

Mapping of Soil Stability based on Shear Wave Velocity Values (V_{s30}) Using the Multichannel Analysis Surface Wave (MASW) Method on Kalimantan Highway, Rawa Makmur Village, Bengkulu City

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Manuscript received: 16 May 2024; Received in revised form: 22 July 2024; Accepted: 2 August 2024

Abstract

Kalimantan Highway in Bengkulu is a heavily traveled route and the main gateway to Bengkulu City from northern areas such as Arga Makmur and Ketahun sub-district, or Mukomuko regency also surrounding areas. Geological formations in the form of alluvium terraces (Qat) cause soil instability, often damaging the road surface. These include the formation of potholes and the occurrence of puddles during heavy rains. This research aims to determine the bearing capacity (stability) of the soil layer along Kalimantan Highway section in Rawa Makmur Village, Muara Bangkahulu District, and provide planning information through mapping. It is imperative to assess the condition of the soil layer. This research uses geophysical methods, specifically the Multichannel Analysis of Surface Wave (MASW) technique, using a MASW PASI 16S24-P digital seismograph to image subsurface soil conditions by analyzing shear wave velocity (V_s). A total of 20 data points were collected along the Kalimantan Highway section. The results of the V_s profile analysis were interpreted into soil classifications based on the criteria set out in SNI 1726:2019. The majority of the road sections were classified as SE (soft soil) and SD (medium soil), with some points designated as SC (hard soil/soft rock). This indicates that the geotechnical design for these road sections should consider supporting factors to maintain structural safety and stability.

Keywords: Bengkulu; Multichannel Analysis Surface Wave; Shear Wave Velocity; Subsoil.

Citation: Putri, A. C. P., Refrizon, R., Hadi, A. I., & Al Ansory, A. R. (2025). Mapping of Soil Stability based on Shear Wave Velocity Values (V_{s30}) Using the Multichannel Analysis Surface Wave (MASW) Method on Kalimantan Highway, Rawa Makmur Village, Bengkulu City. *Jurnal Geocelebes*, 9(1): 1–14, doi: 10.70561/geocelebes.v9i1.34956

Introduction

Kalimantan Highway in Bengkulu City is a road that is classified as a congested road. The road is very important because it serves as the main infrastructure to enter Bengkulu City from northern areas such as Arga Makmur or Ketahun sub-districts and Mukomuko regency and surrounding areas. Since 2016 the government has planned to increase the capacity of this road (Kementerian Pekerjaan Umum dan Perumahan Rakyat, 2016). This road

section is highly supportive of vehicular transport as it facilitates trade, economic growth and access to a range of services (Suparno et al., 2023).

The highway extends for 3.9 kilometers and is between 6 to 8 meters wide. It connects Kalimantan Highway with Sungai Hitam Highway, which is situated in close proximity to numerous commercial establishments and residential neighborhoods. The geological formation

of the alluvium terrace (Qat), which consists of gravel, sand, and clay-silt (Sugianto et al., 2017), also contributes to the instability of the soil due to its expansive nature, high shrinkage-expansion value, and high sensitivity to water. Clay soil can be identified as a potential cause of road construction

instability (Vikki et al., 2022) as shown in Figure 1 by the blue areas. In addition, these roads are often flooded, with high water levels covering the road surface causing community mobility to be disrupted (Budianto et al., 2023).

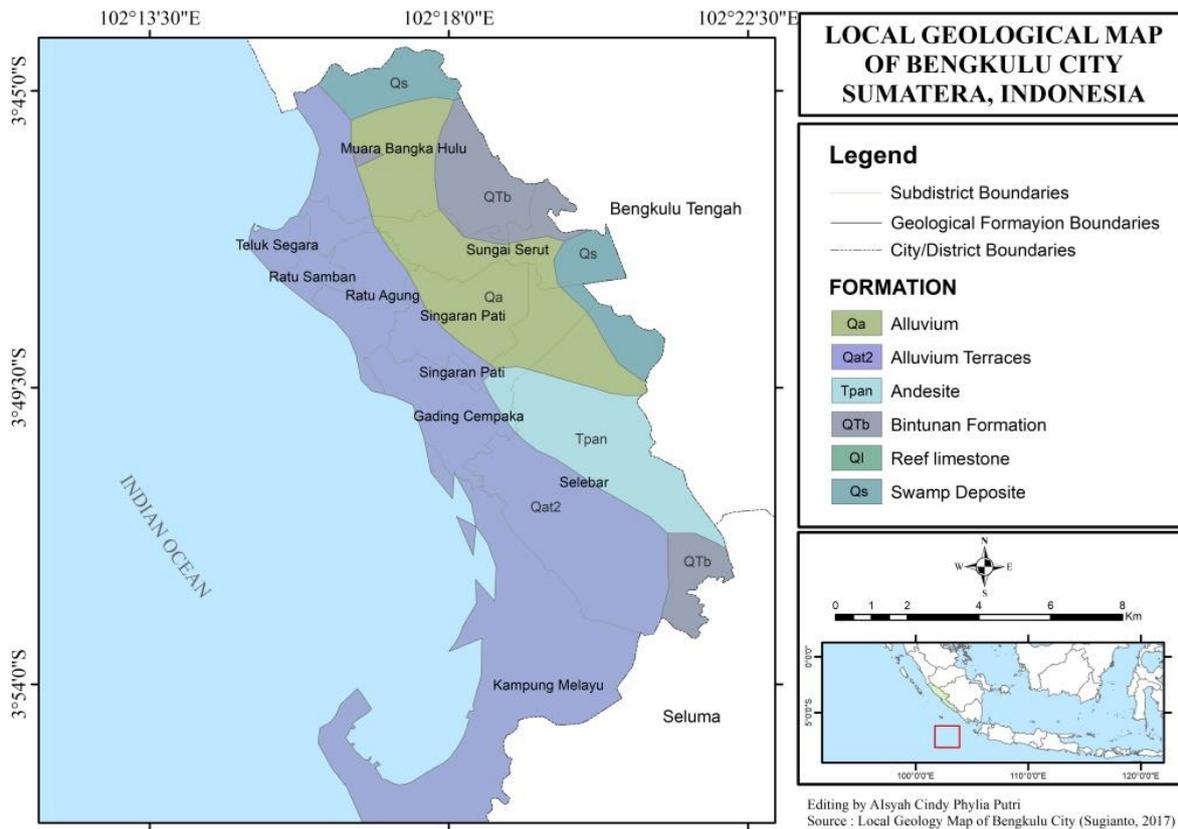


Figure 1. Local Geological Map of Bengkulu City (Modified from Sugianto et al. (2017)).

The terrace alluvium formation (Qat) is a layer of soil composed of sand, silt, clay and gravel collected from deposits in rivers, beaches and swamps. This geological unit does not reach the eastern part of Bengkulu, but is spread throughout the city from north to south (Nofirman, 2016). The soils tend to be different and may not be consistent. The term "alluvium terrace" or Qat refers to the process of deposition of alluvial deposits by river or water flow and is often found around or along roadways (Oldknow & Hooke, 2017). The changing ground movements make building on alluvium terrace (Qat) formations not recommended because alluvium terrace (Qat) formations

have several risks that can threaten the stability of homes and infrastructure, these risks include flooding, earthquakes, liquefaction, and disaster. Infrastructure designed with adequate bearing capacity, or "sustain," is important in sustainable development. This approach allows for considering local geological conditions, enhancing buildings' resilience against potential damage (Al Ansory et al., 2024).

Therefore, to identify stable soil layers, it is necessary to measure the condition of the subsoil. The acquisition was carried out with the Multichannel Analysis Surface Wave (MASW) geophysical method, the

result of MASW data interpretation is the Vs30 value (Shear wave velocity in 30m depth) which produces a profile of subsurface conditions and is considered a good indicator by Park et al. (1999) so it can be used to determine the classification of rocks based on the strength of earthquake vibrations. The Vs30 value can be used to determine earthquake-resistant building standards and estimate an area vulnerable to earthquakes (Prasisila et al., 2021).

The MASW method can record Rayleigh wave propagation to investigate the mechanical properties of subsurface layers and the level of rock density. It is effectively used because it can save costs and time. The steps of applying the MASW method start from data collection, surface wave analysis, velocity modeling, inversion, and finally, interpretation and modelling (Hasya et al., 2021). The MASW method is a non-invasive geophysical technique because it provides detailed information about soil structure without the need for direct drilling or excavation (Susilanto et al., 2019), which is used to collect data about the condition of subsurface soil structure. This technique works by analyzing Rayleigh waves triggered by a vibration source at the ground surface. These waves travel through the soil layers, and their propagation velocity is measured to identify soil properties. One of the critical aspects of an MASW survey is the arrangement of geophones. These geophones are placed in a straight line at specific intervals to detect and record ground vibrations to gather data. Each geophone is responsible for recording vibration signals originating from the sources like hammers or heavy machinery, which cause the propagation of Rayleigh waves through the ground (Mufardis et al., 2023). For quality control of MASW data acquisition results, it is important to check the quality of the Rayleigh wave signal recorded by each geophone. The signal must be clear and free from high noise in order for the main signal to be well-defined,

allowing accurate dispersion analysis. In addition to clarity, the signal should also have sufficient amplitude for preliminary spectral analysis. This analysis is conducted by examining the frequency and amplitude of the signal, which is expected to be sufficient to distinguish between different soil layers (Lin et al., 2004).

Research on sediment layer analysis using shear wave velocity has been conducted by Lubis et al. (2021), using the MASW analysis method in the Liwa area. The results showed that the first layer structure has a shear wave velocity (Vs) value of around 250 – 300 m/s, a density of 1.7 – 2.2 gr/cm³, and is 15 – 20 m thick. The second layer has a Vs value of 600 – 800 m/s with an average thickness of 5m. The third layer has Vs between 800 – 1000 m/s and is 25 – 50 m thick. Based on this research, it can be concluded that the MASW method is effective for mapping and understanding the condition of the soil sediment layer located on Kalimantan Highway to Sungai Hitam Highway in Muara Bangkahulu. By using seismic waves, this study aims to identify the 1D layer profile characteristics, which is Vs, of the soil layer. Vs is a crucial parameter in modelling soil dynamics, especially in the context of cyclic or repetitive loads (Rosyidi, 2015). Seismic methods can be used to measure the Vs of materials to obtain information about the subsurface structure of the soil. In this study, the MASW method is applied to measure the seismic wave velocity and describe the condition of the soil sediment layer in the road section of Muara Bangkahulu area.

Materials and Methods

Regional Geology and Research Area

In general, soils in Bengkulu City consist of alluvium terrace sediments (Qat), especially in the coastal areas and the central part of the city, consisting of various types of sediments, such as sand, silt, clay, and gravel, according to the geological map

of Bengkulu City. When earthquakes occur in the Bengkulu-Mentawai region, liquefaction is often found in places dominated by alluvium (Qa) and alluvium terrace (Qat) (Mase et al., 2021), especially along the coast as shown in Figure 1. Whereas around the measurement location, the geological formation is an Alluvium terrace (Qat), which is formed in a cycle of river terrace formation, which means that the soil type is related to the terrace field and is formed through the process of river erosion, deposition, or a mixture of both. Each alluvium terrace has diverse geomorphological characteristics compared to other soil types (El Oshebi et al., 2020). Alluvium terraces are plains or landforms formed by sediment deposition by rivers or streams. They are often found along river courses and form when river flow slows down, resulting in the gradual deposition of sediment. The size and elevation of alluvium terrace vary widely (Butzer et al., 1973).

A study by Hadi et al. (2021), indicates that the Alluvium Rock Formation Unit (Qa) in Bengkulu City has a Holocene age and is included in Quaternary Sediments. Furthermore, the Alluvium Terrace (Qat), Reef Limestone (Ql), and Swamp Deposits (Qs) are also Holocene-aged Quaternary Sediments (Table 1). It is important to note that these areas are susceptible to more significant rock deformation during an earthquake due to the hardness of the less compact rocks. However, the foundation must reach hard rock or bedrock to construct facilities and infrastructure in this area.

In the research, primary data of 20 points along Kalimantan Highway to Sungai Hitam Highway were acquired by MASW tool and secondary data from USGS of 8 points. Primary data is data obtained directly from research subjects or is original data that has never been processed before. This data is not available in file format because primary data collection usually involves the use of appropriate research tools or instruments to collect information directly from the source (Suhono & Al Fatta, 2021).

The observations were made by observing the structures visible on the soil surface of the road section with the assumption that it may be a factor in surface rupture of the road at Kalimantan Highway, Kelurahan Rawa Makmur, Bengkulu City, Bengkulu Province. The location of the research measurement point is shown in Figure 2.

Multichannel Analysis of Surface Wave (MASW)

The Multi-channel Analysis of Surface Wave (MASW) method is a geophysical technique that gathers data from the earth's surface through the analysis of Rayleigh waves, which are a type of surface seismic wave that travels along the top of the ground. The MASW method uses the dispersion characteristics of ground roll, a phenomenon where different seismic wave frequencies travel at different velocities, to measure the shear wave velocity (Vs) of subsurface material (Dewi et al., 2020).

Table 1. Rock Formations in Bengkulu City (Modified from Hadi et al. (2021))

Geological Formations	Litology	Collapse	Age
Andesite (Tpan)	The following geological formations were identified: Sand and gravel Reef limestone Conglomerate, breccia, and tuffaceous limestone Boulders, chert, sand, silt, and clay Gravel, sand, and clay-silt	Tertiary	Late Miocene
Reef Limestone (Ql)		Quaternary	Holocene
Bintunan Formation (Qtb)		Tertiary	Pliocene-Pleistocene
Alluvium (Qa)		Quaternary	Holocene
Alluvium Terrace (Qat)		Quaternary	Holocene
Alluvium (Qa) - Swamp Deposits (Qs)		Quaternary	Holocene

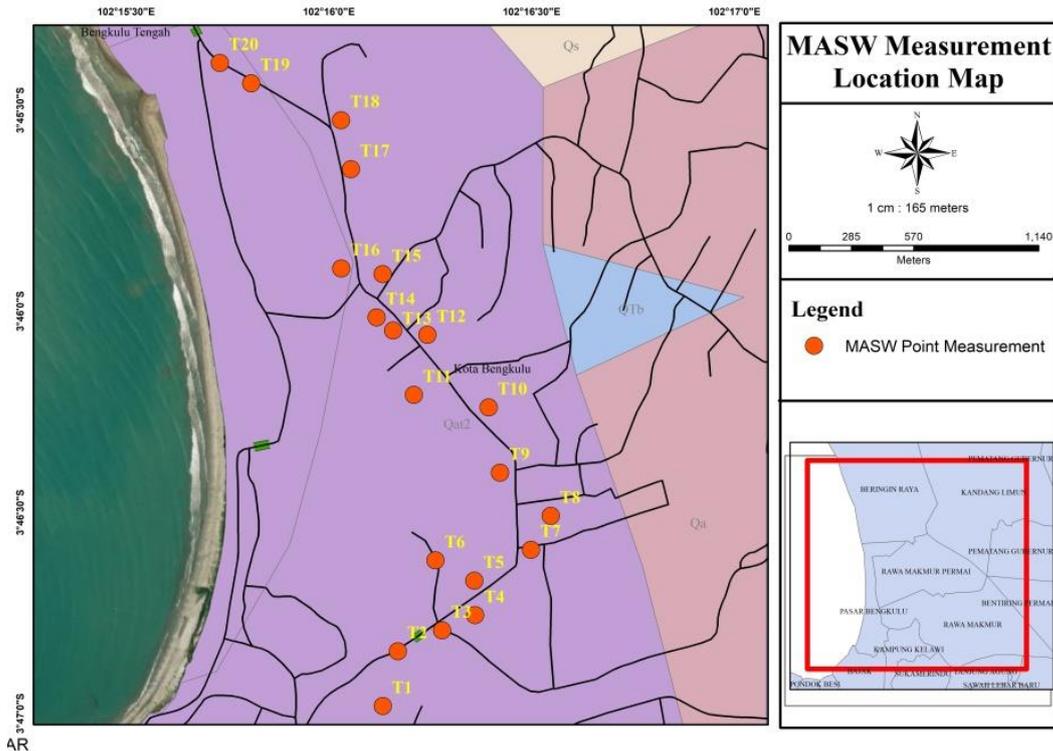


Figure 2. Map of the point measurement of Multichannel Analysis Surface Wave in the research location.

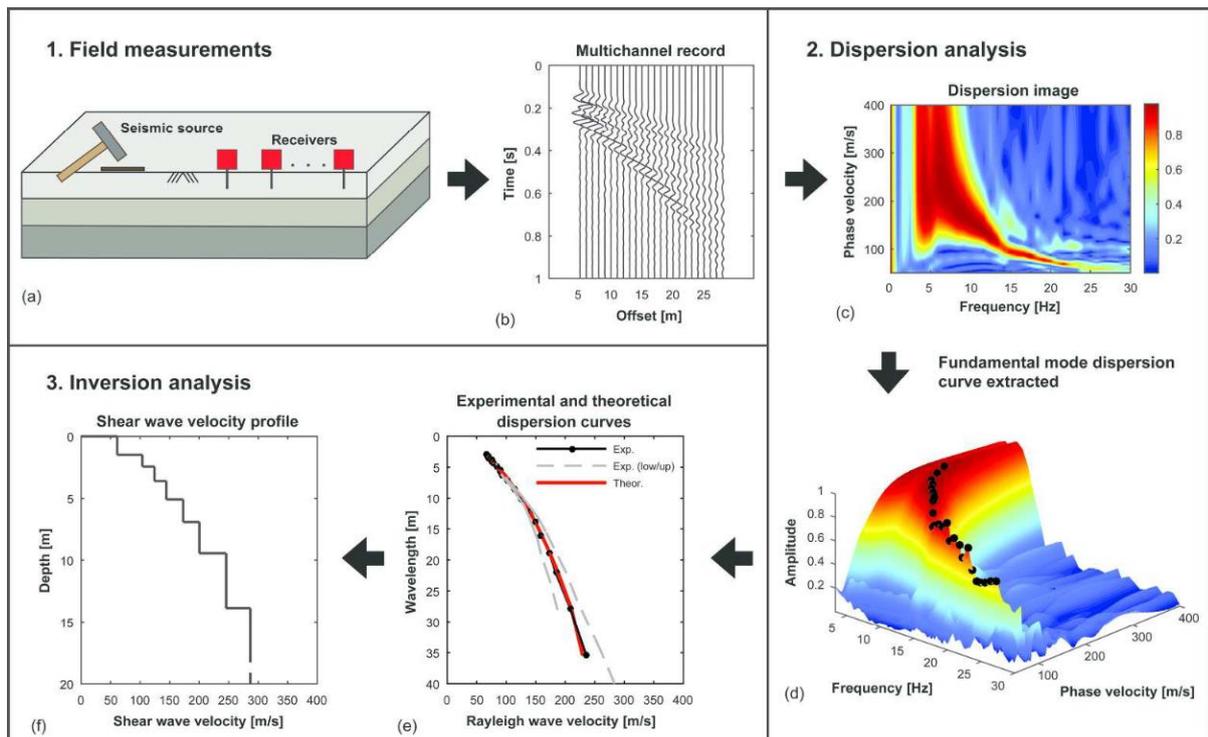


Figure 3. Overview of the MASW method: (a, b) field measurements; (c, d) dispersion analysis; (e, f) inversion analysis (Ólafsdóttir et al., 2017).

A non-invasive geophysical technique known as Multichannel Analysis of Surface Wave (MASW) is often used to identify and quantify subsurface soil structure. MASW is based on the Rayleigh wave

propagation theory, where it is formed through the interaction between shear waves and the surface soil layer. In addition, MASW can identify the Vs as a function of depth. From this velocity data,

information about the soil layers, such as thickness, hardness, and density, can be extracted. MASW is often used in construction planning and geological research (Muzli et al., 2016). It aids in geological research by mapping subsurface conditions and identifying geological formations, which are essential for infrastructure development and environmental assessments. It also evaluates the appropriateness of the ground for building structures in construction planning.

The principle in this method consists of three main steps (Figure 3), i.e., acquisition of seismic data, performing dispersion analysis, and finally converting the dispersion curve (Ólafsdóttir et al., 2017). The data acquisition tool was a MASW PSI 16S24-P digital seismograph. MASW seismic data collection begins with the installation of the tool at the study site. A total of 24 geophones were installed with a distance of 3 meters between geophones in each track, with the first and last far offset distance being 3 metres. A PASI seismograph was installed between the 12th and 13th geophones. The geophone cable was installed and connected between the cable connector and the geophone. Once the installation was complete, the PASI Seismograph was switched on and a new file was created by selecting the acquisition option and adding notes according to the names at the study site and setting the recording time. Triggers were placed near the metal plate and blows from the hammer as a seismic source were channelled to the metal plate. The recorded waves can be viewed by loading them from the PASI Seismograph. The final stage was to copy the data recorded by the Seismograph to a USB Drive and then save it in .DAT format for analysis. Next, the software operated to process seismic data for the MASW method, which is WinMASW, starting from picking data to producing an inversion of the surface wave dispersion curve

obtained by processing results from MASW raw data.

Shear Wave Velocity (Vs)

Shear wave velocity (V_s), or secondary or S-wave velocity, is crucial for assessing soil and rock elasticity properties in geophysics. It measures the speed at which shear waves travel through the subsurface material. Unlike primary (P) waves, which compress and expand the material they move through, shear waves displace the material perpendicularly to their direction of travel, making V_s a direct indicator of the material's rigidity and shear strength. V_s is essential for evaluating the dynamic conditions of soil in shallow subsurface layers, particularly in geotechnical and earthquake engineering. Typically, V_s is higher in solid rocks than primary wave velocity due to the higher rigidity of rocks. However, V_s can vary significantly depending on the type of rock and the geological conditions. For instance, in areas with thick sedimentary deposits, V_s can be lower due to these materials' softer, less rigid nature, which can influence seismic wave behavior during earthquakes (Susilanto & Ngadmanto, 2015). The following is a formula for calculating the average velocity of shear waves at a depth of no more than 30 meters:

$$Vs30 = \frac{30}{\sum_{i=1}^N \frac{h_i}{v_i}} \quad (1)$$

where $Vs30$ is the average velocity of the layer reaching a depth of 30 m, h_i is the layer thickness of 0 to 30 m and V_i is the shear wave velocity of the n th layer, these calculations help classify soil types and assess their seismic response, which is crucial for construction and infrastructure development in disaster-prone areas (Lantu et al., 2018).

Classification of Soils Based on Vs30

Soil classification is the classification of soils based on their physical, chemical and morphological characteristics. Usually, the

soil classification process considers aspects such as texture, structure, organic material content, color, and mineral composition. According to Indonesian National Standard (SNI) 1726:2019, there is a soil classification based on the V_{s30} value as follows in Table 2 (Zawawi et al., 2023).

Table 2. Site classification based on SNI 1726:2019 by (Zawawi et al., 2023).

Classification Class	V_{s30}
SA (Hard Rock)	>1500
SB (Rocks)	>750-1500
SC (Hard, very compact soil and soft rock)	>350-750
SD (Medium soil)	175-350
SE (Soft soil)	<175
SF (Special soil)	Specific investigation

Soils requiring site-specific investigation include (Building Seismic Safety Council - BSSC, 2003):

1. Soils prone to potential failure or collapse under seismic conditions, such as soils susceptible to liquefaction, quick clays, and highly sensitive clays, as well as collapsible weakly cemented soils.
2. Peat and/or highly organic clays where the thickness (H) exceeds 10 feet (3 meters).
3. Very high plasticity clays where the thickness (H) exceeds 25 feet (8 meters) and the plasticity index (PI) exceeds 75.
4. Very thick layers of soft or medium stiff clays where the thickness (H) exceeds 120 feet (36 meters) and the undrained shear strength (s_u) is less than 1,000 pounds per square foot (50 kilopascals).

Classification of soils based on V_{s30} values involves grouping soils based on the velocity of earthquake wave propagation in them at a depth of 30 meters. V_{s30} is a parameter used to assess the potential for earthquake wave amplification as well as the vulnerability of structures to earthquakes. Soils with low V_{s30} values tend to have lower stiffness and may experience earthquake wave amplification,

while soils with high V_{s30} values are typically denser and have a lower risk of damage from earthquakes.

Result and Discussion

The shear wave velocity (V_s) profile in the MASW method is a graphical representation of seismic wave velocity as a function of depth below the ground surface. To determine the seismic wave velocity at various depths below the ground surface, data obtained from seismic waves propagating in the MASW are analysed. The results of this analysis are then depicted in V_s profiles, which show how the seismic wave velocity changes with the depth of the subsoil, which can provide information about the structure of the subsoil.

The measurement results obtained from processing the V_s profile at points T4, T5, T6, T7, T11, T12, T13, T14, T19 and T20 are shown in Figure 4. The interpretation results refer to the soil classification based on the V_{s30} value of SNI 1726:2019, which are 152, 152, 172, 142, 170, 121, 155, 168, 157 and 154 m/s is SE or soft soil.

The measurement results obtained from processing the V_s profile at points T1, T3, T9, T10, T16, T17 and T18 are shown in Figure 5. The interpretation results refer to the soil classification based on the V_{s30} value of SNI 1726:2019, which are 229, 252, 242, 183, 296, 254 and 328 m/s, which are SD or medium soil.

The measurement results obtained from processing the V_s profile at points T2, T8 and T15 are shown in Figure 6. The interpretation results refer to the soil classification based on the V_{s30} value of SNI 1726:2019, which are 438, 479 and 574 m/s is SC or hard soil/ soft rock.

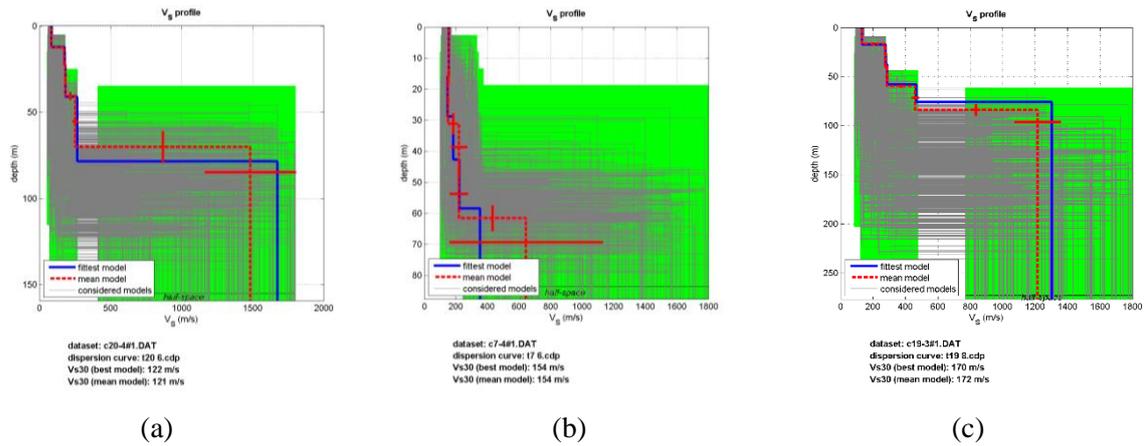


Figure 4. WinMASW Software Vs Profile (a) lowest Vs30 value in SE class. (b) average Vs30 value in SE class. (c) highest Vs30 value in SE class.

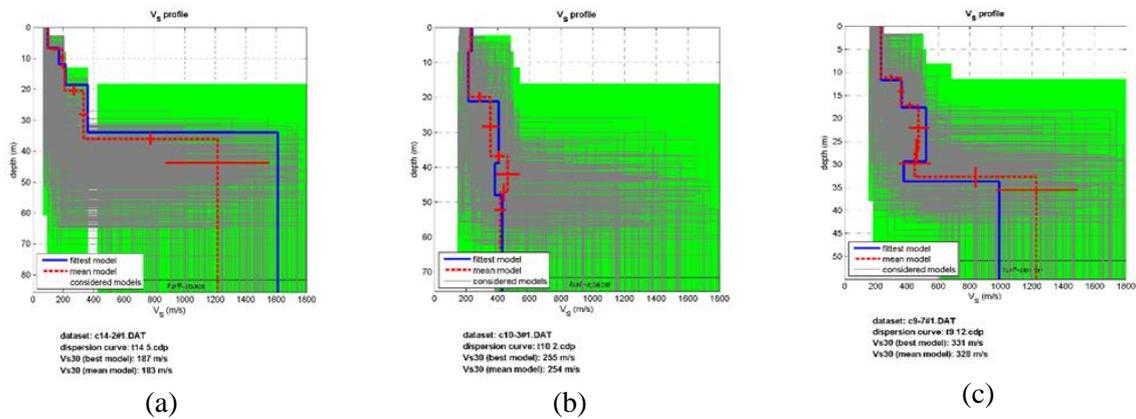


Figure 5. WinMASW Software Vs Profile (a) lowest Vs30 value in SD class. (b) average Vs30 value in SD class. (c) highest Vs30 value in SD class.

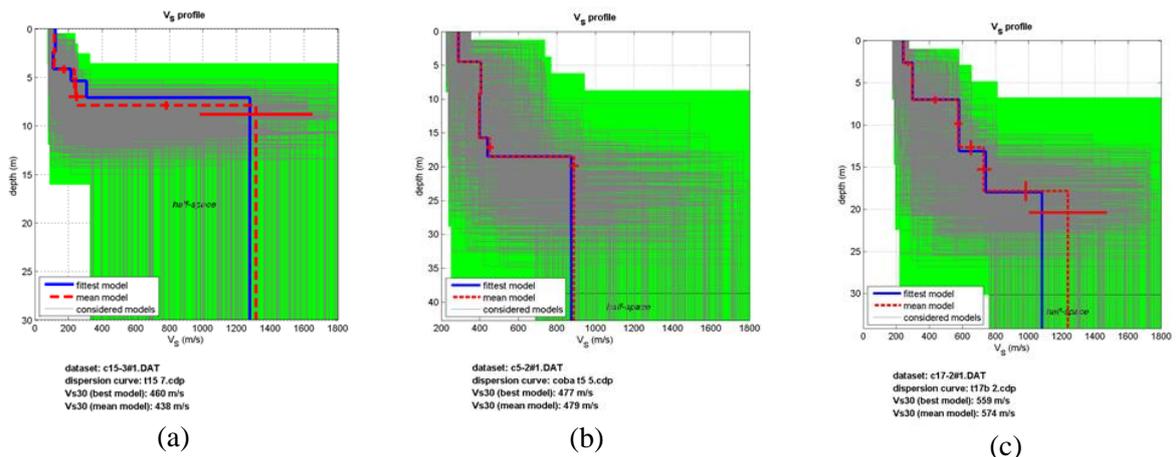


Figure 6. WinMASW Software Vs Profile (a) lowest Vs30 value in SC class. (b) average Vs30 value in SC class. (c) highest Vs30 value in SC class.

Analysis of measurement data using MASW at Rawa Makmur road revealed a variation in Vs30 values between 121 and 574 m/s. The characteristics of these values

are reflected in the site class map (Figure 7) created by the interpolation method, where most areas are marked in dark purple or SD, according to the SNI 1726:2019

classification, with a value range of 175 – 350 m/s representing medium stiffness soils. This area shows adequate soil strength as it is between soft and hard soil but tends to be soft due to the geological formation which is alluvium terrace (Qat).

In general, the soil site classification based on the V_{s30} value at Kalimantan Highway is divided into three types of site classifications, which are soft soil (SE), medium soil (SD), and hard soil, very dense, and soft rock (SC). Where the distribution is seen on the map in Figure 7, which shows that soft soil (SE) is represented in light purple, then medium

soil (SD) is represented in dark purple, while hard soil, very dense and soft rock, is represented in blue. Areas with this soft soil classification are located almost along the highway in the Terrace Alluvium Formation (Qat). This formation is younger than the other soil types and needs to experience more pressure and time to compact and harden like the older soils, so the rocks are tenuous, which causes the V_s to be small that affects how fast the S-wave propagates; the denser the soil, the faster the S-wave propagates. This means that although they are both on alluvium soils, their soil density and compactness different (Ardianto, 2018).

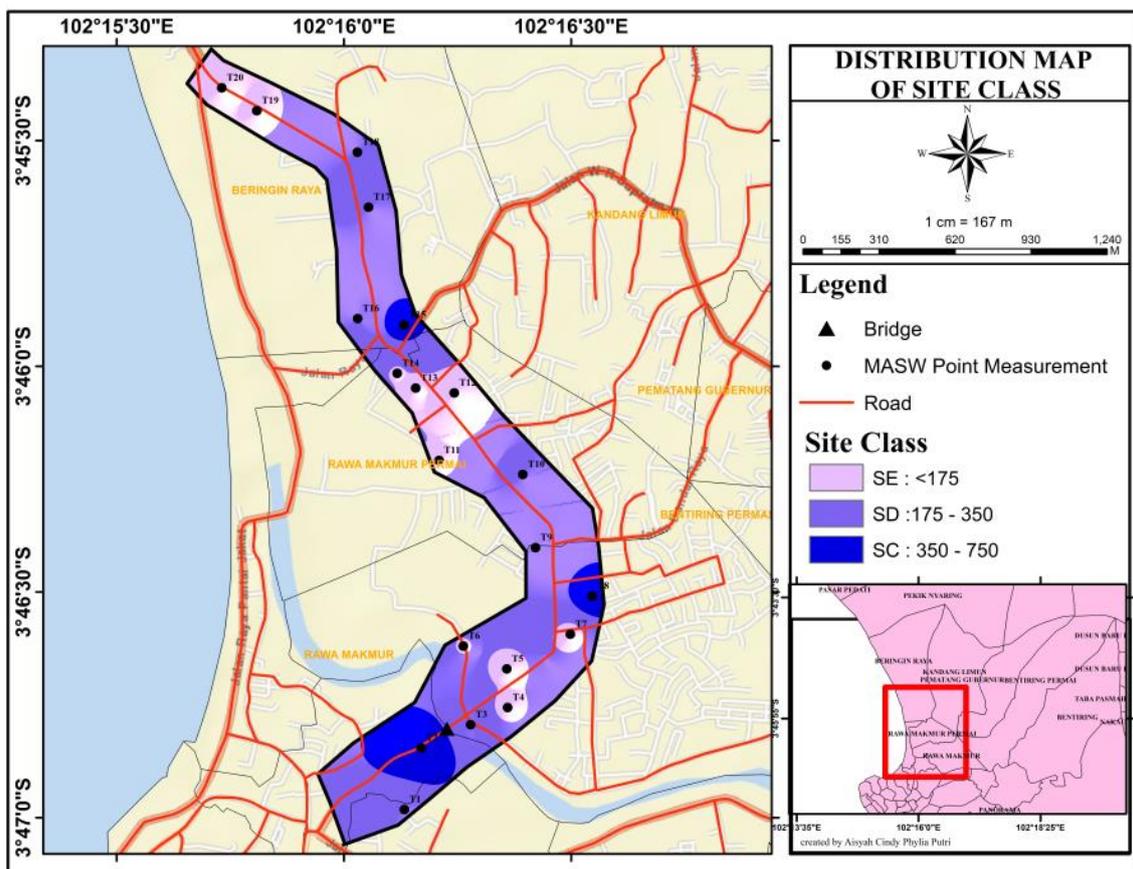


Figure 7. Map of site class.

In Figure 8, areas interpreted as showing moderate to high stiffness, shown in red-brown with V_{s30} values ranging from 435 to 574 m/s, fall into the SC class, indicating hard, very dense soil and soft rock, with potential for deformation. However, higher soil density and consistency only occur at some points, such as at points 2, 8, and 15.

Soils with V_{s30} values greater than 350 m/s can be considered adequate foundations for infrastructure such as highways as they exhibit sufficient stability to withstand forces or shocks. According to research (Bustari & Wibowo, 2023), soils with V_{s30} values between 240 and 410 m/s fall into the low to medium-risk category. However,

if infrastructure is built in areas with Vs30 values of at least 350 m/s, the soil's stability

will be sufficient to support road construction.

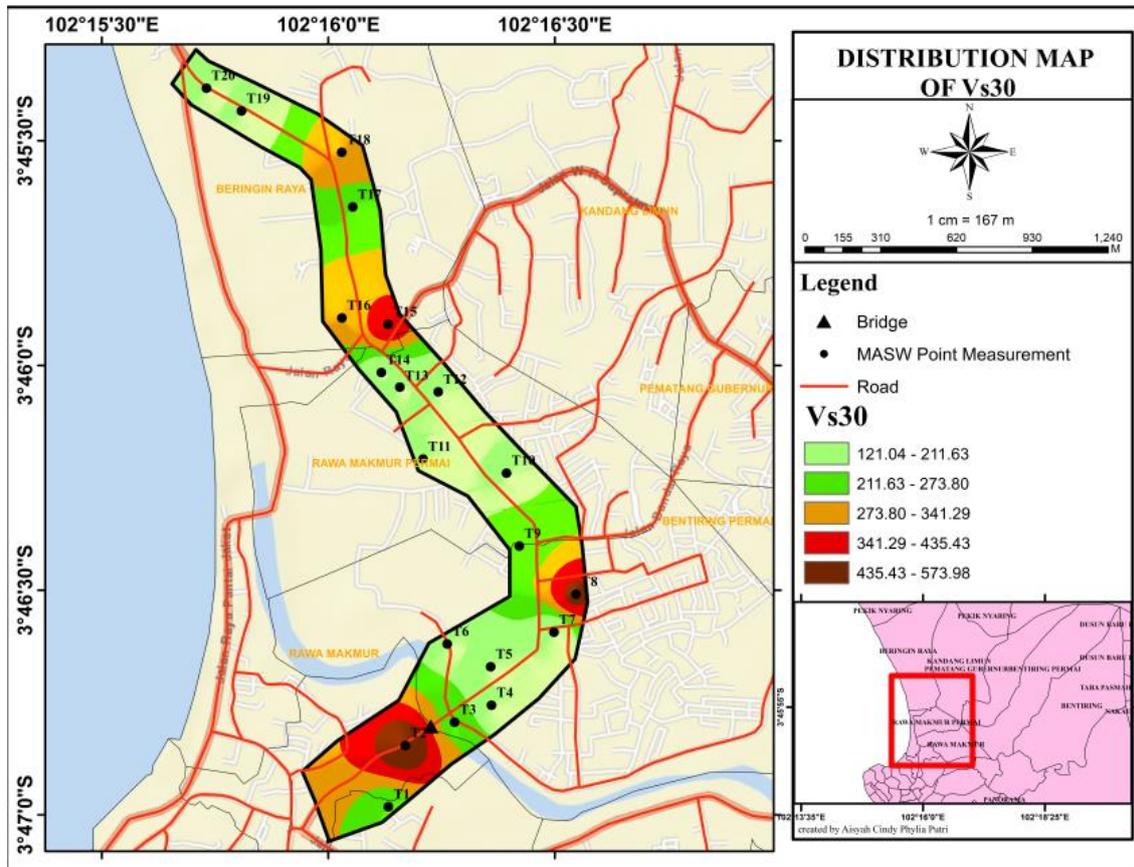


Figure 8. Map of Vs30 by Multichannel Analysis Surface Wave measurements.

Table 3. Vs30 data in the area around Rawa Makmur by USGS.

No.	Longitude	Latitude	Vs30 (m/s)	Class Classification
1.	102.2667	-3.75833	258.982	SD (medium soil)
2.	102.2667	-3.76667	273.008	SD (medium soil)
3.	102.275	-3.76667	251.46	SD (medium soil)
4.	102.2667	-3.775	258.953	SD (medium soil)
5.	102.275	-3.775	238.575	SD (medium soil)
6.	102.2833	-3.775	245.3	SD (medium soil)
7.	102.2667	-3.78333	286.743	SD (medium soil)
8.	102.275	-3.78333	259.862	SD (medium soil)

The SE class classification for soft soil, with the lowest Vs30 value of 121 m/s and the highest of 172 m/s, marked in green, is located at points T11, T12, T13, and T14, stretching along 500 meters of the road body. Sedimentary layers with Vs30 values <175 m/s are considered layers with low seismic wave velocities, so the risk of experiencing changes is quite high. Relatively non-rigid and low-cohesion soils do not have sufficient strength to resist

stresses, so geotechnical planning should be considered to ensure safety and stability.

Data on Vs30 values in the Rawa Makmur area, Bengkulu City (Table 3) published by the USGS shows an average of about 259 m/s which if interpreted this value falls into the soft medium soil classification (SD class) providing strong support for the acquisition results in this study.

As mapped Figure 9, it can be seen that only two locations have Vs30 values exceeding 270 m/s and this value is consistent with the

results obtained by MASW processing in the nearby areas.

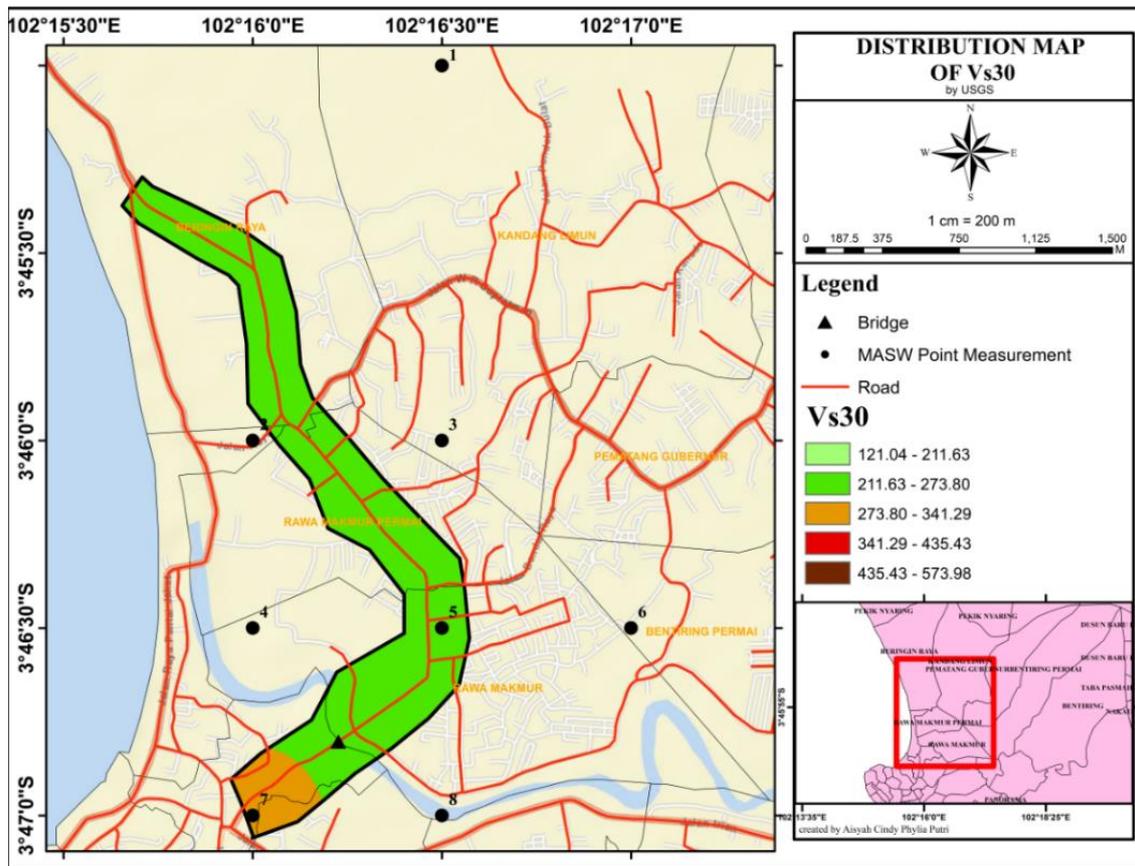


Figure 9. Map of Vs30 values based on USGS data.

Conclusion

The variation of Vs30 values ranges between 121 and 574 m/s, according to measurement data analysis using Multichannel Analysis Surface Wave (MASW) at Rawa Makmur road. The site class map shows the characteristics of these values: Vs30 values between 175 and 350 m/s indicate medium soil and Vs30 values above 350 m/s indicate stable hard soil. However, areas with medium to high stiffness can still experience deformation, especially in some places. Soils with Vs30 below 175 m/s are soft and easily deformed because Kalimantan Highway is located in an area of the Alluvium Terrace Formation (Qat), which is Quaternary in age and thus tends to have an unstable or poorly compacted structure. This condition makes the soil more susceptible to liquefaction and

ground shifting, especially when exposed to earthquakes or heavy loads. Geotechnical planning must consider supporting factors to maintain the safety and stability of the structure.

Acknowledgements

Thanks to the Mitigation and Exploration Laboratory of Geophysics Bengkulu University team who have helped in the research process so that this paper can be useful information for the public and thanks also to the lecturers who have advised a lot.

Author Contribution

Aisyah Cindy Phylia Putri provided the main idea, processed the data, and wrote the article. Aisyah Cindy Phylia Putri and Andre Rahmat collected data, created the

survey design, and created the distribution map of the research results. The lecturers who guided this article are Refrizon and Arif Ismul Hadi.

Conflict of Interest

The authors declare no conflict of interest.

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