SUBSURFACE CHARACTERIZATION USING MULTICHANNEL ANALYSIS OF SURFACE WAVES (MASW) FOR COASTAL ABRASION MITIGATION AND GEOTOURISM PLANNING AT NANGAI BEACH, NORTH BENGKULU

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Received: April 4, 2025 Reviewed: June 3, 2025 Accepted: July 15, 2025

ABSTRACT

Subsurface rock weakness is considered a contributing factor to the high abrasion rate along Nangai Beach, North Bengkulu. This study aims to characterize the subsurface structure using shear wave velocity (Vs) data derived from Multichannel Analysis of Surface Waves (MASW) at 21 measurement points along the coastline. Data were processed using WinMASW 5.0 Professional software, beginning with dispersion curve picking in the fundamental mode, followed by inversion to generate one-dimensional Vs profiles with associated density and layer thickness. The interpreted 1D and 2D Vs profiles indicate that most of the study area consists of soft rock formations, with generally low Vs30 values, highlighting the area's vulnerability to abrasion. Recommended mitigation strategies include natural restoration through coastal vegetation, construction of protective structures, and implementation of regional zoning to safeguard tourism and residential zones. Furthermore, active community participation in tourism management is essential to achieving a sustainable balance between environmental preservation and economic development. The findings provide valuable input for local governments in designing effective abrasion mitigation strategies and sustainable geotourism development plans.

Keywords: Coastal Geophysics; MASW; Shear Wave Velocity (Vs); Vs30; Geotourism; Nangai Beach; Coastal Mitigation

1. Introduction

North Bengkulu Regency is one of the areas in Bengkulu Province most affected by coastal abrasion. This region is included in the top 70 areas in Indonesia that experience coastal abrasion and extreme waves with significant impacts. Based on research, the erosion rate in some regions of Bengkulu Province is estimated to reach 2.5 meters per year [1],while underwater imaging data show shoreline erosion in North Bengkulu ranging from 1.1 to 5.8 meters per year [2]. This abrasion phenomenon has had a profound impact on the surrounding communities. One of the most affected locations is Nangai Beach in North Bengkulu Regency, where satellite data shows a shoreline shift of up to 2.79 meters per year due to coastal abrasion and erosion (Figure 1). As a result, the tourism area, which has excellent potential for the regional economy, has been severely damaged. In addition, abrasion also threatens public infrastructure, including facilities and infrastructure that support people's daily activities. If not addressed immediately, ongoing abrasion can worsen environmental conditions, threaten settlements, and harm the local economic sector [3]. Therefore, immediate and strategic mitigation actions are essential, such as constructing wave barriers, restoring coastal ecosystems, and raising public awareness on coastal conservation.

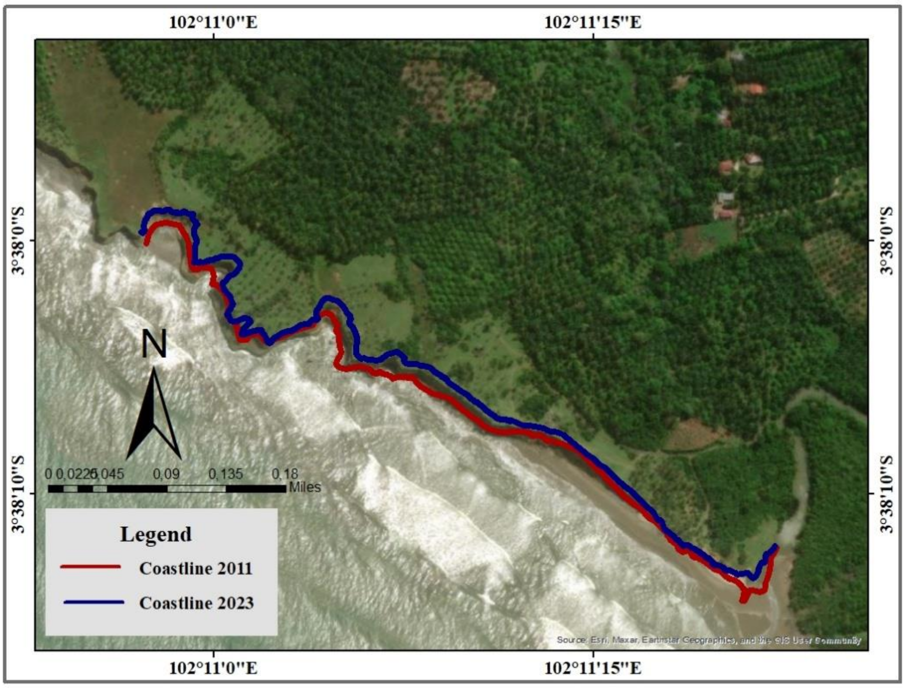

Figure 1. Map of coastline changes based on satellite image data for 2011-2023

Shoreline changes are driven by both natural and anthropogenic factors. Natural processes such as abrasion, sedimentation, sea level rise, and geological variations influence shoreline dynamics and depend on seasonal or annual fluctuations. These factors are closely tied to lithological composition, topography, and hydrodynamic interactions involving waves, tides, and wind [4]. Beaches with sandy or weakly structured soils erode more easily than rocky shores. These changes affect the environment and coastal land use, so careful monitoring is critical [5]. Shorelines composed of unconsolidated materials such as sand or silt are more prone to erosion compared to rocky coasts. Based on previous studies [1], the North Bengkulu Regency area is dominated by sedimentary materials such as sand, gravel, clay, and alluvium with varying densities. The soft soil structure makes this area very vulnerable to deformations such as cracks, settlement, and collapse, which can accelerate the phenomenon of coastal abrasion. Overall, the results indicate that abrasion-prone areas in North Bengkulu have weak subsurface rock structures with low cohesion, making them vulnerable to deformation due to external disturbances.

These geological vulnerabilities emphasize the importance of disaster mitigation, which may be categorized into structural and non-structural measures. Structural mitigation involves engineering interventions such as protective infrastructure, while non-structural approaches encompass regulatory policies and community-based initiatives [6]. To support the sustainability of these efforts, further research is needed to achieve sustainable development goals for the geotourism development of Nangai Beach, North Bengkulu Regency. This research uses the Multichannel Analysis of Surface Wave (MASW) method to obtain the Vs30 profile by analyzing the dispersive Rayleigh surface wave propagation [5].

The main objective of this research is to analyze shoreline changes due to abrasion and its relationship with the Vs30 profile for tourism development at Nangai Beach, North Bengkulu Regency. This research focuses on mapping the subsurface geological conditions that contribute to abrasion. The subsurface geological structure was obtained by interpreting MASW survey results, which resulted in the distribution of shear wave velocity (Vs) at each depth and rock layer. The MASW method, as an active seismic technique, has proven effective in mapping detailed subsurface stratigraphy with minimum misfit values. The analysis of shear wave velocity profiles allows for the identification of lithological layering and material properties, contributing to the formulation of effective mitigation strategies and long-term coastal management plans.

2. Methods

A. Regional Geology

Geologically, Nangai Beach, located in Air Napal Sub-district, North Bengkulu Regency, Bengkulu Province, has varied rock formations. Based on the Bengkulu Sheet Geological Map [7], the area is dominated by the Bintunan Formation (Qtb), which consists of polymictic conglomerate, pumiceous sandstone, siltstone, claystone with plant remains,

lignite inserts, and limestone (Figure 2a). This formation was deposited in a brackish water transition environment during the Plio-Pleistocene period [8].
The soft and brittle characteristics of these sedimentary rocks contribute to the area's susceptibility to coastal processes such as erosion, abrasion, and landslides. The region's topography varies from low-lying coastal plains to undulating inland hills, influencing both drainage patterns and the mechanical behavior of surface materials. The sedimentary rock composition, particularly in coastal zones, increases vulnerability to erosional forces from waves and currents, exacerbating shoreline erosion.

B. MASW Method: Theory, Data Acquisition, Data Processing, and Data Interpretation

This study applied the Multichannel Analysis of Surface Waves (MASW) method at 21 locations along the abrasion-prone zones of Nangai Beach, North Bengkulu Regency (Figure 2b). The initial stage involved a literature review to understand the regional geology, geophysical background, and subsurface material characteristics. Field data acquisition involved the deployment of 24 geophones spaced at 2-meter intervals over a total spread of 48 meters. The geophones, each with a frequency of 4.5 Hz, were connected to a central data acquisition unit via battery-powered cables. A steel plate was struck using a MASW hammer to generate seismic surface waves, which were recorded as shotgathers for further analysis. Prior to measurement, cable connections and instrument integrity were carefully verified.

Data processing was performed using WinMASW 5.0 Professional software (PASI, Torino, Italy) [9]. The software uses genetic algorithms in inversion processing to obtain more accurate Vs profiles in geotechnical and geophysical applications. The analysis process starts with matching the dispersion curve between the field data and the model until it reaches the highest fitness value without further increase, indicating the minimum standard deviation or root mean square error (RMSE). Before converting seismic waves to phase velocity spectra, filtering in the frequency range of 0-50 Hz is performed to generate Rayleigh wave dispersion curves. Once the dispersion curve is formed, an initial model is set up for the inversion process, incorporating parameters such as the number of layers and depth. This process aims to minimize errors, and if accuracy is insufficient, the initial model parameters are adjusted until optimal results are obtained. The final model provides information on shear wave velocity (Vs) profiles, sediment layer thickness, and rock density in 1-D profiles [10].

The Multichannel Analysis of Surface Waves (MASW) method is a high-resolution geophysical technique that utilizes surface waves, particularly Rayleigh waves, to identify the characteristics of rock layers and subsurface geological structures [11]. This method is widely used in geotechnical and geophysical studies because it can provide detailed information about the mechanical properties of soil and rock at various depths. One of the crucial parameters in the geotechnical analysis is the soil bearing capacity (qa), which determines the extent to which the soil can withstand loads before undergoing significant deformation [12]. The ability of the soil to support loads is highly dependent on the shear wave velocity (Vs), which can be measured using the MASW method. In this study, MASW is applied to obtain Vs values with high accuracy. The data processing starts with recording surface waves which are then analysed from time domain to frequency.

Subsequently, this data is converted to the frequency domain against the phase velocity using the Fourier transform, producing a dispersion curve representing wave propagation within the subsurface medium. This dispersion curve becomes the basis for the inversion process, where iterative iterations are performed to obtain geotechnical parameter values that best match the experimental data. The impact of abrasion and erosion in an area is highly dependent on the characteristics of the subsurface rocks identified through Vs analysis.

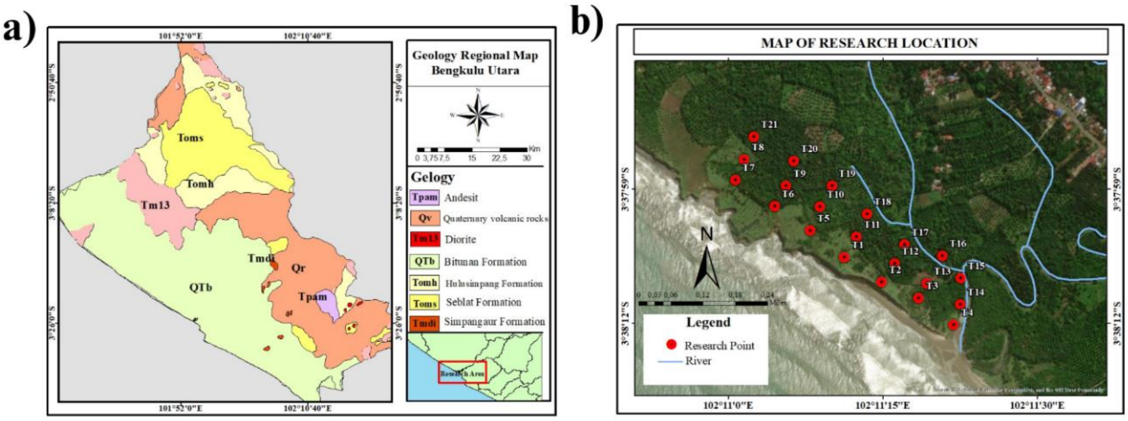

Figure 2. Geological regional conditions of the North Bengkulu Regency area [7] (a) and location of the research area (b).

Table 1. Classification of locations based on shear wave velocity (Vs) obtained from soil investigations and laboratory results, following the standards set by SNI 1726 [18].

No	Site Class	Vs value (m/s)
1	SA	Vs ≥ 1500 (Hard Rock)
2	SB	750 < Vs ≤ 1000 (Rocks)
3	SC	350< Vs ≤ 750 (Hard, very dense soil and soft rock)
4	SD	175 < Vs ≤ 350 (Medium Soil)
5	SE	< 175 (Soft Soil)

By understanding the Vs distribution, it is possible to map the level of soil susceptibility to abrasion and plan more effective mitigation strategies. Therefore, the MASW method not only plays a role in geological exploration but also becomes an important tool in disaster mitigation efforts in coastal areas that are vulnerable to environmental changes due to abrasion and erosion [13].

Shear wave velocity (Vs30) is important in determining soil characteristics [14]. Shear waves can only propagate through solids, causing deformation without changing the rock volume [12]. The Vs30 measurement method is performed by analyzing the propagation time of shear waves from the surface to a depth of 30 meters, which is used to classify soil types [15]. The seismic velocity corresponds to the leading edge beneath the subsurface rocks. Due to the varying composition of the various layers, each layer exhibits a distinctive seismic velocity, usually with consistent intervals [16]. In addition, each layer has a unique stiffness, which causes 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 infer the density and type of rock in the subsurface. The Vs30 classification used in this study follows the Indonesian National Standard SNI 1726 [17] [18], as summarized in Table 1. These classifications are fundamental in determining soil susceptibility to seismic or erosional hazards.

By evaluating the distribution of Vs30 values along the coast, this research aims to determine the geomechanical properties of the subsurface and their influence on abrasion susceptibility. These insights contribute to developing effective mitigation strategies for sustainable tourism and coastal resilience in the Nangai Beach area.

3. Result and Discussion

This study collected data from multiple seismic sources at each study site to ensure representative coverage of subsurface conditions. The 1D model assumes subsurface characteristics vary only with depth without considering possible lateral variations in wave velocity or lithological changes. However, subsurface geological conditions are often more complex, with lateral changes that can affect seismic wave propagation. Therefore, although the 1D model provides a fairly accurate picture in most cases, a more comprehensive interpretation considering other geological factors is required by interpolating the results of the stratigraphic model with 2D modeling.

The MASW analysis at each site identified five primary subsurface layers with varying thicknesses and elastic properties. These variations reflect the geological heterogeneity of the region, which may affect ground’s stability and the seismic response to external loads. By understanding the distribution of these layers, research can provide more accurate information on geotechnical conditions and assist in planning mitigation strategies against geological risks, such as abrasion and erosion in coastal areas. Shear wave velocity (Vs) in the Nangai Beach area, North Bengkulu Regency, was analyzed using 1D stratigraphic model using two modelling approaches. This model was applied to a depth of 30 meters from the ground surface to obtain a more comprehensive picture of the subsurface characteristics. Table 1 presents the Vs. Values are based on the level of hardness and type of rock material. Based on the analysis results, abrasion-prone areas along the Nangai Beach tourist area are dominated by six main rock types: silt, clay, sand, lime, conglomerate, and lignite. In the fifth layer, the sediment structure is denser than the other rock layers. This rock layer can reach several tens of meters thick and is characterized by a gradual increase in mechanical properties with depth. The rock characteristics of the fifth layer are generally very dense soil, soft rock, and highly fractured weathered rock, meaning that rocks with yellow contours are soft rock layers with high fracturing potential. Figures 3 through 9 illustrate the 1D stratigraphy of shear wave velocity at various survey points, providing a detailed depiction of the subsurface variation along the beach zone.

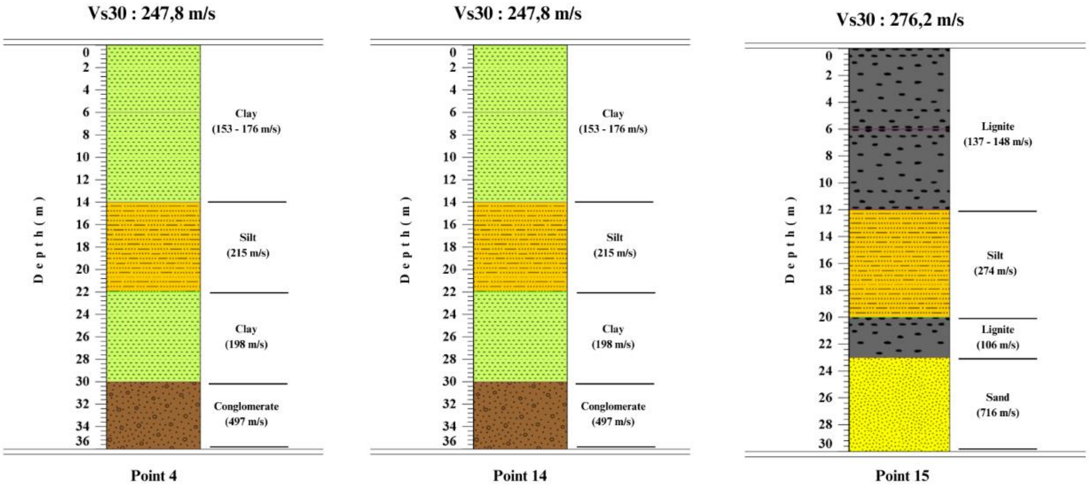

Figure 3. 1D stratigraphic profiles of Vs values at various research points 4, 14, and 15.

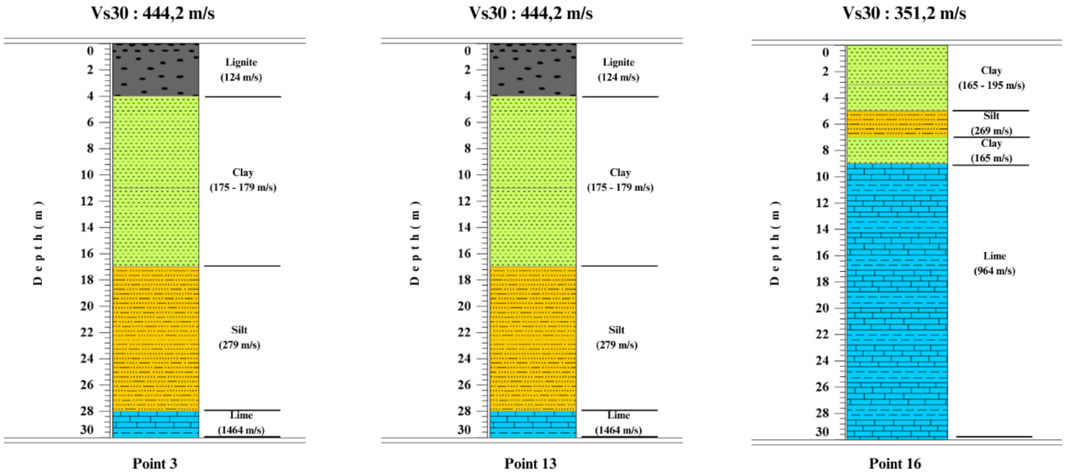

Figure 4. 1D stratigraphic profiles of Vs values at various research points 3, 13, and 16

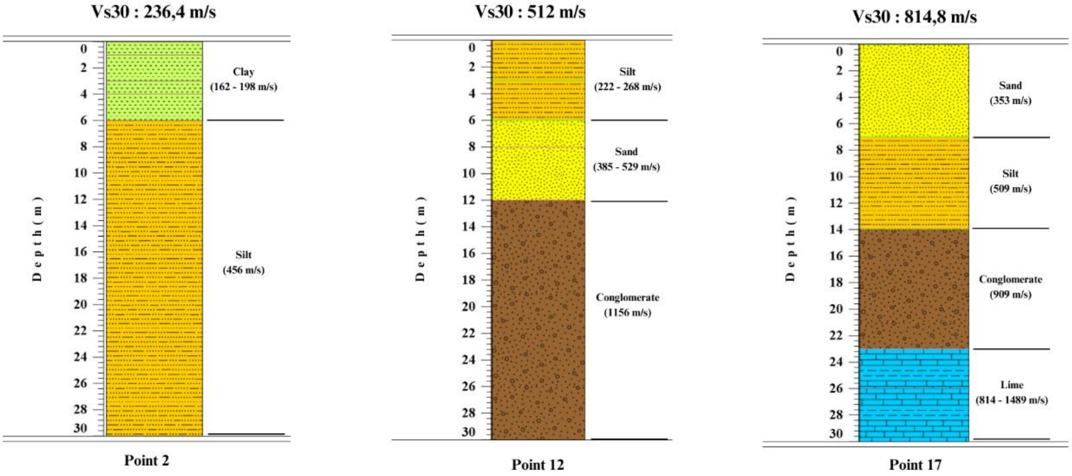

Figure 5. 1D stratigraphic profiles of Vs values at various research points 2, 12, and 17

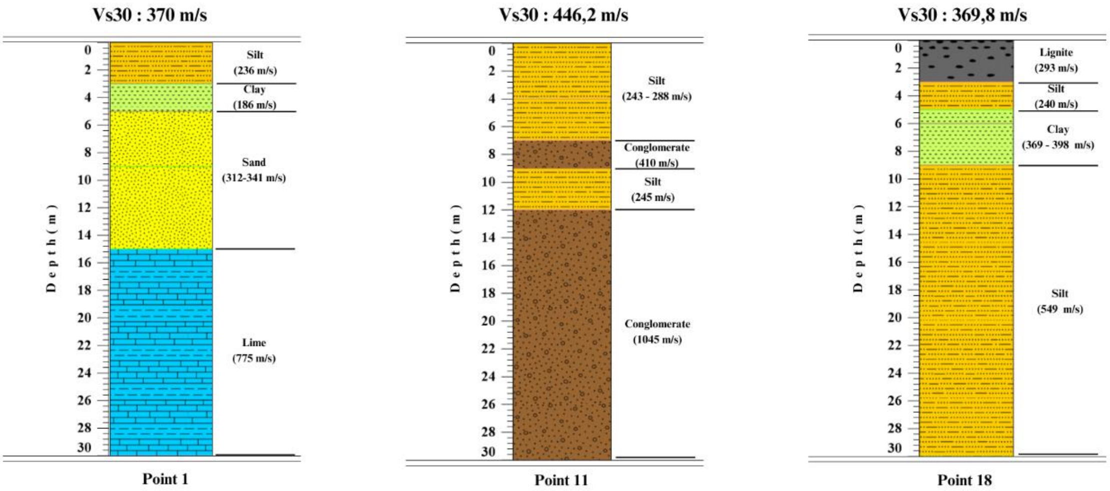

Figure 6. 1D stratigraphic profiles of Vs values at various research points 1, 11, and 18.

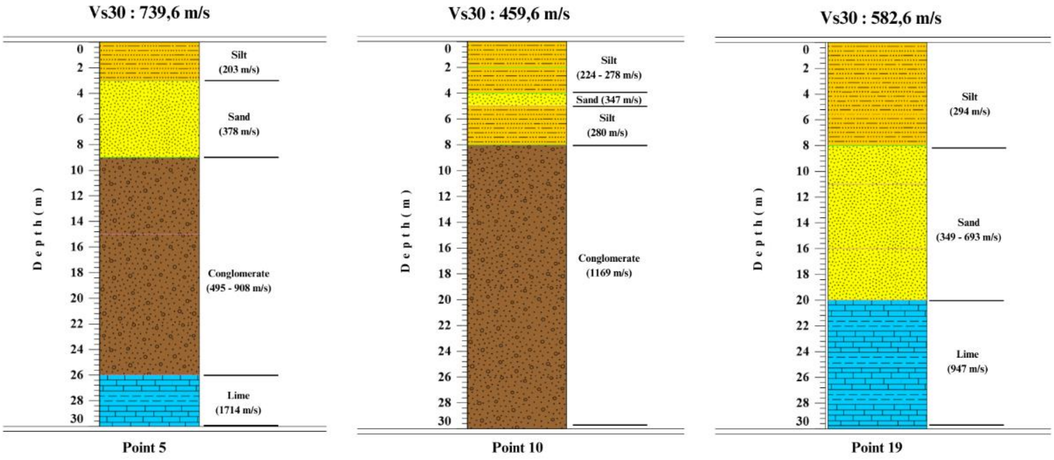

Figure 7. 1D stratigraphic profiles of Vs values at various research points 5, 10, and 19

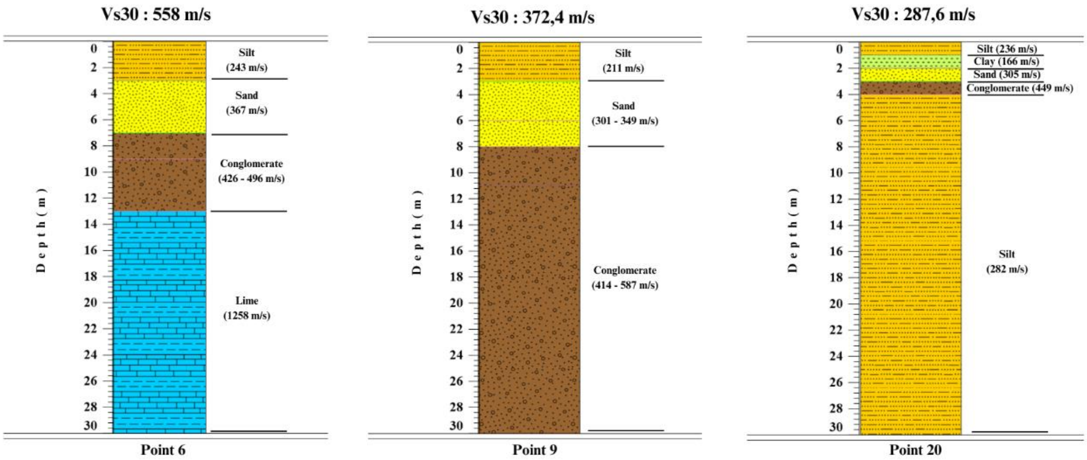

Figure 8. 1D stratigraphic profiles of Vs values at various research points 6, 9, and 20.

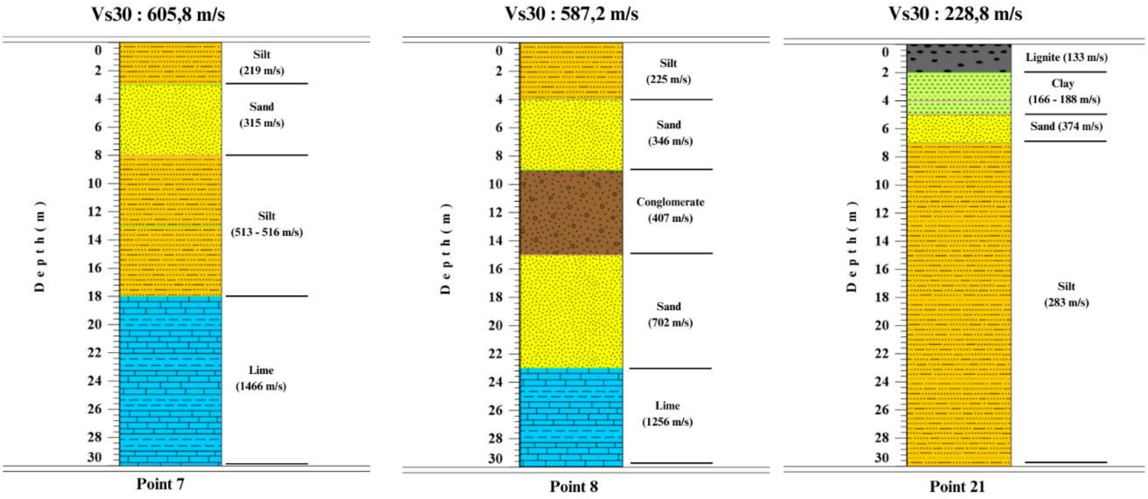

Figure 9. 1D stratigraphic profiles of Vs values at various research points 7, 8, and 21.

The study area is highly vulnerable to abrasion, especially where soft rock formations are exposed to continuous wave activity. The coastal morphology and lithological composition contribute to high erosion rates, which pose threats to local ecosystems, infrastructure, and tourism activities. This research was conducted in an area vulnerable to abrasion due to sea wave activity that continuously hits rock formations with soft characteristics [19]. The geological conditions in this area cause high erosion rates, potentially impacting the environment and human activities in the vicinity [20]. In addition to being an area threatened by abrasion, the research location is also a destination that local people and tourist often visit. Therefore, the results of this study are expected to provide useful information for local governments and communities to improve the safety and comfort of tourism in the area. Based on the results of measurements made in various tracks, the shear wave velocity value (Vs30) is generally low.

This indicates that the most rock formations in the study area have soft characteristics [21]. The study area generally consists of several types of soil and rock layers, namely medium soil, hard soil, soft rock, and rock shown in Table 2. The measurement results in points 2, 4, 14, 15, and 20 show that the Vs30 values are in the range of 236-288 m/s at a depth of 30 meters, indicating that the soil layers in these points belong to the medium soil category (SD). Meanwhile, in points 1, 3, 6, 9, 11, 13, 16, and 18, Vs30 values ranging from 369-558 m/s were obtained, indicating that the soil classification in this area varies between hard soil and soft rock (SC). In travers 17, the shear wave velocity (Vs30) value reached 814 m/s, indicating that the layer is categorized as a rock (SB). Geologically, the Nangai Beach geotourism area, North Bengkulu Regency, has a subsurface rock structure that tends to be unstable, causing abrasion in some areas that have soft rock structures that cannot maintain shoreline stability [22]. Thus, this method has a relationship with shoreline changes caused by abrasion along Nangai Beach, North Bengkulu Regency, with the continuous dynamization of the coastal area being one of the causes of abrasion and shoreline changes as occurred in the west coast of West Sumatra in the study [23].

These classifications align with SNI 1726 standards [24] and reflect the variability of subsurface stiffness, which significantly influences erosion risk. The geotourism zone in Nangai Beach demonstrates subsurface instability in several segments, particularly where soft rocks cannot resist wave impacts leading to accelerated coastal erosion.

Table 2. Interpretation in each points site

No	Site	Vs value (m/s)	Classification
1	Points 2, 4, 14, 15, and 20	236-288	Medium Soil (SD)
2	Points 1, 3, 6, 9, 11, 12, 13, 16, and 18	369-558	Soft Rock (SC)
3	Points 17	814	Rock (SB)

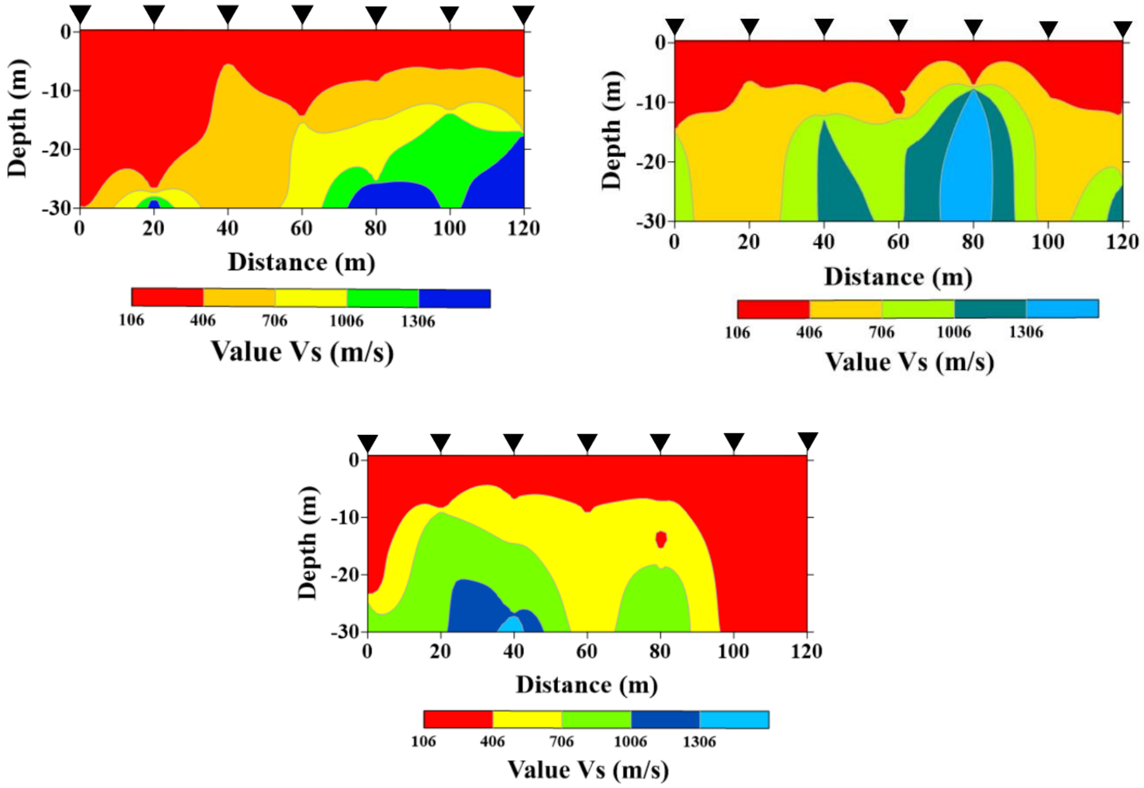

Figure 10. 2D cross-sectional model of the study area

The 2D model (Figure 10) provides an interpolated representation of subsurface conditions across the coastal zone. Areas with Vs < 175 m/s, marked in red contours, are interpreted as soft soils (e.g., clays) with low to medium cohesion. These are highly susceptible to deformation such as cracking, subsidence, and collapse particularly under direct wave impact [25]. The green contours represent moderately stiff soil layers composed of sand, gravel, clay, and alluvium, with better resistance to wave forces. Yellow contours indicate very dense soils or weathered rocks with high fracturing potential, which may still contribute to instability despite their relative stiffness.The MASW results confirmed that hard rock layers at depths of up to 30 meters are only found at a few locations. In general, the identified layers are dominated by soft or fractured materials, reinforcing the region's vulnerability to coastal abrasion.

The high abrasion rate in Nangai Beach is primarily influenced by the interaction between wave energy and the soft subsurface structure. Therefore, mitigation strategies should be multidimensional:

1. Natural mitigation: Coastal vegetation (e.g., mangroves) can enhance shoreline resilience by reducing wave energy and stabilizing sediment.
2. Structural mitigation: Protective infrastructure (e.g., revetments, seawalls) can reduce direct wave impact and erosion risk.
3. Zoning policy: Coastal land-use regulation should prioritize safe zones for tourism and restrict development in high-risk areas.
4. Community involvement: Sustainable tourism should involve the local population to balance ecological preservation and economic benefits.

The results of this study provide essential input for local authorities and stakeholders in designing sustainable coastal management policies. Accurate knowledge of subsurface conditions through Vs30 and MASW analysis can support infrastructure planning, tourism development, and disaster preparedness in abrasion-prone zones.

4. Conclusion

This research concludes that the Nangai Beach area in North Bengkulu Regency is geologically vulnerable to abrasion, primarily due to the dominance of soft and unconsolidated rock formations in the subsurface. The analysis of shear wave velocity (Vs30) using the Multichannel Analysis of Surface Waves (MASW) method indicates that most subsurface layers exhibit low Vs30 values, reflecting weak mechanical properties and limited resistance to dynamic forces such as wave energy. MASW Measurement results show that in several points specifically points 2, 4, 14, 15, and 20 Vs30 values range from 236–288 m/s, classifying them as medium soil (Site Class SD). In contrast, points 1, 3, 6, 9, 11, 13, 16, and 18 exhibit Vs30 values between 369–558 m/s, which correspond to hard soil to soft rock classifications (Site Class SC). Only in points 17 was a significantly higher Vs30 value of 814 m/s observed, which falls into the rock category (Site Class SB). The predominance of medium to soft soils across the study area, combined with dynamic coastal processes such as wave energy and shoreline slope, contributes to the high rate of coastal abrasion. This geological instability poses a threat not only to the natural environment but also to the safety and sustainability of tourism infrastructure in the region. Hence, comprehensive mitigation strategies are needed, including both natural and engineered coastal protection measures. The findings of this study provide critical geotechnical data that can guide regional planning, zoning regulations, and sustainable tourism development to reduce future risk and environmental degradation.

Suggestion

To effectively address the abrasion problem in the Nangai Beach area, North Bengkulu Regency, a combination of planned and sustainable mitigation strategies is essential. One recommended approach is natural restoration through the planting of coastal vegetation, which plays a vital role in stabilizing the shoreline, reducing erosion, and enhancing the beach’s natural resilience to wave energy. In addition to ecological methods, engineering interventions such as the construction of coastal protection structures including concrete embankments, revetments, or retaining walls can serve as effective barriers to absorb and deflect wave energy. These structures help protect vulnerable coastlines and slow the rate of ongoing shoreline erosion. The integration of both nature-based solutions and structural measures is crucial to ensure long-term coastal protection while preserving the ecological and tourism value of the region.

Acknowledgment

We want to thank all parties who have contributed to this research, which is fully supported by the Geophysics Study Program, University of Bengkulu, especially the supervising lecturers who have helped in the data processing process up to the interpretation stage. We would also like to thank the people of Nangai Beach, North Bengkulu Regency, who welcomed us well and warmly during the research. With the implementation of appropriate and sustainable mitigation strategies, the Nangai Beach area can be maintained while providing economic benefits to the local community through environmentally friendly tourism management. This effort not only protects the coastline from the impacts of abrasion but also supports environmentally friendly development for future generations.

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