Jurnal Ilmu Fisika
Vol. 16, No. 2, September 2024, pp. 187–197
ISSN: 1979-4657 (Print); 2614-7386 (Online)
https://doi.org/10.25077/jif.16.2.187-197.2024

Jurnal Ilmu Fisika
Open Access

Subsurface Sediment Layer Analysis at the Dendam Tak Sudah Lake Flyover Construction Site in Bengkulu City Using the HV-Inv Method

Yuni Setyowati, Muchammad Farid, Arif Ismul Hadi, Refrizon, Putri Helinnes, Debi Hardiansyah, Usman Gumanty, Hana Raihana, Andre Rahmat Al Ansory, M Taufiqurrahman Syah

Physics department, Geophysics Study Program, Faculty of Mathematics and Natural Science University of Bengkulu, Bengkulu, 38371, Indonesia.

Article Info

Article History:

Received May 30, 2024
Revised August 17, 2024
Accepted August 24, 2024
Published online August 30, 2024

Keywords:
sediment layer
Bengkulu City
flyover
microseismic
HV-Inv method

Corresponding Author:

Muchammad Farid,
Email: mfarid@unib.ac.id.

ABSTRACT

Bengkulu City is situated within a subduction zone where the Indo-Australian and Eurasian tectonic plates converge, rendering the area highly susceptible to seismic activity. This study employs the microseismic method to assess seismic vulnerability and the subsurface rock structure at the Dendam Tak Sudah Lake Flyover Construction Site in Bengkulu City, which encompasses a swampy region. The microseismic method used was an inversion of the horizontal to vertical (H/V) spectral ratio (HV-Inv) for determining the dominant frequency (f_0), amplification factor (A_0), seismic sensitivity index (K_g), and shear wave velocity (V_s). The findings reveal that f_0 in the study area range from 2.16 to 7.53 Hz, A_0 vary from 0.40 to 3.79, and K_g values span from 0.03 to 6.04. The sedimentary layers exhibit an average thickness of 5-10 meters, with some locations showing significantly thicker sedimentary deposits. Notably, the highest seismic susceptibility is recorded at point T8. The V_s values range from 185.19 to 539.49 m/s, which are inversely proportional to the Kg values and indicate soil classifications varying from soft to medium. The overall seismic risk in the study area is moderate. These results offer key insights into geophysical and geological conditions in Bengkulu City, crucial for earthquake mitigation.

1. INTRODUCTION

Bengkulu City is situated within the complex tectonic environment of the Indo-Australian and Eurasian plate subduction zones, making it highly vulnerable to seismic activities (Hadi et al., 2012). Approximately 95% of earthquake origins in the region are linked to these tectonic movements (Hadi, Refrizon, et al., 2021). The city's proximity to the Sumatran fault system and subduction zones significantly increases the likelihood of tectonic earthquakes (Chasanah et al., 2022). Given the correlation between earthquake impact and regional vulnerability, understanding the seismic risk in Bengkulu is crucial for disaster preparedness and mitigation.

Extensive studies in engineering, seismology, and geoscience have examined the causes and consequences of earthquakes, highlighting the need for effective mitigation strategies (Hadi et al., 2010). One such strategy is the assessment of rock hardness in areas prone to seismic hazards (Farid & Mase, 2020). This analysis is essential to mitigate the impact of seismic events on infrastructure and minimize damage.

Despite similar earthquake magnitudes and distances from the epicenter, Bengkulu City has experienced varying levels of damage across different areas. This variability suggests that factors beyond earthquake magnitude and distance, such as local geological conditions and building design, play a critical role in determining the extent of seismic damage (Hadi et al., 2021). Given that building quality is generally comparable across the city, it is likely that topographical conditions have a significant impact on earthquake damage distribution. Several studies have indicated that variations in seismic response are influenced by the composition, continuity, and thickness of sediments in different regions.

The foundation of any overpass construction must be designed to withstand the mass load, with soil conditions carefully evaluated to ensure stability. Local geological conditions are a key factor in this evaluation. The construction of overpasses, particularly in earthquake-prone areas like Bengkulu, must align with sustainable development principles, ensuring that these public facilities remain resilient over time (Lestari & Susiloningtyas, 2022). Building infrastructure that incorporates earthquake mitigation strategies is vital for long-term stability in seismic zones.

Geophysical methods, such as microtremor analysis, are valuable tools for assessing subsurface conditions. The Horizontal to Vertical Spectral Ratio (HVSR) method, used to process microtremor data, provides insights into seismic vulnerability and sediment thickness in the study area. The HV-Inv (inversion of HVSR) module further refines this analysis by inverting the measured HVSR curve to develop an underground model using a Monte Carlo search algorithm. Accurate determination of shear wave velocity (V_s) requires careful constraints during this inversion process.

This study focuses on analyzing the subsurface sedimentary layers in the flyover construction area of Bengkulu City by evaluating amplification, frequency, and seismic vulnerability. These factors are correlated with V_s values obtained from microtremor data and geological analysis. The primary objective is to determine the characteristics of the sedimentary rock layers, based on parameters such as dominant frequency (f_0), amplification factor (A_0), and seismic sensitivity index (K_g), as part of earthquake disaster mitigation efforts. This research aims to support the construction of resilient public facilities in Bengkulu City.

2. METHOD

2.1 Geographical Setting at Bengkulu

The western part of Bengkulu City is the most densely populated area, and it is within this region that the Dendam Tak Sudah Lake flyover is being constructed. This area is characterized by alluvium (Qa) deposits. Historical seismic data indicate that the western portion of Bengkulu City experienced the most severe damage during the 2000 and 2007 earthquakes. This area, consisting of densely populated settlements, lies on a geological formation composed of rock, sand, silt, mud, and clay (Sugianto et al., 2016). The significant damage observed in this region highlights the varying physical properties of the different geological formations. Alluvium, in particular, typically has a relatively young geological age and lacks the consolidation found in older rock formations (Figure 1a).

2.2 Acquisition data

This study utilized a portable 3D axial seismometer to measure microtremor data at 28 points within the construction area of the Lake Dendam Tak Sudah flyover in Bengkulu City (Figure 1b). The raw data were collected directly from the site. The research process began with a comprehensive literature review of the geological, geophysical, and subsurface rock properties in the Danawarden Dam viaduct construction area. The characteristics of seismograms vary according to the geological formations in Bengkulu City, which consists of six primary geological types: Alluvium (Qa), Reef Limestone (Q_l), Swamp Sediment (Q_s), Alluvial Terraces (Q_{at}), Andesite (*Tpan*), and the Bintunan Formation (Q_{tb}).

A key geophysical technique employed in this study was the microtremor method, which detects low-amplitude ground vibrations generated by natural or anthropogenic sources, such as wind, ocean waves, and vehicular traffic. These microtremors provide valuable insights into the geological conditions near the surface (Susilanto et al., 2016). Microtremors are resonant vibrations within soil layers that are reflected near layer interfaces and repeated through continuous subsurface movements (Dal Moro & Panza, 2022).

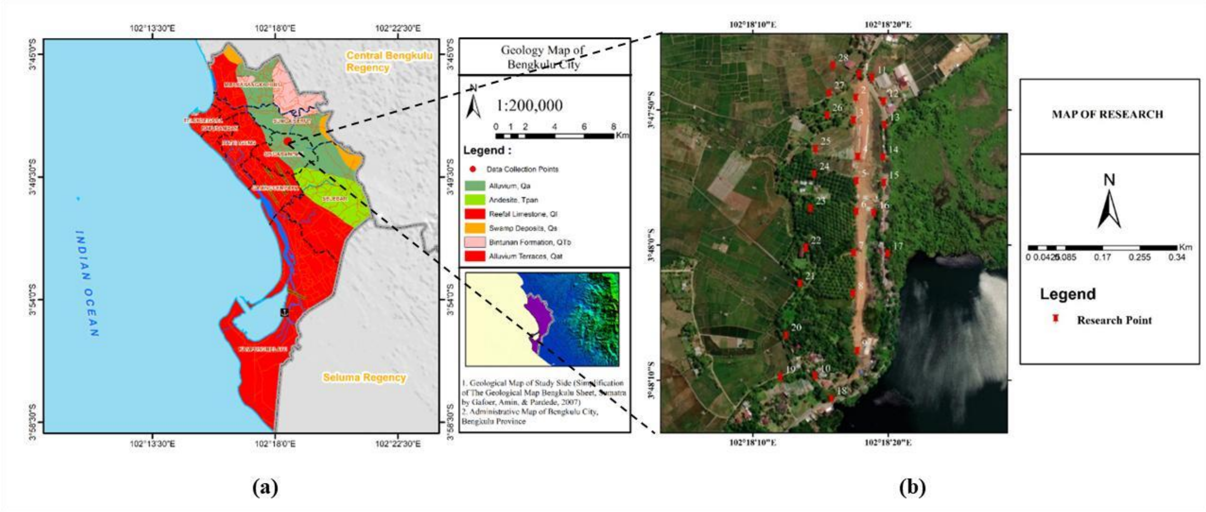

Figure 1 Geology setting of Bengkulu City area (Gafoer, S., Amin, T.C., 2012) (a) and location of research area (b).

The microtremor method can be used to characterize subsurface properties based on the spatial distribution of repetitive seismic waves. It is widely applied in various fields, including volcanic monitoring, geothermal exploration, micro zonation studies, physical geophysics, and geotechnical applications. Microtremors are characterized by ground vibrations with displacement magnitudes ranging from approximately 0.1 to 1 μm, typically associated with short-duration events (Amirudin & Madrinovella, 2023).

Microtremors can be induced by human activities, such as walking or machinery operations, or by natural phenomena, including wind, ocean waves, and ground vibrations (Fazriati et al., 2023). Low-frequency microtremors (below 1 Hz) are often caused by ocean waves and large-scale weather patterns, while intermediate frequencies (1-5 Hz) are influenced by both natural events and human activities. High-frequency microtremors (above 5 Hz) are primarily caused by human movement and infrastructure vibrations (Mase et al., 2021).

The microtremor data collected in this study were processed using the Horizontal-to-Vertical Spectral Ratio (HVSR) method to obtain HVSR curves. These curves were then analyzed to derive key parameters describing the subsurface structure, including resonance frequency and amplification factor (Prabowo et al., 2021). The HVSR method is particularly effective in identifying the resonance characteristics of surface layers without relying on additional subsurface information, as it estimates the horizontal (north-south and east-west) and vertical components of seismic waves (Ridwan et al., 2021).

This method has proven effective in identifying resonance responses in sedimentary basins and valleys. It is a cost-effective, environmentally friendly technique that can be applied in both urban and residential settings. The HVSR method enables the characterization of subsurface structures without invasive procedures by analyzing the ratio of the Fourier spectra of horizontal and vertical microtremor components (Nguyen-Tien et al., 2022). Additionally, it helps determine the dominant frequency of soil, which is crucial for geohazard assessments and seismic site classification (Haerudin et al., 2020).

The Site Effect (T_{SITE}) on the surface of a sediment layer, usually described as by comparing the amplification factors of horizontal and vertical motion at the sedimentary soil surface (SESAME, 2004).

$$T_{SITE} = \frac{T_H}{T_V} \tag{1}$$

$$T_H = \frac{S_{HS}}{S_{HB}} \tag{2}$$

where S_{HS} represents the spectrum of the horizontal motion component at the surface, and SHBSHB represents the spectrum of the horizontal motion component at the bottom of the soil layer. The magnitude of the vertical amplification factor, T_V, is given by:

$$T_V = \frac{S_{VS}}{S_{VB}} \tag{3}$$

where S_{VS} is the spectrum of the vertical motion component at the ground surface, and S_{VB} is the spectrum of the vertical motion component at the subsoil base.

Rayleigh waves account for most of the vibration data compared to several other types of waves. The effect of Rayleigh waves on microtremor registration is the same for the vertical and horizontal components in the frequency range from 0.2 to 20.0 Hz, so the spectral ratio of the horizontal and vertical components of the rock mass is close to unity:

$$\frac{S_{HB}}{S_{VB}} \approx 1. \tag{4}$$

By substituting the horizontal amplification equation with the vertical amplification equation, the vertical amplification into the horizontal and vertical amplification at the sedimentary soil surface:

$$T_{SITE} = \frac{S_{HS}}{S_{HB}} \tag{5}$$

This equation is the basis for calculating the ratio between the spectral component of the microtremor and its vertical component (HVSR), which can be expressed by the equation:

$$HVSR = T_{SITE} = \frac{\sqrt{f\ (S_{Utara-Selatan}) + (S_{Barat-Timur})^2}}{S_{Vertikal}}. \tag{6}$$

In order to obtain a reliable HVSR curve there are several criteria that need to be considered (Bard et.al., 2004).

Seismic velocities correspond to the leading edges beneath subsurface rocks. Due to the varying compositions of different strata, each layer exhibits characteristic seismic velocities, typically at consistent intervals. Additionally, each layer possesses unique stiffness, leading to variations in deflection, which in turn causes differences in seismic wave propagation. As a result, each layer vibrates at a different velocity. These seismic wave velocities can be used to infer the density and type of rocks beneath the surface. The rock type can be determined using the V_s (shear wave velocity) table (Rasyid et al., 2024).

Table 1 Site classification is based on the shear wave velocity (V_s) obtained from soil investigations and laboratory results, following the standards set by SNI 1726 (Honarto, 2019)

No	Site Classification	Shear Wave Velocity Vs (m/s)
1	Hard	$Vs \geq 1500$
2	Rock	$750 < Vs \leq 1000$
3	Very Solid Soil and Soft Rock	$350 < Vs \leq 750$
4	Medium Soil	$175 < Vs \leq 350$
5	Soft Soil	< 175

This literature review provided an initial understanding of the geological and geophysical conditions of the area. Subsequently, a data collection exercise was conducted to gather information on the subsurface rocks in the construction area of the Dendam Tak Sudah Lake flyover. The aim was to preliminarily characterize the nature and geometry of the subsurface rocks.

The geophysical data were analyzed and processed using Geopsy software. This process involved importing microtremor recording data, followed by smoothing and windowing to obtain the H/V curve, which provides the dominant frequency (f_0) and the peak amplification factor (A_0). The resulting frequency and amplification value curves were then input into the HV-Inv software for further analysis. HV-Inv, a MATLAB-based application developed by García-Jerez et al. (2016), employs the Monte Carlo (MC) method to model subsurface structures. The Monte Carlo simulation helps determine the most suitable curve by minimizing the misfit value and ensuring that the H/V graph aligns with the data. Through the HV-Inv analysis, parameters such as thickness, shear wave velocity, compressive wave velocity, and density were derived (Rahmawati et al., 2024). The processed geophysical data were then interpreted to correlate f_0, A_0, seismic sensitivity index (K_g), and V_s values within the construction area of the Dendam Tak Sudah flyover.

A 2D relational model was developed to enhance understanding of the rock shape, nature, and hardness of the subsurface sedimentary rock layers. Variables in the study included subsurface rock structure, depth, type, sedimentary rock layer classification, and geological conditions. Geological analysis provided insights into the rock formations present in the study area, which is predominantly characterized by alluvium (Q_a), including gravel, pebbles, silt, sand, and clay, as illustrated in Figure 1.

Table 2 Classification of soils based on microseism natural value of the frequency of microseismic oscillations according to Kanai (Ridwan et.al., 2021).

Soil Classification		**Natural Frequency**	**Kanai Classification**	**Description**	**Location**	**Color**
Type	**Class**					
Type IV	Class I	6.67 – 20	Tertiary or older rocks. Consists of sand and pebble hard rocks, etc..	The thickness of the sedimentary surface is very thin and hard rocks predominate.	-	-
Type III	Class II	4.0 – 10	Tertiary rocks or older rocks. Consists of sand, gravel and other hard rocks	Surface thickness of sediments in the medium category 5-10 m.	T5, T6, T7, T11, T18, T20	
Type II	Class III	2.5 – 4	Alluvial rocks with thickness exceeding 5 m. They are composed of sandy gravel, sandy hard clay, loam, etc..	Surface thickness of sediments in the thick sediment category, about 10-30 m thick.	-	-
Type I	Class IV	Less than 2.5	Alluvial rocks formed by deposition of deta, topsoil, silt, etc. Depth ≥30 m	The thickness of the sludge surface is very thick	T1, T2, T3, T4, T8, T9, T10, T11, T12, T13, T14, T15, T16, T17, T19, T21, T22, T23, T24, T25, T26, T27, T28	

3. RESULTS

3.1 Dominant Frequency Value Analysis (f_0) Analysis

The natural frequency value reflects the thickness of the weathering layer beneath the Earth's surface and the velocity of wave propagation through the medium (Mucciarelli et al., 2008). A higher natural frequency value typically indicates a thinner weathering layer, while a lower value suggests a thicker layer. Areas with high natural frequency values are generally less vulnerable to seismic activity.

The HVSR data processing yielded a dominant frequency distribution map, as shown in Figure 2. The dominant frequencies in the Lake Dendam Tak Sudah flyover construction area range from 2.16 to 4.46 Hz. Table 1 presents these dominant frequency values, which help determine sediment thickness and rock type in the area. The distribution of dominant frequencies (2.16 < f_0 < 7.53 Hz) indicates that the area is classified as Type III. This classification suggests that the surface sediments are moderately thick, approximately 10 meters, and consist primarily of Tertiary rocks. In contrast, Type I classifications show several measurement points with very thick sediments, as indicated by dominant frequency values below 2.5 Hz (Ridwan et al., 2021). The central sedimentary rock formation in this area is associated with a moderate seismic risk.

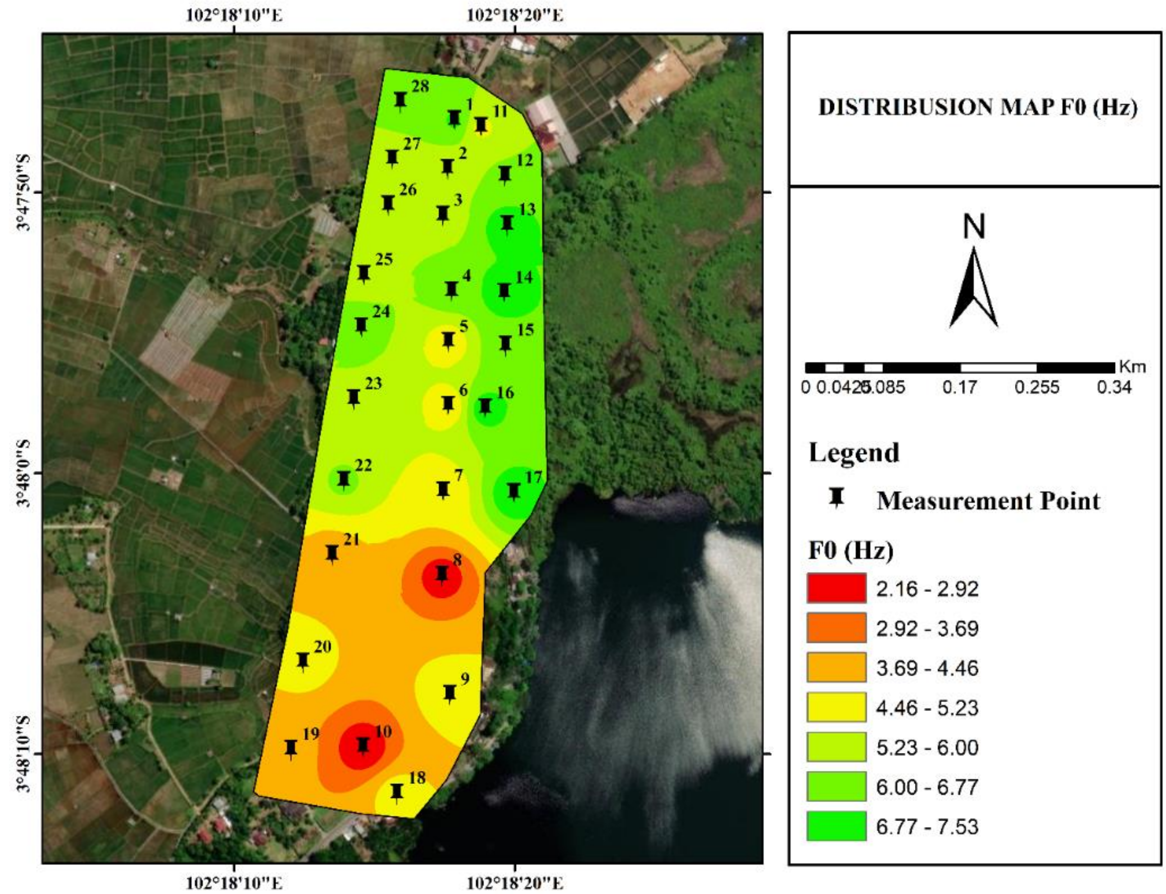

Figure 2 Distribution map of dominant frequency (f_0) at the Lake Dendam Tak Sudah flyover in the Bengkulu City.

3.2 Amplification Value Analysis (A_0) Analysis

A_0 represents the amplification of seismic waves resulting from significant differences between geological layers. Table 2 presents the amplitude classification based on the magnitude of the amplitude values, as illustrated in Figure 3 (Supriyadi et al., 2022).

The distribution map of amplification values in Figure 3 indicates that in the Lake Dendam Tak Sudah flyover construction area, the amplitude values range from 1.96 to 3.11 times. According to Setianegara et al. (2023), amplification values are categorized into four risk levels: low risk (0 < A_0 < 3 times), medium risk (3 < A_0 < 6 times), high risk (6 < A_0 < 9 times), and very high risk (A_0 > 9 times).

Table 3 Classification of amplification values.

Zone	Clasification	Amplification Factor Value	Location	Color
1	Low	$A_0 < 3$	T1, T2, T3,T4, T5, T6, T7, T9, T10, T11, T12, T13, T14, T15, T16, T17, T18, T19, T20, T21, T22, T23, T24, T25, T26, T27, T28	
2	Medium	$3 \leq A_0 < 6$	T8	
3	High	$6 \leq A_0 < 9$	-	
4	Very High	$A_0 \geq 9$	-	

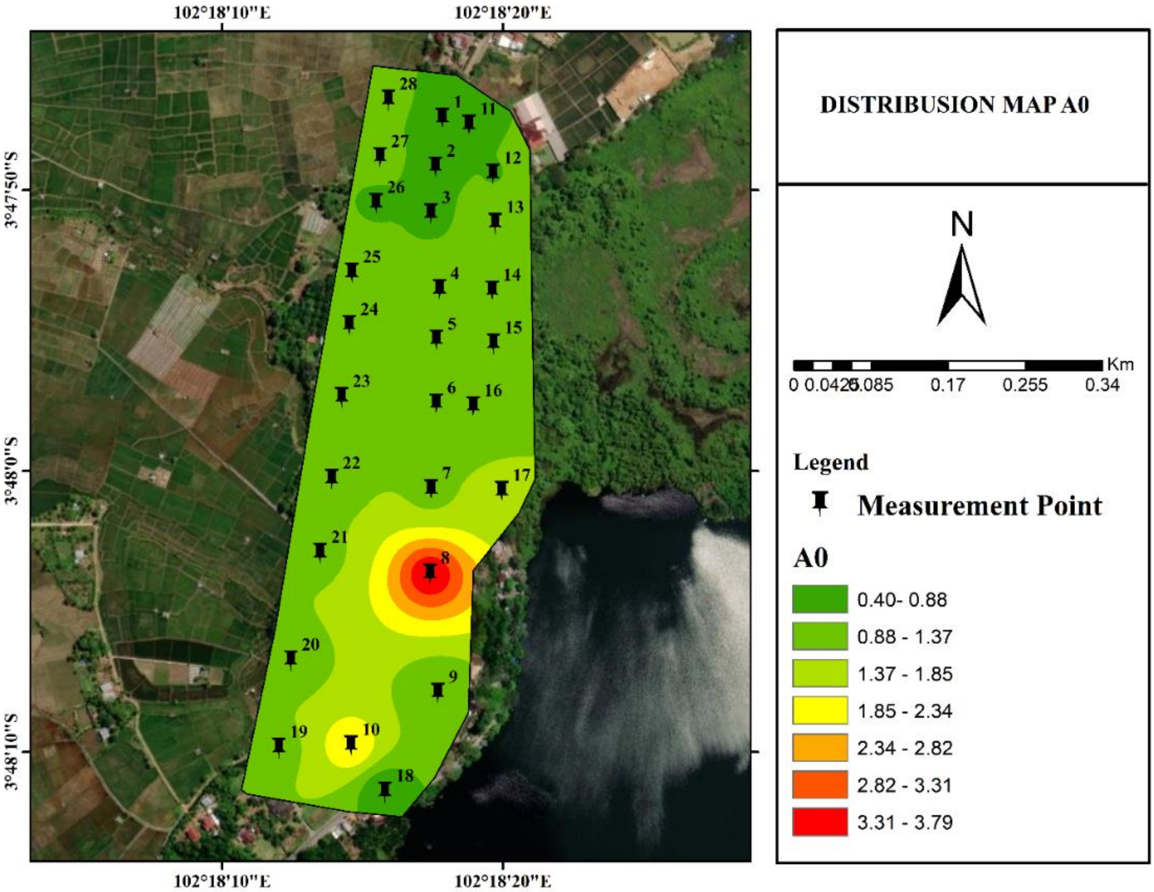

Figure 3 Same as Figure 2, but for A_0.

Based on the calculations, amplification values in the Lake Dendam Tak Sudah flyover area range from 0.40 to 3.79 times. This range places the area predominantly in the low-risk category, though some measurement points fall into the medium-risk category. Therefore, the seismic risk in the Dendam Tak Sudah Lake development area can be categorized as low to medium.

3.3 Seismic Vulnerability Index Distribution Map (K_g) Analysis

The seismic vulnerability index (K_g) quantifies the susceptibility of the overburden layer to deformation during an earthquake. This index is influenced by the amplitude and natural frequency of seismic waves. Specifically, a high amplitude combined with a low natural frequency results in a high seismic vulnerability index, while a low natural frequency with a high amplitude results in a low seismic vulnerability index (Tanjung et al., 2019).

Based on measurements taken at 28 points, the seismic vulnerability index in the Lake Dendam Tak Sudah flyover construction area ranges from 0.03 to 6.04 (Figure 4). The highest vulnerability index, ranging between 4.32 and 6.04, is observed at point T8, located approximately 200 meters from the flyover structure. This zone, T8, is identified as the most vulnerable area within the Lake Dendam Tak Sudah flyover construction site.

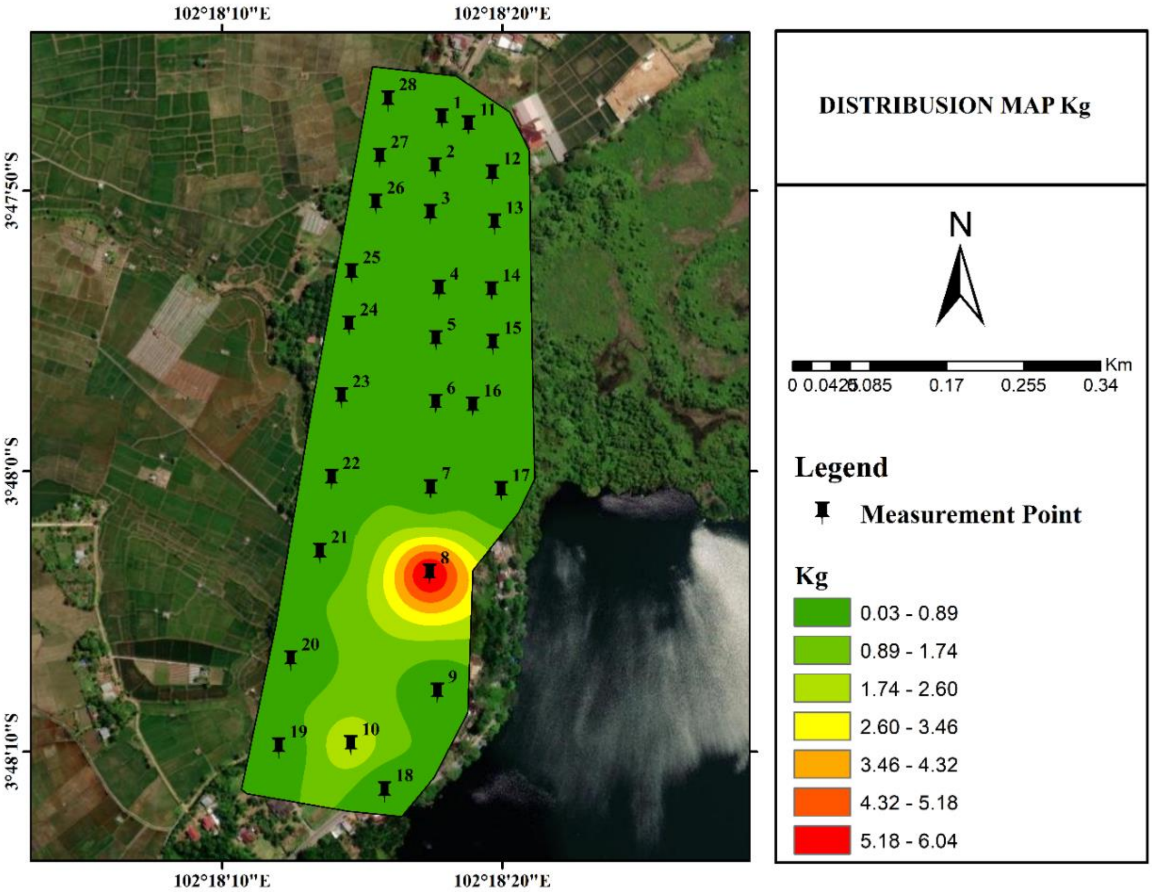

Figure 4 Same as Figure 2, but for K_g.

3.4 Shear Velocity (V_s) Analysis

Based on the seismic vulnerability assessment for the construction of the Dendam Tak Sudah Lake Flyover in Bengkulu City, relatively low vulnerability values were observed. The shear wave velocity (V_s) is directly proportional to the dominant frequency value and inversely proportional to the seismic vulnerability index (K_g). Dynamic soil characterization, such as estimating Vs values at various depths from multiple measurements, is a common geophysical method used for seismic microzonation (Motalleb Nejad et al., 2018).

The shear wave velocity (V_s) reflects the shear properties of the soil structure and is a critical parameter for determining the dynamic characteristics of the soil. Shear wave analysis helps evaluate local site effects, particularly within sedimentary layers overlying bedrock. In the study area, V_s values range from 185.19 to 539.49 m/s (Figure 5), indicating a mix of soft, medium, and hard soil classifications. The predominant soil types in this area include clay, silt, sand, and gravel. The spatial distribution of V_s values is a crucial component of disaster mitigation efforts and provides a foundation for regional development aimed at reducing earthquake risk.

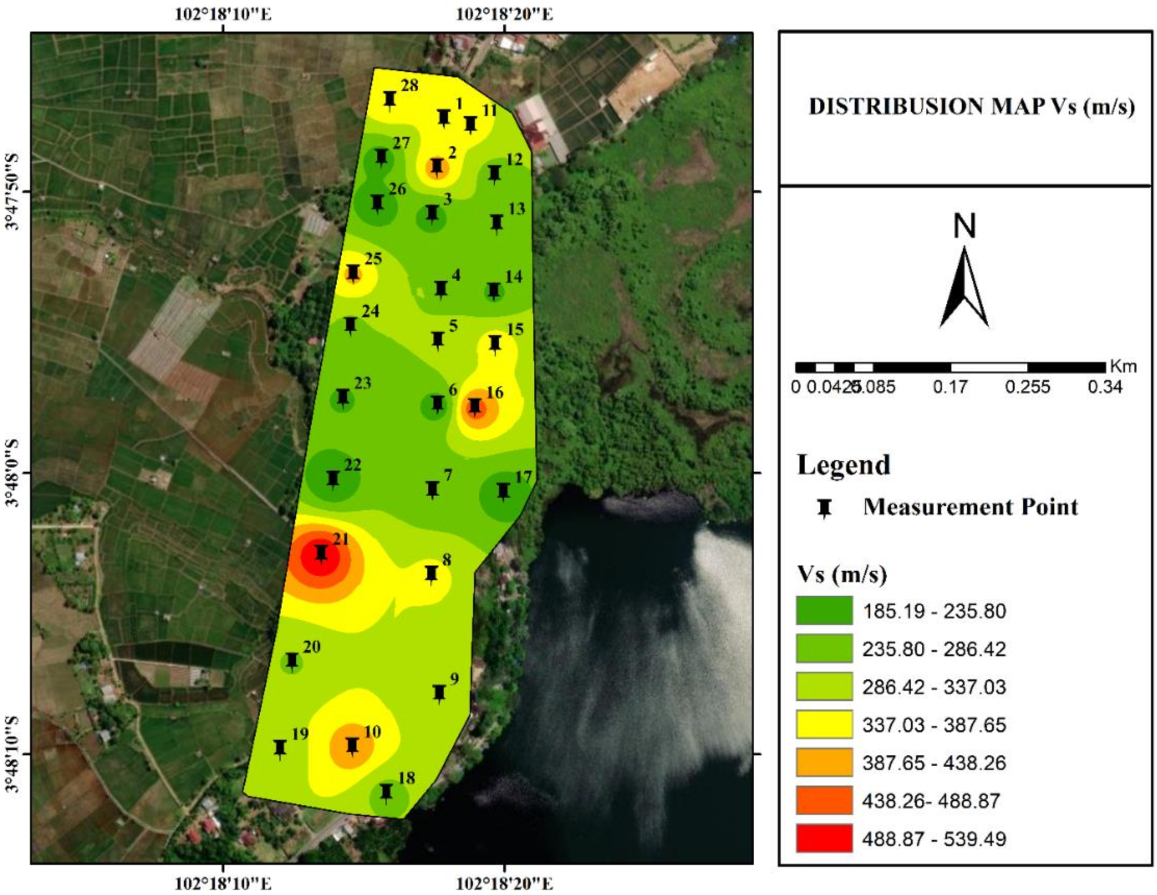

Figure 5 Same as Figure 2, but for V_s.

4. CONCLUSION

Based on the results of this study, the natural frequency values in the research area range from 2.16 to 7.53 Hz, indicating a classification of soil types I and III, predominantly consisting of alluvial sediments formed through sedimentation processes with thicknesses between 5 and 10 meters. The analysis reveals that the area falls into the medium vulnerability category with respect to seismic risk. Notably, the highest amplification values and seismic susceptibility index are observed at site T8, where the Vs value is found to be inversely proportional to the Kg value. The Vs values range from 185.19 to 539.49 m/s, corresponding to classifications of soft, medium, and hard soils. These findings provide preliminary geophysical and geological insights into the seismic conditions at the Dendam Tak Sudah Lake Flyover construction site in Bengkulu City.

In terms of mitigation strategies, it is essential to integrate these findings into the design and construction phases to enhance seismic resilience. Given the medium vulnerability classification, incorporating seismic design principles, such as base isolation and energy dissipation systems, can significantly reduce the impact of potential seismic events. Additionally, regular monitoring and updating of the seismic risk assessments, along with adopting construction practices that consider the site's specific soil and amplification characteristics, will contribute to a more robust and resilient infrastructure.

ACKNOWLEDGEMENT

Thank you to the friends of the Geophysics Study Program at Bengkulu University who have helped in this research, especially to the supervisors who have helped in the data processing to the interpretation stage, and have accompanied the process of writing this journal very well.

REFERENCE

Amirudin, Iktri Madrinovella, S. (2023). *Seismic Vulnerability Analysis Using the Horizontal to Vertical Spectral Ratio (HVSR) Method on the West Palu Bay Coastline*. *08*(02), 23–34. https://doi.org/10.25299/jgeet.2023.8.02-2.13879

Bard, P., Duval, A., Koehler, A., & Rao, S. (2004). SESAME European research project. *SESAME: Site EffectS assessment using Ambient Excitations*, *D23.12*(December), 62 pp.

Chasanah, U., Handoyo, E., Rahmawati, N. N., & Musfiana, M. (2022). Mapping Risk Level Based on Peak Ground Acceleration (PGA) and Earthquake Intensity Using Multievent Earthquake Data in Malang Regency, East Java, Indonesia. *Jurnal Ilmu Fisika | Universitas Andalas*, *14*(1), 64–72. https://doi.org/10.25077/jif.14.1.64-72.2022

Dal Moro, G., & Panza, G. F. (2022). Multiple-peak HVSR curves: Management and statistical assessment. *Engineering Geology*, *297*(December 2021). https://doi.org/10.1016/j.enggeo.2021.106500

Farid, M., & Mase, L. Z. (2020). Implementation of seismic hazard mitigation on the basis of ground shear strain indicator for spatial plan of Bengkulu city, Indonesia. *International Journal of GEOMATE*, *18*(69), 199–207. https://doi.org/10.21660/2020.69.24759

Fazriati, E., Azhari, M. R., Hakam, A., Utama, W., & Rosandi, Y. (2023). Horizontal to Vertical Spectral Ratio (HVSR) Analysis of the Passive Seismic Data on Alluvial Lithology: An Example from Bandung Basin Rim. *Jurnal Penelitian Pendidikan IPA*, *9*(1), 402–411. https://doi.org/10.29303/jppipa.v9i1.2962

Gafoer, S., Amin, T.C., and P. (2012). Geology of the Bengkulu Quadrangle, Sumatra. Department of Mines and Energy. *Directorate General of Geology and Mineral Resources, Geological Research and Development Centre. Bandung*, 99.

García-Jerez, A., Piña-Flores, J., Sánchez-Sesma, F. J., Luzón, F., & Perton, M. (2016). A computer code for forward calculation and inversion of the H/V spectral ratio under the diffuse field assumption. *Computers and Geosciences*, *97*, 67–78. https://doi.org/10.1016/j.cageo.2016.06.016

Hadi, A. I., Farid, M., & Fauzi, Y. (2012). Pemetaan Percepatan Getaran Tanah Maksimum dan Kerentanan Seismik Akibat Gempa Bumi untuk Mendukung Rencana Tata Ruang dan Wilayah (RTRW) Kota Bengkulu. *SIMETRI, Jurnal Ilmu Fisika Indonesia*, *1*(2D), 81–86.

Hadi, A. I., Farid, M., Refrizon, R., Harlianto, B., Hudayat, N., & Krisbudianto, M. (2021). Pemetaan Potensi Kerentanan Gempabumi Pada Kota Bengkulu Menggunakan Data Mikrotremor dan Metode Analytical Hierarchy Process. *Jurnal Fisika Flux: Jurnal Ilmiah Fisika FMIPA Universitas Lambung Mangkurat*, *18*(2), 105. https://doi.org/10.20527/flux.v18i2.9479

Hadi, A. I., Refrizon, R., Halauddin, H., Lidiawati, L., & Edo, P. (2021). Interpretasi Tingkat Kekerasan Batuan Bawah Permukaan di Daerah Rawan Gempa Bumi Kota Bengkulu. *Indonesian Journal of Applied Physics*, *11*(1), 11. https://doi.org/10.13057/ijap.v11i1.46525

Hadi, A. I., Suhendra, S., & Efriyadi, E. (2010). Bengkulu Earthquake Parameter Analysis Study Based on Single-Station and Multi-Station Data and Their Distribution Pattern. *Berkala Fisika*, *13*(4), 105–112.

Haerudin, N., Rustadi, Alami, F., & Yogi, I. B. S. (2020). The effect site analysis based on microtremor data using the Horizontal to Vertical Spectral Ratio (HVSR) method in the Bandar Lampung City. *Journal of Physics: Conference Series*, *1572*(1). https://doi.org/10.1088/1742-6596/1572/1/012075

Haryanto, Y., Hu, H.-T., Han, A. L., Hidayat, B. A., Widyaningrum, A., & Yulianita, P. E. (2020). Seismic Vulnerability Assessment Using Rapid Visual Screening: Case Study of Educational Facility Buildings of Jenderal Soedirman University, Indonesia. *Civil Engineering Dimension*, *22*(1), 13–21. https://doi.org/10.9744/ced.22.1.13-21

Honarto, R. J. (2019). Perencanaan Bangunan Beton Bertulang Dengan Sistem Rangka Pemikul Momen Khusus Di Kota Manado. *Jurnal Sipil Statik*, *7*(2), 201–208.

Lestari, D. A., & Susiloningtyas, D. (2022). Spatial Analysis of Social Vulnerability to Earthquake Hazard in Bengkulu City. *International Journal on Advanced Science, Engineering and Information Technology*, *12*(5), 1989–1996. https://doi.org/10.18517/ijaseit.12.5.11889

Lindung Zalbuin Mase, Khairul Amri, Kyohei Ueda, Rita Apriani, Fazriati Utami, Tetsuo Tobita, S. L. (2024).

Geophysical investigation on the subsoil characteristics of the Dendam Tak Sudah Lake site in Bengkulu City, Indonesia. *Acta Geophysica*, *72*(2), 893–913.

Mase, L. Z., Sugianto, N., & Refrizon. (2021). Seismic hazard microzonation of Bengkulu City, Indonesia. *Geoenvironmental Disasters*, *8*(1). https://doi.org/10.1186/s40677-021-00178-y

Motalleb Nejad, M., Momeni, M. S., & Manahiloh, K. N. (2018). Shear wave velocity and soil type microzonation using neural networks and geographic information system. *Soil Dynamics and Earthquake Engineering*, *104*, 54–63. https://doi.org/10.1016/j.soildyn.2017.10.001

Mucciarelli, M., Herak, M., & Cassidy, J. (2008). *Increasing seismic safety by combining engineering technologies and seismological data (Google eBook)* (Vol. 2008, Nomor 1). http://books.google.com/books?hl=it&lr=&id=2zoNLkp_qxAC&pgis=1%5Cnhttp://link.springer.com/10.1007/978-1-4020-9196-4

Nguyen-Tien, H., Nguyen-Hong, P., Nguyen-Le, M., Che-Min, L., Tran-An, N., Pham-The, T., & Nguyen-Van, D. (2022). Establishment of the correlation between the near-surface sedimentary thickness and the microtremor dominant frequency in the Hanoi area. *Vietnam Journal of Earth Sciences*, 1–18. https://doi.org/10.15625/2615-9783/17569

Prabowo, U. N., Sehah, S., & Ferdiyan, A. (2021). Estimasi ketebalan lapisan sedimen permukaan menggunakan pengukuran mikrotremor di Pemalang, Jawa Tengah. *Jurnal Teras Fisika*, *4*(1), 187. https://doi.org/10.20884/1.jtf.2021.4.1.3436

Rahmawati, N. I., Refrizon, R., Kusuma, B. P., Ansory, A. R. Al, Syah, M. T., Anggria, D. C., & Triutami, O. (2024). Delineation of Coal Identification Using Inversion Microtremor and Borehole at PT X. *Journal of Technomaterial Physics*, *6*(1), 62–68. https://doi.org/10.32734/jotp.v6i1.16077

Rasyid, A. M., Rochman, J. P. G. N., Widodo, A., Nabiha, M. R., Mikael Mario, P. P., & Salam, I. F. (2024). Site classification Based on Shear Wave Velocity Inversion in the Jlantah Dam Construction Project using the HVSR (Horizontal to Vertical Spectral Ratio) Analysis Method. *IOP Conference Series: Earth and Environmental Science*, *1307*(1). https://doi.org/10.1088/1755-1315/1307/1/012006

Refrizon, Fadli, D. I., Utami, O. T., Putri, A. C. P., & Nurul Ilmi Rahmawati. (2024). Microzonation Analysis in Manna City & Pasar Manna Subdistricts Utilizing Microtremor Data, South Bengkulu Regency. *Indonesian Physical Review*, *7*(1), 107–118. https://doi.org/10.29303/ipr.v7i1.252

Ridwan, M., Yatini, Y., & Pramono, S. (2021). Mapping of Potential Damages Area in Lombok Island Base on Microtremor Data. *Jurnal Pendidikan Fisika Indonesia*, *17*(1), 49–59. https://doi.org/10.15294/jpfi.v17i1.27028

SESAME. (2004). Guidelines for the Implementation of the H/V Spectral Ratio Technique on Ambient Vibrations: Measurements, Processing and Interpretation. *SESAME European Research Project WP12*.

Setianegara, R., DickY Muslim, Ismawan, & Marjiyono. (2023). Potensi Penguatan Gelombang Gempabumi oleh Sedimen Permukaan Berdasarkan Analisis Mikrotremor: Studi Kasus di Cekungan Bandung Bagian Selatan. *Jurnal Geologi dan Sumberdaya Mineral*, *24*(2), 107–115. https://doi.org/10.33332/jgsm.geologi.v24i2.749

Sugianto, N., Farid, M., & Suryanto, W. (2016). Local geology condition of Bengkulu city based on seismic vulnerability index (Kg). *ARPN Journal of Engineering and Applied Sciences*, *11*(7), 4797–4803.

Supriyadi, Khumaedi, Sugiyanto, Fadilah, A. R., & Muttaqin, W. H. (2022). Study of the Subsurface Structure Based on Microseismic Data in the Heritage Area of Kota Lama Semarang, Indonesia. *International Journal of GEOMATE*, *23*(97), 211–219. https://doi.org/10.21660/2022.97.j2357

Susilanto, P., Ngadmanto, D., Hardy, T., & Pakpahan, S. (2016). Penerapan Metode Mikrotremor HVSR untuk Penentuan Respons Dinamika Kegempaan di Kota Padang. *Jurnal Lingkungan dan Bencana Geologi*, *7*(2), 79–88.

Tanjung, N. A. F., Yuniarto, H. P., & Widyawarman, D. (2019). Analisis Amplifikasi Dan Indeks Kerentanan Seismik Di Kawasan Fmipa Ugm Menggunakan Metode HVSR. *Jurnal Geosaintek*, *5*(2), 60. https://doi.org/10.12962/j25023659.v5i2.5726