government. This heritage area is located in northern Semarang city, Central Java, Indonesia, and consists of 50 ancient sturdy buildings with typical 1700s European ornament [11]. There are several Dutch colonial heritage buildings in Kota Lama Semarang, including the Blenduk church, MARBA building, Jiwasraya insurance building, Mandiri bank office (Fig. 1), and many others. The beauty of ancient ornate European buildings supports Kota Lama Semarang as a fascinating tourist destination. The arrangement and revitalization of Kota Lama Semarang attract both local and foreign tourists. In 2019, the Central Java Provincial Tourism Office reported that approximately 61000 foreign tourists and 2.6 million local tourists visited the Kota Lama

Semarang, making it one of the top three tourist destinations in Central Java.

a b c d

Fig. 1. Old buildings in Kota Lama Semarang: (a) Blenduk church, (b) MARBA building, (c) Mandiri bank, and (d) Jiwa Raya insurance building

In 2018, the Mayor of Semarang declared Kota Lama Semarang a cultural heritage area. The cultural heritage status is planned to be upgraded to a national cultural heritage so that it can be proposed to UNESCO as a world heritage site [12]. This decision requires supporting data related to the ancient buildings located in this area and the subsurface conditions where the buildings stand.

Research on the Kota Lama Semarang thus far has focused only on social, cultural, and economic aspects, such as the analysis of the tourism carrying capacity of the Kota Loma Semarang for the development of cultural tourism [13-15], the mapping of the economic potential in the old city of Semarang to support sustainability [16] and studies on the problem of changing the function of cultural heritage buildings [17]. In general, research related to subsurface structures is often carried out in the scope of Semarang city, which does not specifically cover Kota Lama Semarang, such as the determination of soft lithology causing land subsidence in coastal Semarang city by resistivity methods [18] and 3D inversion of gravity data modeling using the chi fact algorithm for revealing the subsurface structure in Semarang city [19]. Subsurface structures can be identified by using geophysical methods, such as geoelectricity and gravity. The geoelectric method is related to the differences in the resistivity of the rock layers, and gravity is related to the density difference between the formation layers. They cannot be used to describe soil vulnerability.

This study describes the subsurface structure in Kota Lama in 2 dimensions based on Kg, PGA, and GSS data by measuring microtremors using the HVSR method. This method was chosen because it has been used for various purposes worldwide, including monitoring the hydrocarbon productivity of the Nauquen basin in Argentina [20], estimating site effects in the southern part of Marsa Alam city, Egypt [21], estimating earthquake amplification [22], analyzing rock slides based on seismic data on earth surfaces [23], estimating the thickness of basalt profiles [24], assessing the seismic site effect in the Ngipik landfill in Gresik Indonesia [25], detecting sediment thickness in the karst delta of China's Pearl River [26], utilizing microtremors for surveys in the Hakkari region of eastern Turkey [27], and studying groundwater [28].

2. METHOD

The basic concept of the HVSR method is the similarity between the horizontal to vertical spectra ratio and the transfer of waves from the bedrock to the surface [4]. Nakamura stated that the dominant period and peak value of the ratio spectra (H/V) have similarities with the natural period and amplification factor of the soil layer, and the H/V value is obtained from the comparison between the Fourier amplitude spectrum of the horizontal wave component and the vertical wave.

The measurement of the dominant period of the soil is carried out using ambient vibrations by reducing the tremors yielded by humans and machines or other unwanted tremor sources; thus, the seismometer records vibrations generated only by ground movement. For optimum results, research was preferably conducted at night and away from human activities.

The passive seismic survey started from the discovery of an interesting phenomenon, namely, the presence of a microseismic signal detected above a hydrocarbon reservoir and not detected on the surface of a medium that does not contain hydrocarbons. This phenomenon was first discovered in 1997, wen at the top of an oil reservoir, a sharp natural earth noise spectrum was found at frequencies within 2–6 Hz. This phenomenon has been found in several different locations, in different reservoirs, and, in different countries with different geological and environmental conditions. Based on these findings, a technology was developed to detect hydrocarbons directly that can be used in exploration, field development, and monitoring of hydrocarbon fields.

Nakamura [29] reported that the value of the amplification factor in a certain area could be estimated from the peak height of the HVSR curve spectrum from microtremor measurements. The value of the dominant frequency of the HVSR curve correlates with the thickness of the sediment layer. Several stages of the microseismic survey using microtremor measurements are described as follows.

2.1 Data Acquisition

This research was conducted at the heritage site of Kota Lama Semarang. Measurement points were placed at 40 stations at a distance of 100 m, as shown in Fig. 2. We used a sampling frequency of 250 Hz for ± 30 minutes as suggested by SESAME (2004). Further processing of microseismic data and interpretation of the results were carried out at the Physics Laboratory of Universitas Negeri Semarang.

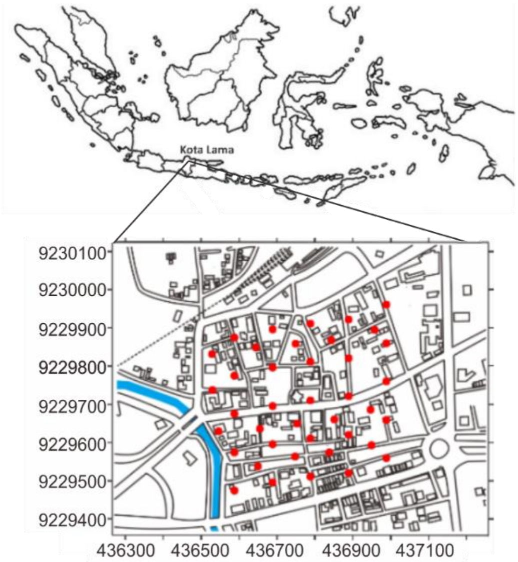

Fig. 2. Map of the research area in Kota Lama Semarang

The HVSR method uses three components of ambient seismic noise in the horizontal direction of the west-east, north-south, and vertical directions consisting of long-term microtremors generated by natural activities, such as wind, sea waves, and rain, with periods of greater than 2 seconds; short-term microtremors produced by human activities, such as traffic and machinery; and other tremor sources with periods of less than 2 seconds [30]. This microtremor method is a passive seismic method with a single measurement station. Microtremor measurement-produced data are in the form of wave propagation time with a recording duration of 30 minutes.

The recorded data were then processed using Geopsy software to transform the time function into a frequency function. Windowing was then conducted to eliminate the noise signal to obtain the expected frequency. We used the output sampling frequency of Geopsy software ranging from 4.5–20 Hz with a Konno-Ohmaci frequency filter. The results are H/V curves, as shown in Fig. 3. The peak of the curve shows the dominant frequency value (f_0) and the amplification value (A_0) [31], and these two parameters could be used to determine the values of Kg, PGA, and GSS [32].

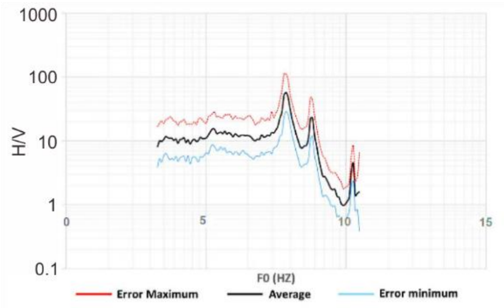

Fig. 3. Example of the HVSR curve resulting from microtremor data processing at the research location

2.2 Analysis of microtremor data

The dominant frequency is the peak frequency on the H/V curve, which is assumed to be the resonant frequency of a site [33]. The dominant frequency shows a simple sedimentary structure [34]. According to Arifin [35], the dominant frequency is defined as the frequency value that mostly appears under a rock layer and therefore indicates the type and characteristics of the rock. Previous studies have been reported regarding the estimation of sediment layer thickness using dominant frequency parameters [6, 8, 36].

Amplification can be interpreted as an amplification of waves from the bedrock to the soil surface due to the differences in the shear wave velocity Vs [37]. According to Tanjung [38], the amplification of earthquake waves can occur when a wave propagates to the ground surface where the dominant frequency of the land has the same frequency as the frequency of the incoming earthquake. The amplification value is related to the crude index of impedance between the soil and bedrock layers [21].

The vulnerability index (Kg) is calculated based on the value of the dominant frequency (f_0) and amplification (A_0), which are obtained from the HVSR curve. Nakamura [29] formulated the Kg value as expressed by Eq. (1).

$$K_g = \frac{{A_0}^2}{f_0} \tag{1}$$

Kg values with higher numbers are usually found in areas with low f_0 values in thick sediment layers [39]. A thick sediment layer accompanied by a high A_0 value results in a high Kg value [40]. The higher the Kg is, the more vulnerable the area is to the impact of shocks or vibrations [41].

Peak ground acceleration (PGA) is a record of the highest value of ground vibration acceleration that occurs in a certain area due to an earthquake. The PGA value describes the level of danger and risk of an area or building to an earthquake [39]. The PGA value can be formulated mathematically, as in Eq. (2).

$$a_{max} = \frac{5}{\sqrt{T_0}} 10^{(0,61M)-\left(1,66+\frac{3,6}{R}\right)logR+\left(0,16-\frac{1,87}{R}\right)} \qquad (2)$$

where M is the earthquake magnitude (SR), the hypocenter radius of the earthquake (km), and T_0 is the dominant period.

The ground shear strain (GSS) value describes the ability of the soil material to stretch and shift during ground vibrations, such as earthquakes. A high GSS value indicates an area with a high risk of deformation when vibration occurs [31]. The calculation of γ requires the values of Kg and a_{max}, which have a mathematical relationship, as shown in Eq. (3).

$$\gamma = \frac{A_0 \delta}{H} \qquad (3)$$

where A_0 is the amplification factor, H is the thickness of the soil layer, and δ is the deformation of the soil surface layer shown in Eq. (4).

$$\delta = K_g \left(\frac{a_{max}}{(2\pi f_0)^2}\right) \qquad (4)$$

According to Equation (3), a higher value of Kg is aligned with a higher value of γ [42].

2.3 Analysis of the subsurface structure based on shear wave velocity (Vs)

Microtremor signal processing was analyzed using the Dinver program in the Sesarray Geopsy software with the ellipticity curve method. The results of this processing are ground profiles of shear wave velocity (Vs) with various models and misfit values. The model with the lowest misfit value (0<misfit<1) is considered the best model criterion [43]. The results of the analysis using the Dinver program are shown in Figure 4. The value of Vs and its depth in each layer became input data in processing 3D solid modeling and stratigraphic modeling using Rockworks 15 software, and a slice (cross-section) was also constructed to simplify the reading of the depth of the sediment layers and their values of Vs.

3. RESULTS AND DISCUSSION

The dominant frequency determined the distribution of the dominant frequency value in the study area. We used the dominant frequency to assess the thickness of the sediment layer at each point, as shown in Fig. 5. The dominant frequency described the physical conditions of the soil on the surface or below the soil surface, in which a lower predominant frequency value indicated a thick layer of sediment in the area and vice versa.

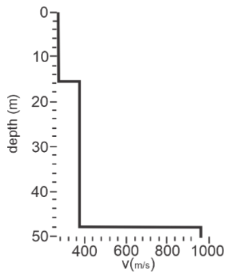

Fig. 4 Ground profile Vs with the finest misfit value

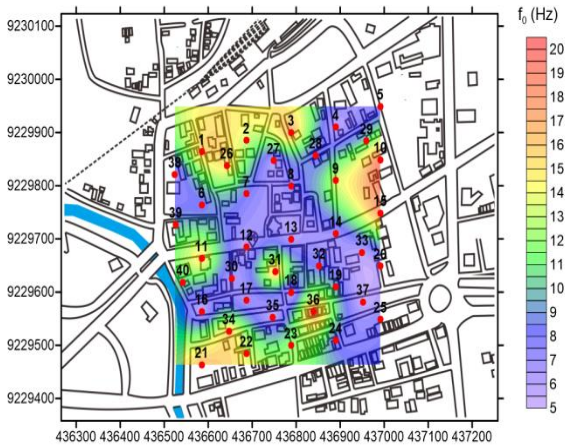

Fig. 5. Map of the predominant frequency distribution

According to Fig. 5, the distribution of the dominant frequency values is quite varied, ranging from 5.36 Hz – 17.86 Hz. The lowest frequency value is 5.36 Hz, located at point 37, indicating that the area has the thickest sediment layer depth, while the highest frequency value is 17.86 Hz, located at point 15, indicating the thinnest sediment layer depth. The area with a low dominant frequency (as at point 37) has a high vulnerability to the danger of earthquakes.

The amplification value described the magnification of the seismic wave that occurred due to the difference in the density of the layers traversed by the seismic wave. In this study, the dominant amplification value was then processed using Surfer software to obtain the amplification value distribution, as shown in Fig. 6. Based on Fig. 6, the distribution of amplification values varies between 0.25 and 0.87. The lowest amplification value of 0.25 is at point 4, while the highest amplification value of 0.87 is at point 9. According to the classification table of amplification values, the study area is included in the small classification ($A_0 \leq 9$), where the area is classified as not vulnerable to earthquakes.

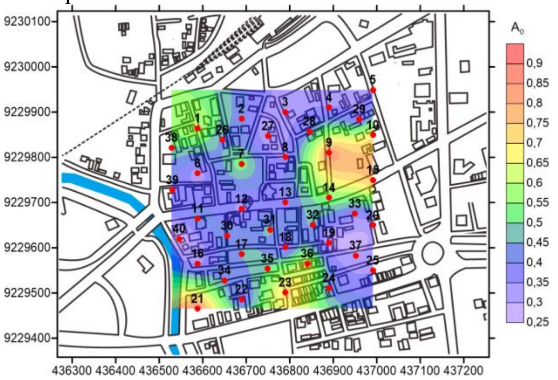

Fig. 6. Map of the amplification value distribution

The earthquake vulnerability index shows the level of soil surface layer vulnerability to deformation during an earthquake; therefore, this index can be used to determine the level of potential damage to an area due to an earthquake. In this study, the results of data processing were then plotted using Surfer software to obtain the distribution of the earthquake vulnerability index (Kg) values, as shown in Fig. 7.

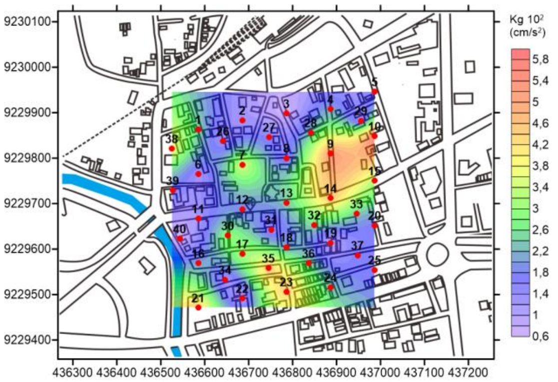

Fig. 7. Map of Kg value distribution.

According to Figure 7, the lowest Kg value is 0,62 (x 10^{-2}) cm/s², shown by a purple color scale located at point 40, while the highest Kg value is 5.8 (x 10^{-2}) cm/s², shown by a red color scale located at point 10. In Kota Lama Semarang, the average Kg value is not excessively high, except at points 9, 10, and 14, which have the highest values compared to the others. These point areas are especially vulnerable to earthquakes. According to Chieffo & Formisano [44], a high Kg value in an area is due to significant differences in the geological composition structure and causes a high amplification value at the site, affecting the level of subsurface shaking.

Peak ground acceleration, also known as maximum vibration acceleration, is a parameter used to determine the value of the shaking intensity due to an earthquake. The results of the PGA calculation using the Kanai Method in the Kota Lama Semarang area due to the 2006 Yogyakarta earthquake range from 3.9 to 7.5 (x 10^{-2}) gal, as shown in Fig. 8.

Fig. 8. Map of the PGA value distribution

Fig. 8 shows that the highest PGA value is at point 10 and is 7.5 (x 10^{-2}) g , which is located in the field of the former city park of Kota Lama Semarang. The smallest PGA value is located at point 37 and is 3.9 (x 10^{-2}) gal. Generally, the PGA value in Kota Lama Semarang due to the 2006 Yogyakarta earthquake is classified as MMI I-II, where the vibration effect can be felt without any damage. The PGA value is affected by the magnitude of the earthquake, the distance from the hypocenter to the measurement point, and the dominant frequency of the soil.

Ground shear strain (GSS) is the ability to stretch and shift a soil or rock layer structure due to an earthquake. The results of the GSS calculation of Kota Lama Semarang range from 0.6 to 12.58 (x 10^{-6}), own in Fig. 9.

Fig. 9. Map of the GSS value distribution

Areas with high GSS values have a greater risk of ground movement due to earthquakes, such as land subsidence and liquefaction. Fig. 9 shows that the area with the largest GSS value of 12.58 (x 10^{-6}) is at point 10. Moreover, the area with the smallest GSS value of 0.6 (x 10^{-6}) is at point 40. These results indicate that the area at point 10 has a high level of vulnerability to damage due to earthquakes.

According to the geological map of the Magelang-Semarang sheet, Kota Lama Semarang is an alluvial formation that is composed of clay and sand with a thickness of more than 50 m. The composition of the subsurface structure can be estimated by the value of Vs. The value of Vs can reveal the type of soil. The 2D slice based on the value of Vs can be used to analyze the distribution of soil sediment. In this study, we made 5 slices based on the value of Vs.

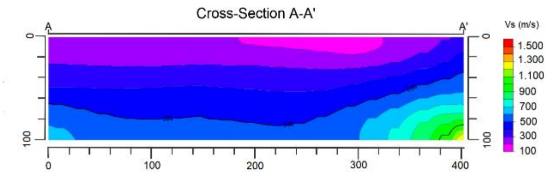

Fig. 10. 2D slice based on Vs values at points 1-5

Fig. 10 shows a 2D slice at points 1-5 based on the value of Vs. The A-A' cross-section has a track length of 400 m with a depth of 100 m. The results of the interpretation showed that the A-A' slice has Vs values ranging from 100–11300 m/s with a lower distribution, and the Vs values increase. Overall, slice 1 is composed of sedimentary rock. This composition is indicated by the Vs value at the slice <1500 m/s. The highest Vs value is located around point A', which is approximately 1300 m/s. The distribution of the sediment layer seems to become thicker from point A' to point A.

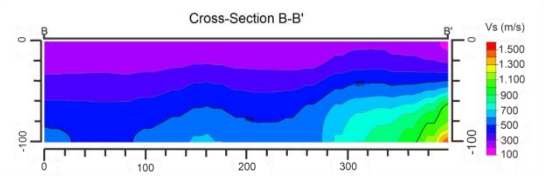

Fig. 11. 2D slice based on the Vs values of points 6–10

Fig. 11 shows a 2D slice at points 6-10 based on the Vs value. The second slice of B-B' has a track length of 400 m with a depth of 100 m. The results of the interpretation showed that the B-B' slice has Vs values ranging from 100–1600 m/s with a lower distribution, and the Vs values increase. In slice 2, the hard rock layer is located around point B' or point 10 indicated by red, which has values of Vs > 1500 m/s. Overall, the closer to the east, the harder the rock layers and the thinner the sedimentary layers.

Fig. 12 shows a 2D slice at points 11-16 based on the Vs value. The 2D C-C' has a track length of 400 m with a depth of 100 m. The results of the interpretation showed that the C-C' slice has a Vs value ranging from 100–800 m/s, which means that the rock composition is a soft layer. The highest Vs is located around point C' or point 15, as indicated by light green. Overall, the rock constituent layers become harder and the sediment layers become thinner closer to the east.

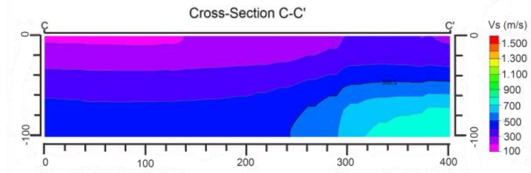

Fig. 12. 2D slice based on Vs values at points 11-15.

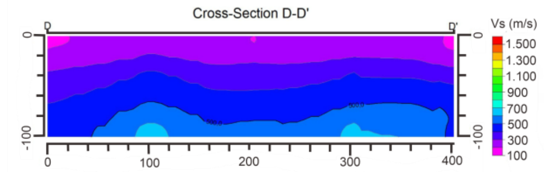

Fig. 13. 2D slice based on Vs values at points 16-20

Fig. 13 shows a 2D slice at points 16-20 based on the Vs value. The length of the 2D D-D' slice is approximately 400 m at a depth of 100 m. The interpretation results show that the D-D' slice has Vs values ranging from 100-800 m/s, which indicates that the rock composition is a soft layer. Overall, the 2D incisions at points 16-20 have a thick and even sediment layer thickness.

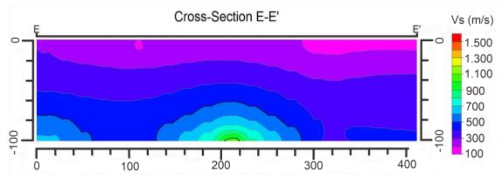

Fig. 14. 2D slice based on Vs values at points 21-25

Fig. 14 shows a 2D slice at points 21-25 based on the Vs value. The length of the 2D E-E' slice is approximately 400 m at a depth of 100 m. The interpretation results showed that the E-E' slice has Vs values ranging from 100-1200 m/s, where the highest Vs value, i.e., 1200 m/s, is in the middle of the slice indicated by green. In the east, at point 25 or E', the highest Vs values range from 400-500 m/s, which indicates that the rock constituents are soft rocks. In the west at point 20 or E, the highest Vs values range from 700 to 800 m/s, which indicates that the rock composition in the area is soft rock. Overall, at points 21-25 at a depth of 100 m, the rock structure is still a soft layer.

According to slices 10–14, all measurement points showed soft rock layers at a depth of 100 m.

This soft layer is thick at the west point and shifts to thin at the east point. The hard layer is visible in the second slice of B-B' at point 10, indicated by the value of Vs > 1500 m/s. This value is aligned with the geological map of the Magelang-Semarang sheet, where the subsurface structure of Kota Lama Semarang is a layer of clay and sand sediment with a thickness of more than 50 m.

The results of this study support the previous research conducted by Nurse in Sari [45] regarding the development of Kota Lama Semarang, which is described in five areas, namely, roads, districts, regional edges, landmarks, and activity centers. Moreover, this study will hopefully become a part of the improvement and arrangement of Kota Lama Semarang as an area with historical value; therefore, hopefully, it will not become a marginalized historical site with a quiet atmosphere and tidal wave inundation.

4. CONCLUSION

The seismic response in the Kota Lama Semarang area resulted in f_0 values ranging from 5.36–17.86 Hz, A_0 values ranging from 0.25–0.87, Kg values ranging from 0.62–5.8 x 10^{-2} cm/s², PGA values ranging from 3.9–7.5 x 10^{-2} gal, and GSS value ranging from 0.6–12.58 x 10^{-6}. These parameters are used to create a distribution map to investigate the distribution of seismic responses at the research site. According to the distribution map, the higher values of f_0, A_0, Kg, PGA, and GSS are investigated in the areas of points 9, 10, 14, and 15, which indicate the presence of a basic rock structure. This causes a significant difference in density between rock layers, which is indicated by the shear wave velocity.

According to the Vs values ascertained by the 2D profile consisting of 5 slices at a depth of 100 m, slice 1 has Vs values ranging from 100–1300 m/s, slice 2 has values ranging from 100–1600 m/s, slice 3 has values ranging from 100–800 m/s, slice 4 has values ranging from 100–800 m/s, and slice 5 has values ranging from 100–1200 m/s; the subsurface area of Kota Lama Semarang is dominated by soft rocks with Vs values < 1500 m/s.

5. ACKNOWLEDGMENT

This study is financially sponsored by Direktorat Sumber Daya, Dirjen Dikti Republic of Indonesia, with contract number 24.14.7/UN37/PPK.6.8/2021 July 14th 2021.

6. REFERENCES

[1] Stanko, D., Markušić, S., Gazdek, M., Sanković, V., Slukan, I., and Ivančić, I., Assessment of the Seismic Site Amplification in the City of Ivanec (NW part of Croatia) Using the Microtremor HVSR Method and Equivalent-Linear Site Response Analysis, Geosci, vol. 9, no. 7, 2019.

[2] Kanai, K., Engineering Seismology, Tokyo, University of Tokyo Press, 1983.

[3] Nogoshi, M., and Igarashi, T., On the Amplitude Characteristics of Microtremor Part 2, J. Seismological Soc. Japan, Vol. 24, 1971, pp. 26-40.

[4] Nakamura, Y., A Method for Dynamics Characteristics Estimation of Subsurface using Microtremor on The Ground Surface. QR RTRI, Vol. 30, Issue 1, 1989, pp. 25–33.

[5] Widyawarman, D., and Fauzi, E.R., Aplikasi Mikrotremor Untuk Mikrozonasi Tingkat Potensi Bencana Gempa Bumi Di Kampus I Universitas Pgri Yogyakarta, J. Geosaintek, Vol. 6, No 2, 2020, pp. 87–96.

[6] Picotti, S., Francese, R., Giorgi, M., Pettenati, F., and Carcione, J.M., Estimation of Glacier Thicknesses and Basal Properties Using the Horizontal-to-Vertical Component Spectral Ratio (HVSR) Technique from Passive Seismic Data, J. Glaciol, Vol. 63, No 238, 2017, pp. 229–248.

[7] Maresca, R., Nardone, L., Gizzi, F.T., and Potenza, M.R., Ambient Noise HVSR Measurements in the Avellino Historical Centre and Surrounding Area (Southern Italy). Correlation With Surface Geology and Damage Caused by the 1980 Irpinia-Basilicata Earthquake, Meas. J. Int. Meas. Confed, Vol. 130, 2018, pp. 211–222.

[8] Kang, S.Y., Kim, K.H., Chiu, J. M., and Liu, L., Microtremor HVSR Analysis of Heterogeneous Shallow Sedimentary Structures at Pohang, South Korea, J. Geophys. Eng, Vol. 17, No 5, 2020, pp. 861–869.

[9] Haerudin, N., Rustadi., Alami, F., and Yogi, I.B.S., The Effect Site Analysis Based on Microtremor Data Using the Horizontal to Vertical Spectral Ratio (HVSR) Method in the Bandar Lampung City, J. Phys. Conf. Ser, 2020, pp. 1–9.

[10] Kang, S.Y., Kim, K., and Kim, B., Assessment of Seismic Vulnerability using the Horizontal-to-Vertical Spectral Ratio (HVSR) Method in Haenam Korea, Geosci. J, 2020.

[11] Pravita, V.D., Karakter Generasi Milenial Dalam Berwisata di Destinasi Wisata Budaya Lawang Sewu dan Kota Lama Semarang, Pringgitan, Vol. 1, No 1, 2020, pp. 17–24.

[12] Yuliati, D., Susilowati, E., and Suliyati, T., Manajemen Berbasis Komunitas untuk Pengembangan Kota Lama Semarang Berwawasan World Heritage, Endogami J. Ilm. Kaji. Antropol, Vol. 3, No 1, 2019.

[13] Lukito C.S., Santoso A.B., and Kurniawan E., Analysis of Support Capacity of Kota Lama Tourism for the Development of Cultural Tourism in Semarang, IOP Conf. Ser. Earth Environ. Sci, Vol. 243, No 1, 2019.

[14] Amin, S., Pramono S.E., Atno., and Kurniawan G.F., A Model for Promoting Inclusive and Sustainable Tourism in Kota Lama Semarang, J. Southwest Jiaotong Univ, Vol. 55, No 5, 2020, pp. 1–24.

[15] Nastabiq M., and Soesanto H., The Effect of Destination Attractiveness, Destination Service Quality And Tourist Satisfaction On The Intention Of Revisit To Kota Lama Semarang, Int. J. Econ. Bus. Account. Res, Vol. 2021, No 2, 2021, pp. 342–353.

[16] Kurniawati W., Kurniati R., Soetomo S., Rahmat R.R.B., and Firdaus A.S., Mapping the Potential Economy in The Old Town of Semarang to Support Its Sustainability, J. Tek. Sipil dan Perenc, Vol. 22, No 2, 2020, pp. 110–116.

[17] Darmawan E., and Murtini T.W., The Problem Change Function of Heritage Building at the Old Cities in Central Java, Eur. J. Interdiscip. Stud, Vol. 9, No 1, 2017, pp. 142–152.

[18] Widada, S., Saputra., and Hariadi., Determination of Soft Lithology Causes the Land Subsidence in Coastal Semarang City by Resistivity Methods, IOP Conf. Ser. Earth Environ. Sci, Vol. 116, No 1, 2018.

[19] Indriana, R.D., Adhi M.A., Tampubolon D.L.P., and Koesuma S., 3D Inversion of Gravity Data Modeling using the Chi Fact Algorithm for Revealing Subsurface Structure in Semarang City, Vol. 12, No 1, 2022, pp. 67–79.

[20] Curia, D., Duncan, P. M., Grealy, M., McKenna, J., and Hill, A., Microseismic Monitoring of Vaca Muerta Completions in the Neuquén Basin, Argentina, Lead. Edge, Vol. 37, No 4, 2018, pp. 262–269.

[21] Fat-Helbary, R.E.S., El-Faragawy, K.O., and Hamed, A., Application of HVSR Technique in the Site Effects Estimation at the South of Marsa Alam city, Egypt, J. African Earth Sci, Vol. 154, 2019, pp. 89–100.

[22] Zhu, C., Pilz, M., and Cotton, F., Evaluation of A Novel Application of Earthquake HVSR in Site-Specific Amplification Estimation, Soil Dyn. Earthq. Eng, Vol. 139, 2020.

[23] Lotti, A., Pazzi, V., Saccorotti, G., Fiaschi, A., Matassoni, L., and Gigli, G., HVSR Analysis of Rockslide Seismic Signals to Assess the Subsoil Conditions and the Site Seismic Response, Int. J. Geophys, Vol. 2018, pp. 1–11.

[24] Nelson, S., and McBride, J., Application of HVSR to Estimating Thickness of Laterite Weathering Profiles in Basalt, Earth Surf. Process. Landforms, Vol. 44, No 7, 2019, pp. 1365–1376.

[25] Fitri, S. N., Soemitro, R.A.A., Warnana, D.D., and Sutra, N., Application of Microtremor HVSR Method for Preliminary Assessment of Seismic Site Effect in Ngipik Landfill, Gresik, MATEC Web Conf., Vol. 195, 2018, pp. 1–5.

[26] Liang, D.,Gan, F., Zhang, W., and Jia, L., The Application of HVSR Method in Detecting Sediment Thickness in Karst Collapse Area of Pearl River Delta, China. Environ. Earth Sci, Vol. 77, No 6, 2018, pp. 1–9.

[27] Akkaya, I., Availability of Seismic Vulnerability Index (Kg) in the Assessment of Building Damage in Van, Eastern Turkey, Earthq. Eng. Eng. Vib., Vol. 19, No 1, 2020, pp. 189–204.

[28] Sorensen, C., and Asten, M., Microtremor Methods Applied to Groundwater Studies. Explor, Geophys, Vol. 38, No 2, 2007, pp. 125–131.

[29] Nakamura, Y., On the H/V spectrum, 14th World Conf. Earthq, Eng, 2008, pp. 1–10.

[30] Yamanaka, H., Takemura, M., and Ishida, H., Characteristics of Long-Period Microtremors and Their Applicability in Exploration of Deep Sedimentary Layers, Bull. Seismol. Soc. Am, Vol. 84, No 6, 1994.

[31] Yuliyanto, G., Harmoko, U., and Widada, S., Identify the Slip Surface of Land Slide in Wirogomo Banyubiru Semarang Regency Using HVSR Method, International Journal of Applied Environmental Sciences, Vol. 12, No 12, 2017, pp. 2069–2078.

[32] Warnana, D. D., Soemitro, R. A. A., and Utama, W., Application of Microtremor HVSR Method for Assessing Site Effect in Residual Soil Slope, Int. J. Basic Appl. Sci. IJBAS-IJENS, Vol. 11, No 4, 2011, pp. 73–78.

[33] Cox, B., Cheng, T., Vantasell, J., and Manuel, L., A statistical Representation and Frequency-Domain Window-Rejection Algorithm for Single-Station HVSR Measurements, Geophys. J. Int, Vol. 221, 2020, pp. 2170–2183.

[34] Chávez-García, F. J., and Kang, T. S., Lateral Heterogeneities and Microtremors: Limitations of HVSR and SPAC Based Studies for Site Response, Eng. Geol, Vol. 174, 2014, pp. 1–10.

[35] Arifin, S. S., Mulyatno, B. S., Marjiyono., and Setianegara, R., Penentuan Zona Rawan Guncangan Gempabumi Berdasarkan Analisis Nilai Amplifikasi HVSR Mikrotremor dan Analisis Periode Dominan Daerah Liwa dan Sekitarnya, J. Geofis. Eksplor, Vol. 2, No 1, 2014.

[36] Bignardi, S., 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, Vol. 145, 2017, pp. 28–38.

[37] Siska, D., Fithra, H., Lisa, N., Haerudin, N., and Farid, M., Seismic Vulnerability Mapping to Support Spatial Plans in Lhokseumawe City Area, Int. J. Adv. Sci. Eng. Inf. Technol, Vol. 10, No 1, 2020, pp. 269–273.

[38] Tanjung, N. A. F., Yuniarto, H. P., and Widyawarman, D., Analisis Amplifikasi Dan Indeks Kerentanan Seismik Di Kawasan Fmipa Ugm Menggunakan Metode HVSR, J. Geosaintek, Vol. 5, No 2, 2019, pp. 60–67.

[39] Putri, A., Purwanto, M., and Widodo, A., Identifikasi Percepatan Tanah Maksimum (PGA) dan Kerentanan Tanah Menggunakan Metode Mikrotremor I Jalur Sesar Kendeng, J. Geosaintek, Vol. 3, No 2, 2017, pp. 107–114.

[40] Hadi, A. I., Farid, M., and Fauzi, Y., Pemetaan Percepatan Getaran Tanah Maksimum dan Kerentanan Seismik Akibat Gempa Bumi untuk Mendukung Rencana Tata Ruang dan Wilayah (RT RW) Kota Bengkulu, J. Ilmu Fis. Indonesi, Vol. 1, No 2, 2012, pp. 81–86.

[41] Mala, H. U., Susilo, A., and Sunaryo., Kajian Mikrotremor dan Geolistrik Restivitas di Sekitar Jalan Asteri Primer Trans Timor untuk Mitigasi Bencana, J. Nat. B, Vol. 3, No 1, 2015, pp. 24–34.

[42] Shaleha, A., Supriyadi, and Putra, N. M. D., Identifikasi Struktur Lapisan Tanah Daerah Rawan Longsor di Kecamatan Banyubiru Kabupaten Semarang dengan metode Horizontal to Vertical Spectral Ratio (HVSR), Unnes Phys. J, Vol. 5, No 2, 2016, pp. 1–6.

[43] Patimah, S., Analisis Litologi Bawah Permukaan Berdasarkan Ground Profiles Kecepatan Gelombang Geser dengan Metode Ellipticity Curve di Kecamatan Prambanan dan Kecamatan Gantiwarnno Kabupaten Klaten, J. Fis, Vol. 7, 2018, pp. 59–65.

[44] Chieffo, N., and Formisano, A., Geo-Hazard-Based Approach for the Estimation of Seismic Vulnerability and Damage Scenarios of the Old City of Senerchia (Avellino, Italy), Geosciences, Vol. 9, No 2, 2019.

[45] Sari, I. D. R., Kota Lama Semarang Situs Sejarah Yang Terpinggirkan, Berk. Arkeol, Vol. 32, No 2, 2012, pp. 195–207.