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RESEARCH ARTICLE

Site Characterization Based on Shear-Wave Velocity Using Multichannel Analysis of Surface Waves (MASW) Method in Urban Areas of Aceh Besar, Indonesia

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Abstract

Seismic site characterization is needed for earthquake risk mitigation and also for geotechnical infrastructure design. Multichannel Analysis of Surface Waves (MASW) can be used for seismic site characterization. The method extracts shear-wave velocity (Vs) profiles from surface wave analysis that reveal geotechnical conditions and subsurface structures. This study aims to characterize the subsurface layers using the MASW method in Aceh Besar. Data acquisition was carried out along three measurement profiles, each 69 meters long and with a receiver spacing of 3 meters. Shear-wave velocities (Vs) of the subsurface soil and rock layers were estimated using dispersion curve analysis and 1D inversion. The surface wave spectral analysis produced a high-quality dispersion at the fundamental mode frequency of 20–30 Hz. The inversion process, validated by an excellent misfit curve, yields a seven-layer Vs model with RMS values mostly below 0.01. The 2D pseudo-section models based on 1D inversion results show a subsurface stratification consisting of a soft to medium overburden (Vs < 350 m/s) layer of 15 meters thick, followed by a transition zone of dense soil, and engineering bedrock (Vs > 750 m/s) found at a depth of 30 to 40 meters. In general, lateral variations were identified as undulating bedrock topography and local basin structures. Based on SNI 1726:2019, the site is classified as Medium Soil (SD) to Very Dense Soil (SC), with an estimated Vs value influenced by the thickness of the surface sediment. These results provide a valuable overview of subsurface conditions from site characterization and can serve as a basis for geotechnical planning in the study area.

Keywords: MASW, Surface Wave, Shear Wave Velociites, Site Characterization, Aceh Besar

1. Introduction

Aceh Besar is one of the regions in Indonesia located on a subduction zone with a high level of seismicity, due to its position between the Indo-Australian and Eurasian Plates (Sieh and Natawidjaja, 2000; Syukri et al., 2021). Since the Mw 9.2 earthquake that triggered the 2004 tsunami (Lay et al., 2005), the Aceh Besar region has remained seismically active, characterized by frequent moderate to large earthquakes. A recent example is the 5.4 magnitude tremor on March 30, 2025, which propagated as far as Banda Aceh (BMKG, 2025). This seismic activity is linked to the Seulimum Fault in eastern Aceh Besar, a territory primarily defined by its young volcanic sequences and alluvial deposits (Bennet, 1981).

Seismic events occurring on land tend to be more destructive, primarily due to their shallow focal depths and proximity to human settlements (Ma et al., 1999). This pattern was evident during the 2018 Palu and 2022 Cianjur disasters, where the most severe structural damage was concentrated in areas situated on soft sediment layers (Socquet et al., 2019; Supendi et al., 2023). Such soft deposits can amplify seismic waves, producing surface vibrations far more intense than those felt on solid rock formations (Aki, 1993). In Banda Aceh, studies identified a 4.3-fold surge in amplification (Yunita et al., 2018), a phenomenon that also poses a significant threat to Jakarta given its soft soil geological profile (Delfebriyadi et al., 2019).

Effective seismic risk assessment extends beyond monitoring seismic activity and requires a comprehensive understanding of local soil conditions that influence structural damage. The multi-channel analysis of surface waves (MASW) method is a highly reliable, non-invasive tool for seismic site classification and characterizing shallow shear-wave velocity profiles (Park et al., 1999; Wibowo et al., 2024). By quantifying shear wave velocity (Vs), the MASW method yields critical parameters necessary for site caracterizationas specified by SNI 1726:2019 (Masrurah et al., 2024). In regions such as Darussalam, Ingin Jaya, and Jantho City in Aceh Besar, where high population density and soft lithology are prevalent, systematic seismic vulnerability mapping is essential to support disaster-resilient urban development and effective mitigation planning.

Previous research on site caracterication in Aceh Besar used the Horizontal-to-Vertical Spectral Ratio (HVSR) method in Lamteuba (Asnawi et al., 2022; Khalqillah et al., 2019). The HVSR method is a passive geophysical approach to delineate the shear wave velocity (Vs) zone using microtremor signals. Findings from these studies indicate that 40% of the Lamteuba study area is highly susceptible to seismic hazards due to soft soil conditions.

While the HVSR method is widely used, it has inherent limitations in resolution and accuracy, as shear wave velocity (Vs) is estimated indirectly from the dominant frequency (Kuo et al., 2015). Furthermore, HVSR reliability depends on data quality and ambient noise levels, which can introduce significant uncertainty under varying environmental conditions (Nagamani et al., 2020). To overcome these constraints and achieve higher fidelity subsurface imaging, this research integrates the MASW method. MASW was specifically selected for the Aceh Besar region because it yields a more granular subsurface model by directly capturing Vs as a function of depth, offering a more robust framework for site caracterization assessment (Khadrouf et al., 2024).

2. Method

This study focuses on the Aceh Besar region, targeting three residential areas near the airport, a tourist area, and near the Seulimum Fault (Fig. 1). The MASW sites were selected for their proximity to the Seulimum Fault, a major active tectonic structure with a high potential for generating significant seismic events within the Aceh Besar district.

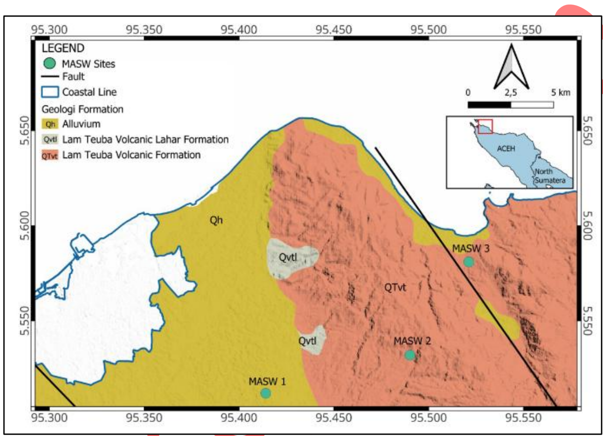

Fig. 1. Geological and MASW site distributions map in Aceh Besar region.

Data was recorded using a PASI 162:24P seismometer with 24 geophones. The geophones were arranged linearly, and the space between geophones was a 3-meter spacing and a 10-meter offset (Fig. 2). The seismic source was generated using a seismic hammer that struck the seismic plate. Data collection or shots were conducted at 11 points and two offset positions.

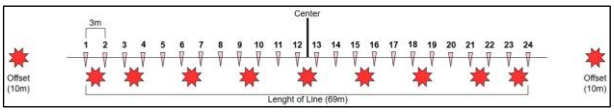

Fig. 2. MASW data acquisition configuration.

Data processing in this study was conducted in several stages. Geopsy (Wathelet et al., 2020) was used to process MASW data. In the initial processing stage, several data-acquisition parameters are required, including the number of geophones, geophone spacing, source locations, sampling rate, and data acquisition duration. The recorded signal was segmented into time windows to select waveforms exhibiting Rayleigh-wave dominance and to reduce noise.

The signal that has been filtered was transformed from the time to the frequency domain using the Fourier transform (Nussbaumer and Nussbaumer, 1982). The transformation process and filtering thereby clarify the Rayleigh-wave energy spectrum, while reducing interference from unwanted frequencies.

The next stage was the depiction of the frequency-velocity spectrum (fk-spectrum), presented as a visualization with the x-axis representing frequency and the y-axis representing velocity (Deodatis et al., 1990). From the fk-spectrum, a picking process was performed to extract the Rayleigh wave dispersion curve, which describes the relationship between frequency and phase velocity.

The dispersion curve inversion was performed using Dinver software to obtain a 1D Vs profile with depth. The inversion process was carried out iteratively until a theoretical model was obtained that matched the observed dispersion curve well or had a low misfit. The 1D inversion process is repeated for each shot point. Once the 1D model at each shot point is obtained, the next step is to construct a 2D pseudo-section from it. The 2D model will be interpreted in accordance with Table 1 of SNI 1726-2019, classified by seismic vulnerability level, to support earthquake disaster mitigation and infrastructure development planning.

Table 1. Site classification based on SNI 1726-2019

Site Classification	Code	Vs (m/s)
Hard Rock	SA	> 1500
Rock	SB	750-1500
Soft Rock/Very Dense Soil	SC	350-750
Stiff Soil	SD	175-350
Soft Soil	SE	<175

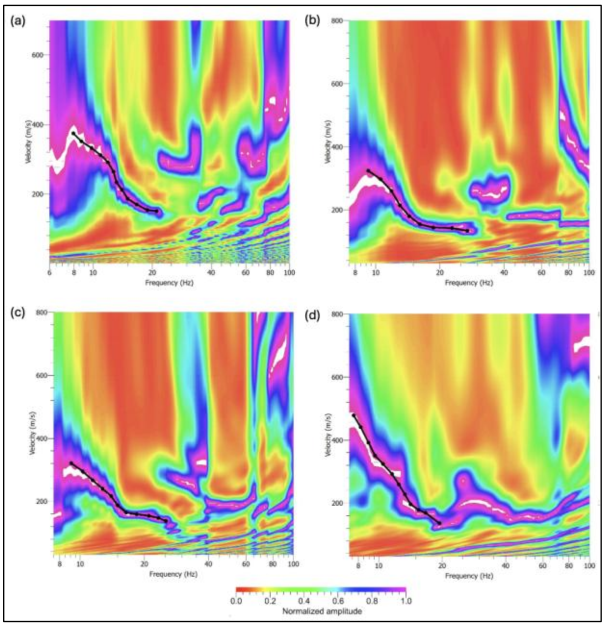

Fig. 3. Dispersion curve of profile MASW 1 (a) x = 7.5 m, (b) x = 25.5 m, (c) x = 43.5 m or center point, and (d) x = 61.5 m.

3. Results and Discussion

After preprocessing and Fourier transformation, the dispersion curve is obtained, as shown in Fig. 3 at selected shot points. Theoretically, the phase velocity should decrease with increasing frequency. At high frequencies (20-30 Hz), the relatively low velocity ranges from 100 to 150 m/s. At lower frequencies of 5-10 Hz, the velocity increases to 300-500 m/s, indicating the presence of more complex layers at greater depths.

The inversion process was done based on the dispersion curve to provide the shear wave velocity (Vs) vertical profile, as an example at the several shot points of profile MASW 1 (Fig. 4). The quality of this data is further confirmed by the misfit curve (Fig. 5) with RMS mostly less than of 0.01, where the observed slowness curve has a very high correlation with the theoretical model response.

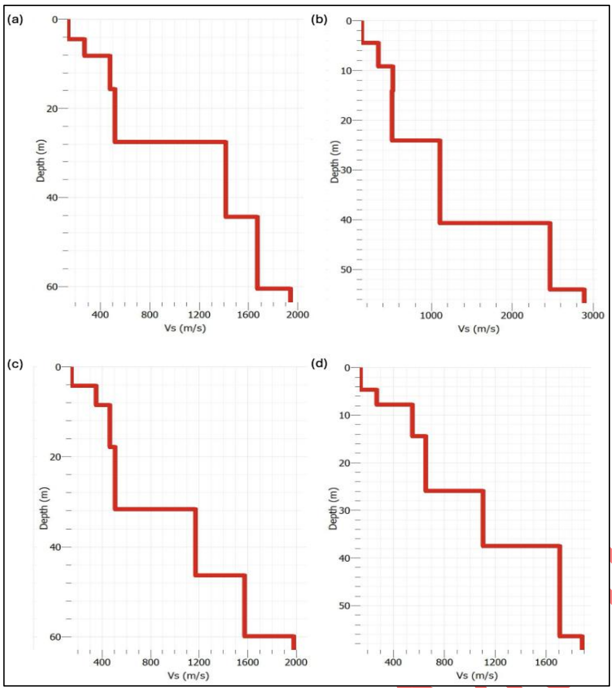

Fig 4. Selected 1D Vs model at profile MASW 1 (a) x = 7.5 m, (b) x = 25.5 m, (c) x = 43.5 m or center point, and (d) x = 61.5 m.

Based on the 1D inversion results at the MASW 1 center point (Fig. 4), the 1D Vs velocity models have a similar pattern. The top layers have velocities of 200-600 m/s, and the bottom layers have velocities of 2,000-3,000 m/s. The velocity increases with depth, indicating that the soil or rock becomes denser or harder.For subsurface interpretation that shows lateral and vertical variations in the Vs velocity model, spatial extrapolation was performed from 1D data to 2D cross sections along the three profiles (MASW 1, MASW 2, and MASW 3). In profile MASW 1 (Fig. 6), the result shows lateral heterogeneity. However, a local high velocity anomaly is found at shallow depths, from 10 m to 15 m, and at the initial edge of the profile (offset -10 m to 5 m), likely representing solid blocks within a soft soil matrix. The bedrock boundary in this profile appears undulating. In contrast, profile MASW 2 (Fig. 7) exhibits a more horizontal, uniform stratigraphy, indicating a more stable depositional environment. The boundary between the soft sediments (Vs 0-800 m/s) and the more complex layers (Vs > 1200 m/s) is sharp and continuous at a depth of approximately 35 meters. Meanwhile, profile MASW 3 (Fig. 8) reveals a unique subsurface topographic feature: a basin-like structure at the center of the profile (distance 30–50 m). Overall, the bedrock exhibits the highest stiffness at a depth of 50 m for all profiles, as indicated by the red zone (Vs > 1800 m/s), suggesting a massive, fresh rock mass (intact rock).

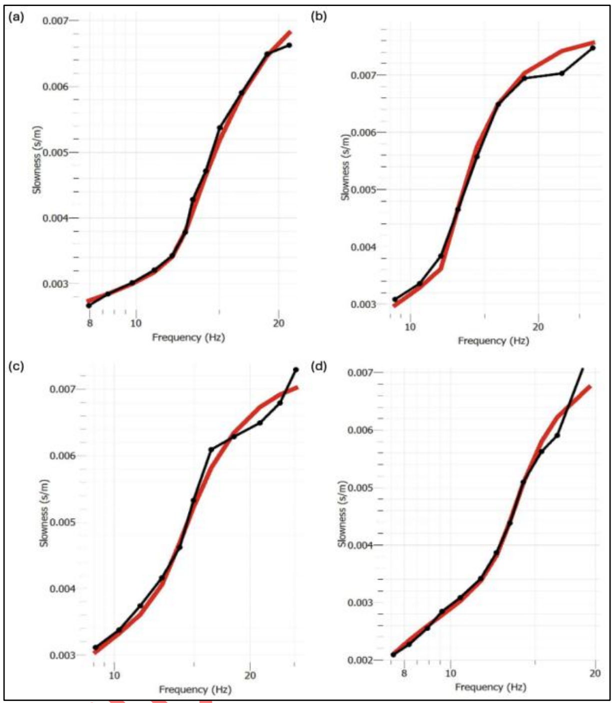

Fig 5. Selected misfit between data and model profile MASW 1 (a) x = 7.5 m, (b) x = 25.5 m, (c) x = 43.5 m or center point, and (d) x = 61.5 m.

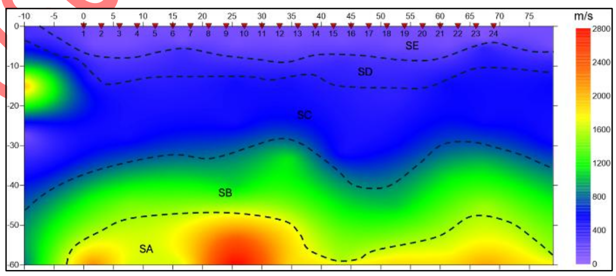

Fig. 6. 2D pseudo-section of Vs at profile MASW 1

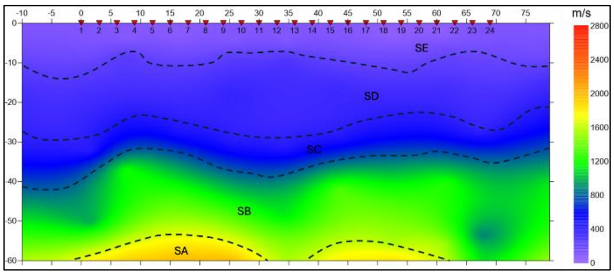

Fig. 7. 2D pseudo-section of Vs at profile MASW 2

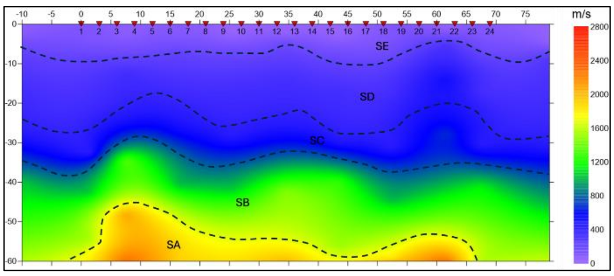

Fig. 8. 2D pseudo-section of Vs at MASW 3

The 2D model interpretation is correlated with the SNI 1726:2019 site classification standard to determine the soil engineering characteristics (Table 1). The dominance of the gradation of purple to blue colour in the upper layer (0–15 meters) across the profiles indicates material with Vs < 175 m/s to 350 m/s, classifying this surface layer as Soft Soil (SE) to the lower limit of Medium Soil (SD). The intermediate layer at a depth of 15–30 meters, indicated by a blue colour, has a velocity range of 350–750 m/s, corresponding to the Very Dense Soil (SC) category. Bedrock found below a depth of ~35 meters generally has Vs > 750 m/s, placing it in the Rock (SB) category. The presence of layers with Vs > 1500 m/s indicates Hard Rock (Class SA). Although the bedrock is classified as SB/SA, the thickness of the soft overburden at the surface causes the average Vs30 value (average velocity in the first 30 meters) to most likely fall into the Medium Soil (SD) or Very Dense Soil (SC) category. This condition warrants special attention in the design of earthquake-resistant structures due to the difference in stiffness between the soft soil on top and the solid bedrock below, which can amplify waves.

4. Conclusion

This study successfully applied the MASW method to evaluate the 1D shear-wave velocity (Vs) profile and determine the seismic site classification at three representative locations in Aceh Besar. The results of the dispersion curve and misfit function indicate high data quality, yielding shear wave velocity (Vs) profiles to a depth of 60 meters. The 2D pseudo-section of the three profiles at MASW 1, MASW 2, and MASW 3 shows a five-layer lithology based on SNI 1726-2019. The sedimentary layer is interpreted to be up to 30 m to 40 m, followed by the bedrock. In general, the site classification is expected to indicate a vertical transition from Soft/Medium Soil (SE/SD) in the surface layer (0–15 m) to Very Dense Soil (SC) and Rock (SB/SA) at greater depths. Considering the average value of Vs30, which is influenced by the thickness of the overburden, the site is globally categorized as Medium Soil (SD) to Very Dense Soil (SC), however, the presence of sharp impedance contrasts at intermediate depths indicates the potential for significant earthquake wave amplification, thus requiring special attention in the design of earthquake-resistant building foundations and structures.

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