SUBSURFACE
Vol. 02 No. 01, Februari 2024

SOIL CHARACTERISTICS AND SHEAR WAVE VELOCITY STUDY IN NORTH SULAWESI, GORONTALO AND CENTRAL SULAWESI

Ahmad Naufal Fadhil[1], Iktri Madrinovella*[1], Bayu Pranata[2], Elisabet Anggun Pramesthi[2]

[1] Geophysical Engineering, Exploration and Production Technology, Pertamina University

[2] The Meteorological, Climatological and Geophysical Agency (BMKG)

***EMAIL**

iktri.madrinovella@universitaspertamina.ac.id

KEYWORDS

Sulawesi, earthquake, HVSR, dominant frequency, amplification factor, seismic vulnerability index, V_{s30}.

ARTICLE HISTORY

Received: 11 September 2023
Accepted: 27 February 2024

HOW TO CITE

Fadhil, A.N., Madrinovella, I., Pranata, B., & Pramesthi, E.A. (2024). Soil Characteristics and Shear Wave Velocity Study in North Sulawesi, Gorontalo and Central Sulawesi. Subsurface 02(01) 16-25.

ABSTRACT

The Sulawesi region has a high level of earthquake vulnerability because it is bounded by two major plates, the Eurasian plate and the Indo-Australian plate, which leads to several paths and faults scattered throughout the region, including the volcanoes in North Sulawesi Province, the Gorontalo fault in Gorontalo Province, and the Palu-Koro fault in Central Sulawesi Province. In North Sulawesi, Gorontalo, and Central Sulawesi, soil characteristics were studied utilizing the Horizontal and Vertical Spectral Ratio (HVSR) approach. The dominant frequency (f_0), the amplification factor (A_0), the seismic vulnerability index (Kg), and the shear wave velocity at a depth of 30 m (V_{s30}) were all measured in this study. According to the findings of this study, the distribution of dominant frequency values ranged from 0.6 to 17 Hz, the amplification factor ranged from 2.2 to 8.4, the seismic vulnerability index ranged from 0.2 to 41, and the shear wave velocity at the depth of 30 meters (V_{s30}) ranged from 226 to 519 m/s.

INTRODUCTION

Sulawesi Island is surrounded by active tectonic plates, including the Eurasian Plate and the large Indo-Australian Plate. In addition to tectonic plate interactions, Sulawesi has a high risk of natural disasters, especially earthquakes, due to numerous tectonic faults scattered throughout the island. There are many active faults in Sulawesi such as the Gorontalo Fault in Gorontalo Province, and the Palu-Koro Fault in Central Sulawesi Province. These fault zones triggered the occurrence of earthquakes and other tectonic activities.

One of the disastrous earthquakes that occurred in Sulawesi was the September 28th, 2018 earthquake in Palu-Donggala (Central Sulawesi) which triggered tsunami (Mw 7.4). This earthquake was identified as the activity of left-lateral NW-SE trending Palu-Koro fault. A series of earthquake hit Tomini Bay (Gorontalo) on June 11th and August 4th, 2023, with moment magnitude 5.4 and 5.7 respectively.

The Horizontal-to-Vertical Spectral Ratio (HVSR) method is a geophysical technique used to analyze the resonance characteristics and natural frequency of soil or rock at a particular location. If the ground movement recorded by the horizontal components are greater than the vertical component during seismic events, it means the soil or rock is vulnerable to the ground shaking. The HVSR method is employed in geotechnical studies, earthquake modeling, and structural planning to comprehend earthquake risks and optimize building designs.

According to Nakamura (1989) and Nakamura (2000), the dominant frequency is the frequency that dominates the spectral response and provides insight into the properties and features of rocks beneath the surface. By analyzing the spectral comparison between horizontal and vertical components of seismic waves, we can identify the frequency that has the strongest influence on the geological structure beneath the ground. In other words, the dominant frequency value in the HVSR approach can offer an indication of the subsurface geological structure. This becomes a valuable tool in understanding the characteristics of rock layers and the geological environment of a particular region.

The amplification factor is the phenomenon where seismic waves experience an amplitude increase due to significant differences between the layers where they traverse. The seismic waves can undergo amplification when they propagate through materials with lower stiffness properties compared to the initial medium. This phenomenon results in a change in the intensity or amplitude of the waves as they pass through layers with different characteristics. The greater the differences in wave propagation characteristics such as density and velocity, the larger the amplification factor that occurs (Nakamura, 2000).

The seismic vulnerability index is derived from the equation relating the amplification factor to the dominant frequency, where this soil vulnerability index can assist in understanding the resonance characteristics of the ground at a specific location during an earthquake. This has significant applications in construction planning and earthquake risk mitigation, enabling engineers to take appropriate measures to strengthen buildings and infrastructure in earthquake-prone areas (Nakamura, 2000). The seismic vulnerability index (*Kg*) is the ratio of the square of the amplification factor (A_0) and the dominant frequency (f_0) as the equation:

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

The Vs wave or shear wave velocity is a critical parameter in geophysics and geotechnical engineering that measures the velocity of shear waves propagating through soil or rock during an earthquake. They are related to the elasticity and stiffness of the material. This velocity is used in earthquake modeling to predict soil behavior and design earthquake-resistant structures.

The geological map in **Figure 1** shows the granite or intrusive rock (green), the pyroclastic (yellow), the metamorphic rocks (magenta and navy), the igneous rock (orange), the sediment and alluvium (red) and the volcanic rock (cyan). Those lithologies are affected by active volcanoes (Mount Lokon, Mount Kelabat, and Mount Soputan) and also the present of various faults (the Palu-Koro Fault and the Gorontalo Fault). The North Sulawesi and Gorontalo area are dominated by volcanic rocks, while the Central Sulawesi is dominated by sedimentary rocks.

The Tomini Bay (**Figure 2**) divides the northern region, which is characterized by limited Watershed Areas (DAS), relatively short and steep rivers, and surrounded by hills and mountains. This eastern region has small Watershed Areas (DAS), short and swiftly flowing rivers, and steep terrain.

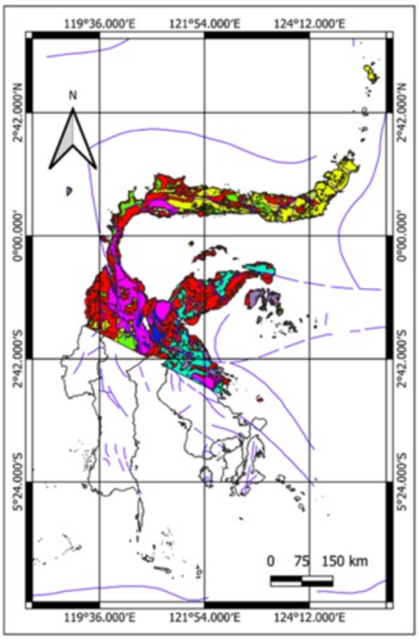

Figure 1. Regional Geological Map of the North Sulawesi, Gorontalo and Central Sulawesi (Lapak GIS, 2023). The study area is dominated by volcanic (yellow, cyan) and sedimentary rocks (red).

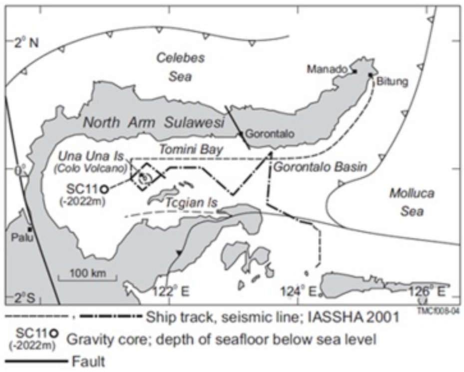

Figure 2. Map of Tomini Bay, Gorontalo fault and Palu-Koro Fault (McConachy et al, 2004).

DATA AND METHODS

The data used in the final analysis of this research is secondary data sourced from the BMKG website (WebDC3), originally total of 23 measurement points in area of 119.12° E to 125.14° E longitude and 1.86° N to 3.37° S latitude. The data is retrieved from the website from May 5th, 2022, and May 3rd 2023.

The data analysis begins with the spectral analysis for three components: NS (North-South), EW (East-West), and Z (Vertical) using the selected ambient noise or small vibrations for investigation.

The bandpass filter used with a range of 0.5 to 20-25 Hz. Then, the time-series filtered signal in three components are converted into frequency domain using Fast Fourier Transform conducted within each window. As the consequence of the FFT procedure, some components need to be smoothed. Following Konno and Ohmachi procedure (1998), a smoothing constant value of 1.00 is used. The signals are selected for the required ratio of STA/LTA (STA = 1 second, LTA = 30 second). STA (short time average) and LTA (long time average) are the windows designed to compute the average amplitude of the waveform. In **Figure 3**, the selected signals are colored after being filtered to be transformed into frequency domain.

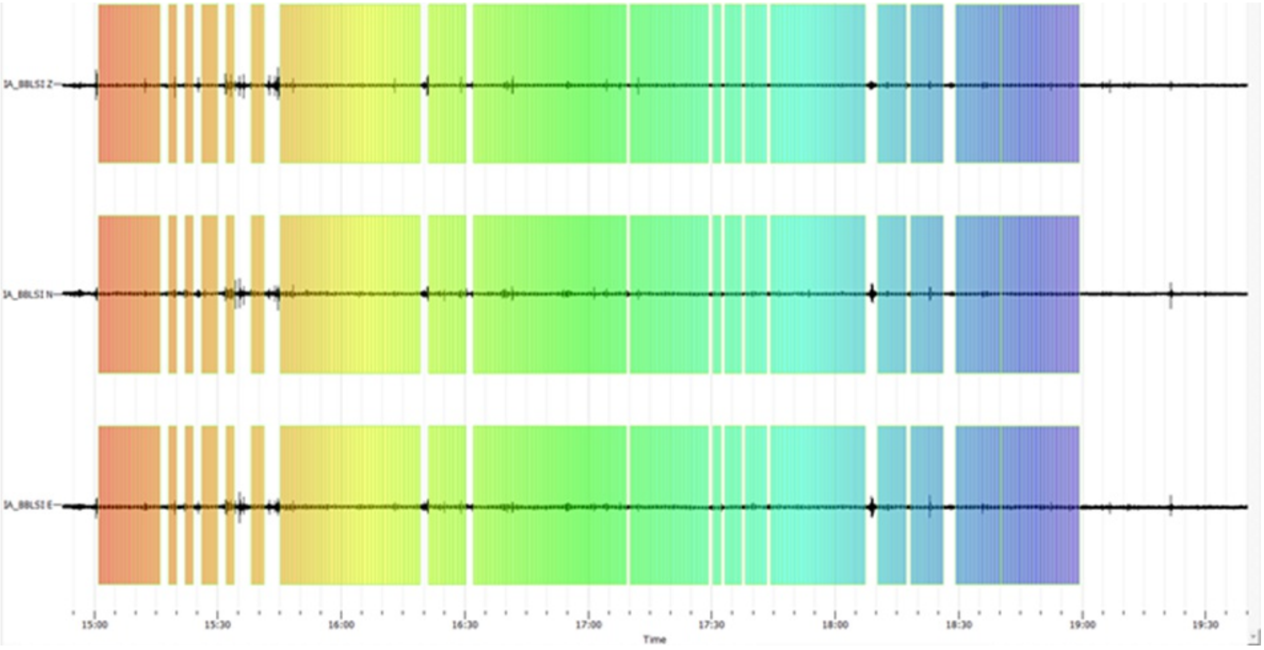

Figure 3. The time-series microtremor signals, after filtering and windowing (BBLSI station). The signals are divided every 60-second window (colored box) and the unselected signals outside the range of the STA/LTA ratio.

The HVSR analysis are combined as the spectral amplitude ratio using the following equation:

$$R\left(t\right)=\frac{\sqrt{FNS\left(T\right)^{2}+FEW\left(T\right)^{2}}}{FZ\left(T\right)} \quad (2)$$

R(t) represents the ratio of the vertical to the horizontal spectrum, FNS represents the spectrum in the NS direction, FEW represents the spectrum in the EW direction, and FZ represents the spectrum in the Z (vertical) direction. After obtaining the HVSR spectrum for each window, the average HVSR spectrum is displayed for each measurement point.

Figure 4 shows the amplification factor (A_0) and the dominant frequency (f_0). (A_0) can be figured out by the peak or the maximum of the H/V ratio (R(t)) after the averaging of all the window spectrum. (f_0) is the frequency that corresponds to the value of A_0.

The next step involves testing the reliability of the H/V curve and performing a clear peak test on the H/V curve based on the criteria established by Bard & Sesame (2004), which includes assessing the reliability of the H/V curve and identifying clear H/V peaks. These tests are crucial in determining the accuracy and significance of the spectral information extracted from the H/V curve.

These tests are performed based on the specified criteria to confirm that the obtained H/V curve is reliable and can be trusted. This reliability assessment is crucial to ensure that the H/V curve accurately represents the spectral characteristics of the seismic signals and can be used effectively in subsequent analyses and interpretations.

After conducting the reliability test on the H/V curve and checking for clear peaks based on the criteria established by Bard & Sesame (2004), only 17 from 23 measurement points were qualified to be analyzed (**Figure 5**).

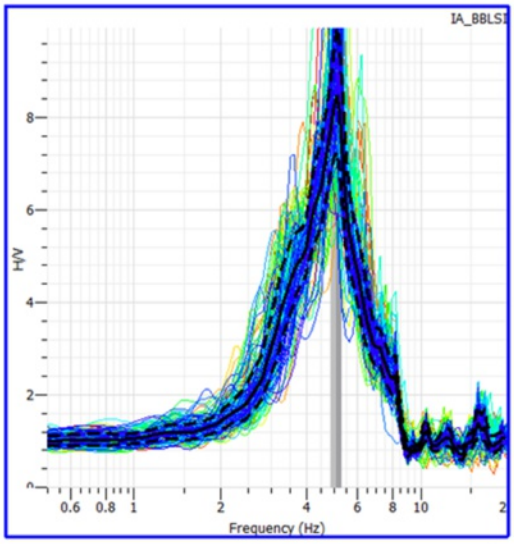

Figure 4. H/V Curve (BBLSI station) shows the A_0 value 8.4 and f_0 value 5.07 Hz.

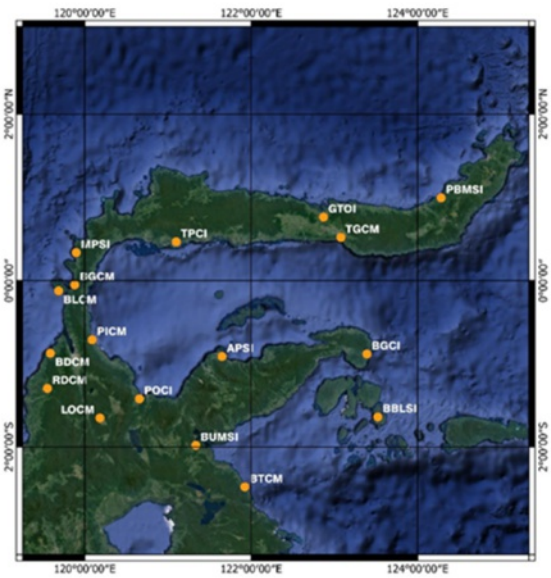

Figure 5. The measurement points that being analyzed using HVSR method.

By using the H/V curve, the shear wave velocity is estimated using the HVSR inversion, to provide the insights into the site seismic characteristics.

The program used for the inversion process in this final research study is OpenHVSR (Bignardi et al., 2016), which allows for simulating the implicit structure of the HVSR curve using the Monte Carlo propagation method. This program was created using the Matlab GUI-based software, as also elaborated in the previous study (Gazali et al., 2018; Herak, 2008). Additionally, two initial models are used to determine which initial model has the smallest misfit value between the two. The first initial model is based on the previous study (Persada et al., 2021) (**Table 1**), and the second initial model is derived from USGS website (**Table 2**).

The initial model with the lowest misfit value is then selected for further processing. The first initial model has an average misfit of 49 ms, and the second initial model has average misfit of 93 ms. The first model is utilized for the inversion process.

Table 1. The initial model from previous study (Persada et al., 2021).

Vp	Vs	Rho	H	Qp	Qs
500	200	2	20	15	5
1000	500	2.3	30	30	10
2000	1000	2.5	50	60	20
3000	1500	2.7	150	120	40
4000	2000	3	350	240	80
7000	3500	3.5	650	480	160

Table 2. The initial model from USGS .

Vp	Vs	Rho	H	Qp	Qs
597.36	500	2	20	15	5
697.36	600	2.3	30	30	10
797.36	700	2.5	50	60	20
897.36	800	2.7	70	120	40

The left part of **Figure 6** shows the H/V spectrum (black line), the initial velocity model applied to the spectrum (yellow line), the outcome of the iteration process (blue line) and the best-fitting model from the inversion process (red line).

The right part of **Figure 6** shows the relationship between depth (Y-axis) and the value of shear wave velocity (X-axis). The blue line represents the initial model, and the black line represents the final model as the result of the inversion. The red and green lines show the misfit after the iteration of the inversion process.

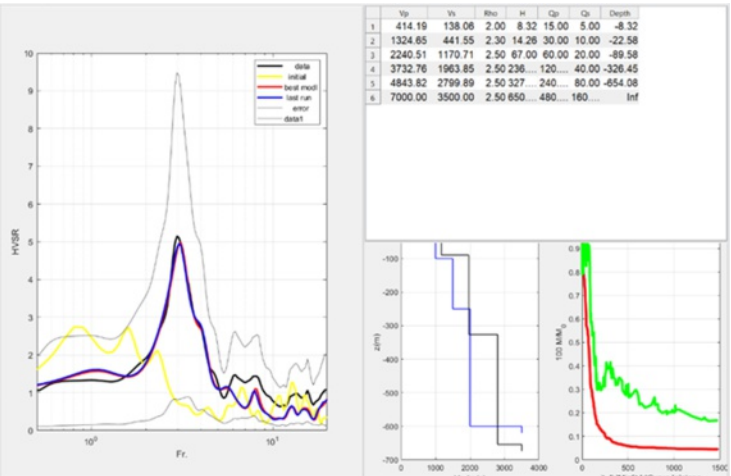

Figure 6. The inversion result (BTCM station), the fitting model derived from H/V curve (left) and the updated shear wave velocity value using the model (right).

The calculation of the V_{s30} (shear wave velocity averaged over the top 30 meters) values using the following equation:

$$Vs_{30} = \frac{h_{30}}{\sum \frac{h_i}{Vs_i}} \quad (3)$$

h_{30} is 30 m (depth at 30 meter), h_i is the depth at i (before 30 meter) and V_{si} is the shear wave velocity at the depth i.

RESULT AND DISCUSSION

DOMINANT FREQUENCY

The dominant frequency ranges between 0.6 – 17 Hz (**Figure 7**), with the lowest value in Central Sulawesi around the Palu-Koro fault area. The BGCM point has the lowest f_0 value, which is located at the Balaesang District of Donggala Regency. The low values of dominant frequency are also spotted in the North Sulawesi in the eastern of the Gorontalo fault, the middle of Gorontalo province between Gorontalo fault and Palu-Koro fault (TPCI and MPSI stations), and in the south-eastern side of the Tomini Bay (BGCI station).

The yellow and green zones are indicated as hard rock that has lower probability to be damaged by the earthquakes. However, the value of the amplification factor and the seismic vulnerability index must be estimated to obtain more reliable analysis.

AMPLIFICATION FACTOR

The amplification factor ranges between 2.2 – 8.4 (**Figure 7**), with the highest value in Banggai Island, Central Sulawesi (BBLSI station). The moderate-to-high values are located around the Palu-Koro fault area, the North Sulawesi area, and the area between Gorontalo fault dan Palu-Koro fault (TPCI station). The high A_0 values are correlated to the low f_0 value.

The green zones or low A_0 values are detected in the Gorontalo area, which are also correlated to the high f_0 values. Based on this result, it can be interpreted that the western part of the Gorontalo fault is not as active as its eastern part.

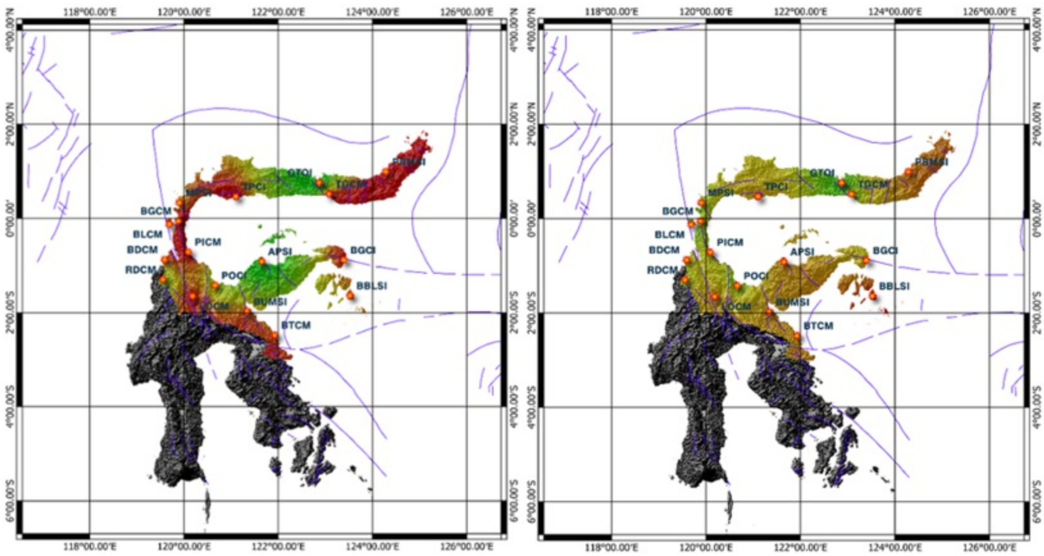

Figure 7. The dominant frequency (f_0) map (left) and the amplification factor (A_0) map (right) in North Sulawesi, Gorontalo and Central Sulawesi.

SEISMIC VULNERABILITY INDEX

The seismic vulnerability index ranges between 0.2 – 41 (**Figure 8**), with the highest value in North Sulawesi, the area between Gorontalo fault dan Palu-Koro fault (TPCI station), and the area around Palu-Koro fault (LOCM station).

The high Kg value in the North Sulawesi area (PBMSI station) is indicated as the result of the active volcanic area, such as Mount Mahawu, Mount Linau, Mount Lokon (Poedjoprajitno, 2012) and Mount Soputan (Kushendratno et al., 2012).

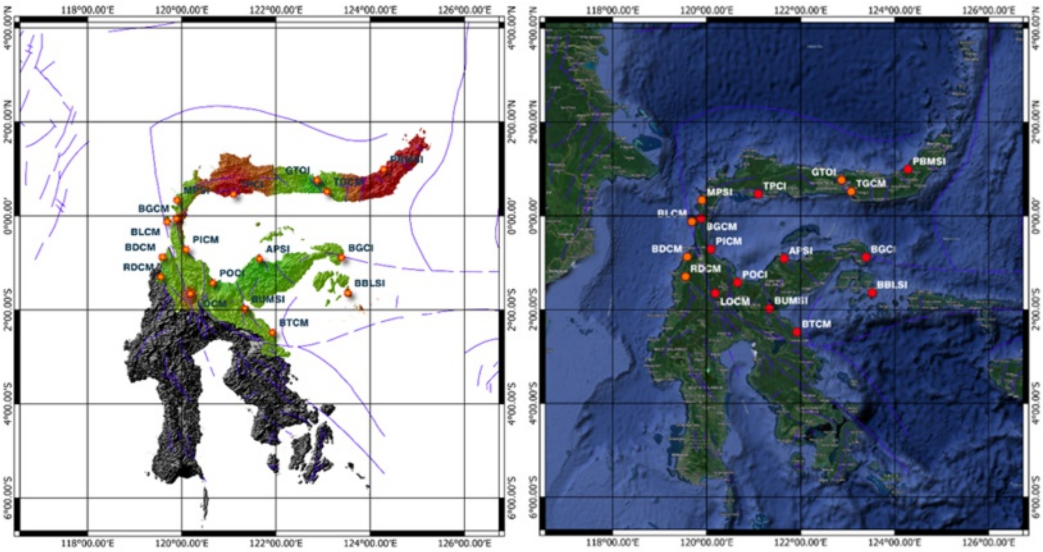

Figure 8. The seismic vulnerability index (Kg) map in North Sulawesi, Gorontalo and Central Sulawesi after interpolation (left) and without interpolation (right).

The area between Gorontalo fault and Palu-Koro fault also has high Kg value (TPCI station). Based on the geological map, there are volcanic and sedimentary rocks in this area. Not only being flanked by two active faults, there is an active volcano (Mount Colo, Una-una Island) in the southern part of this area, as described by **Figure 9** (Sendjaja et al., 2020).

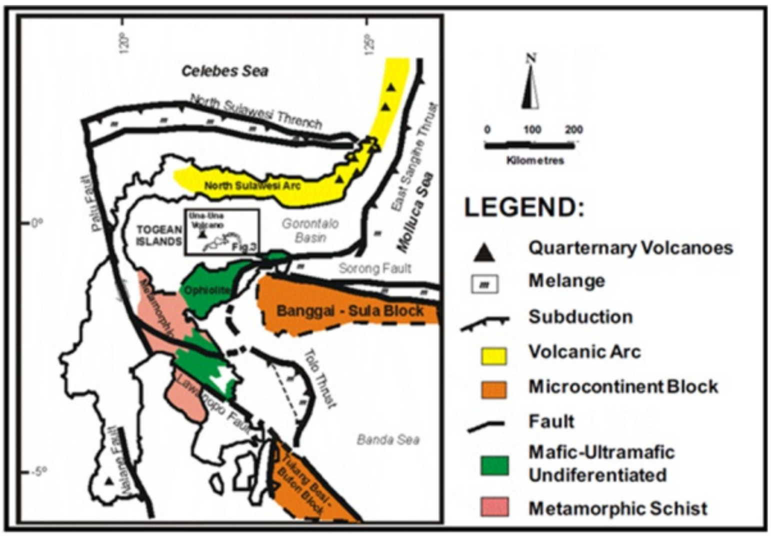

Figure 9. The major structures of Sulawesi (volcanoes in the North Sulawesi and Una-una Island) (Sendjaja et al, 2020).

SHEAR WAVE VELOCITY

The shear wave velocity at the depth of 30 m (V_{s30}) ranges between 226-519 m/s), which only displayed around the measurement points to avoid the oversimplified interpolation. The red dot represents the value of 363 – 519 m/s (dense soil/soft rock), and the orange dot represents the value of 226 – 347 m/s (stiff soil). The soil characteristics are categorized using the soil classification (Zhao et al., 2006).

The values are consistent to the fo, A_0 and Kg values, which the highest values are detected around the Palu-Koro fault, in the North Sulawesi and the area between Gorontalo fault dan Palu-Koro fault.

CONCLUSION

The results of the HVSR method of the microtremor data in North Sulawesi, Gorontalo and Central Sulawesi shows the consistency of the four parameters (the low values of the dominant frequency (f_0) and the high values of the amplification factor (A_0), the seismic vulnerability index (Kg) and the shear wave velocity at the depth of 30 m (V_{s30})).

The values of fo ranges between 0.6 – 17 Hz, the values of A_0 ranges between 2.2 – 8.4, the values of Kg ranges between 0.2 – 41, and the V_{s30} ranges between 226-519 m/s.

The area with the lowest fo values (0.6 – 1.7 Hz), the highest Ao values (6.1 – 8.4), the highest Kg values (19 – 41) and the highest V_{s30} (363 – 519 m/s) are interpreted as the vulnerable area to be damaged by the seismic events or ground shaking by earthquake or volcano activities. Those areas consist of volcanic and sedimentary rocks based on the geological map. There are three main vulnerable area discovered by this study: the North Sulawesi (affected by volcanoes such as Mount Mahawu, Mount Lokon, Mount Linau, Mount Soputan), the area surrounded by the Palu-Koro fault, and the area between Gorontalo fault, Palu-Koro fault and Mount Colo (Una-una Island).

The characteristics of soil in the North Sulawesi, Gorontalo and Central Sulawesi are identified as dense soil/soft rock and stiff soil, where the area with higher velocity is indicated as dense soil/soft rock and the area with lower velocity is indicated as stiff soil.

ACKNOWLEDGEMENT

We acknowledge The Meteorological, Climatological and Geophysical Agency (BMKG) Indonesia for providing the data.

REFERENCES

Bard, P.-Y., & Sesame. (2004). *SESAME: Site EffectS assessment using AMbient Excitations*.

Bignardi, S., Mantovani, A., & Zeid, N. A. (2016). OpenHVSR: Imaging the subsurface 2D/3D elastic properties through multiple HVSR modeling and inversion. *Computers & Geosciences*, *93*, 103–113.

Gazali, I., Purwanto, M. S., & Warnana, D. D. (2018). Estimasi kecepatan gelombang geser (vs) berdasarkan inversi mikrotremor spectrum horizontal to vertikal spectral ratio (HVSR) studi kasus: Tanah longsor Desa Olak-Alen, Blitar. *Jurnal Teknik ITS*, *6*(2), C383–C387.

Herak, M. (2008). ModelHVSR—A Matlab® tool to model horizontal-to-vertical spectral ratio of ambient noise. *Computers & Geosciences*, *34*(11), 1514–1526.

Kushendratno, Pallister, J. S., Kristianto, Bina, F. R., McCausland, W., Carn, S., Haerani, N., Griswold, J., & Keeler, R. (2012). Recent explosive eruptions and volcano hazards at Soputan volcano—A basalt stratovolcano in north Sulawesi, Indonesia. *Bulletin of Volcanology*, *74*(7), 1581–1609. https://doi.org/10.1007/s00445-012-0620-2

Lapak GIS. (2023). *SHP Shapefile Peta Geologi Se-Indonesia*. https://www.lapakgis.com/2019/04/SHP-Shapefile-Peta-Geologi-Seluruh-Indonesia.html.

McConachy, T. F., Permana, H., Binns, R. A., Zulkarnain, I., Parr, J. M., Yeats, C. J., Hananto, N. D., Priadi, B., Burhanuddin, S., & Utomo, E. P. (2004). Recent investigations of submarine hydrothermal activity in Indonesia. *Proc. Hi Tech World Compet. Miner. Success Stories Around Pacific Rim, ANU Research Publications*, 1–488.

Nakamura, Y. (1989). A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. *Railway Technical Research Institute, Quarterly Reports*, *30*(1). https://trid.trb.org/View/294184

Nakamura, Y. (2000). Clear identification of fundamental idea of Nakamura's technique and its applications. *Proceedings of the 12th World Conference on Earthquake Engineering*, *2656*, 1–8. https://www.iitk.ac.in/nicee/wcee/article/2656.pdf

Persada, Y. D., Ilham, I., Amaninida, H. D., Ariyanto, P., & Gustono, S. T. (2021). Pendugaan Awal Deposit Emas Wilayah Poboya, Palu Dengan Metode Inversi HVSR. *JGE (Jurnal Geofisika Eksplorasi)*, *7*(1), 30–40.

Poedjoprajitno, S. (2012). Morphostructure Control Towards the Development of Mahawu Volcanic Complex, North Sulawesi. *Indonesian Journal on Geoscience*, *7*(1), 39–54.

Sendjaja, P., Suparka, E., Abdullah, C. I., & Sucipta, I. E. (2020). Characteristic of the Mount Colo Volcano, Una-Una Island, Central Sulawesi Province: Tectonic Evolution and Disaster Mitigation. *IOP Conference Series: Earth and Environmental Science*, *589*(1), 012005. https://iopscience.iop.org/article/10.1088/1755-1315/589/1/012005/meta

Zhao, J. X., Zhang, J., Asano, A., Ohno, Y., Oouchi, T., Takahashi, T., Ogawa, H., Irikura, K., Thio, H. K., & Somerville, P. G. (2006). Attenuation relations of strong ground motion in Japan using site classification based on predominant period. *Bulletin of the Seismological Society of America*, *96*(3), 898–913.