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Abrasion Investigation Using Shear Wave Velocity and Poisson's Ratio Approaches in Urai Village North Bengkulu Regency

Tiara Sesilia[1,3], Muchammad Farid[1,2,3*], Arif Ismul Hadi[1,2,3*], Andre Rahmat Al Ansory[3]
[1] *Physics Department, Faculty of Mathematics and Natural Sciences University of Bengkulu, Indonesia*
[2] *Disaster Mitigation Study Center, University of Bengkulu, Indonesia*
[3] *Mitigation and Exploration Laboratory. Integrated Faculty Mathematics and Natural Science University of Bengkulu, Indonesia*
Corresponding Authors E-mail: mfarid@unib.ac.id, ismulhadi@unib.ac.id

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Abstract

The coastal areas of North Bengkulu Regency, particularly Urai Village, have been severely impacted by widespread abrasion, posing a high risk of coastal erosion within Bengkulu Province. This study aims to assess the extent of coastal degradation and support disaster mitigation efforts by investigating the properties and structure of rocks using geophysical methods, specifically the Multichannel Analysis of Surface Waves (MASW). The research focuses on determining shear wave velocity (Vs) to model the rock layers and produce a stratigraphic profile with a minimal misfit value. The obtained Vs30 values, ranging from 146 m/s to 603 m/s, indicate that the coastal region primarily comprises soft soils, which are highly susceptible to deformation, including abrasion. These findings provide essential data for understanding the underlying causes of coastal erosion and contribute to future disaster mitigation strategies.

Introduction

Coastal areas are unique because they are transitional zones between land and water, known as ecotones [1]. Coastal resources are frequently exploited without considering conservation, balance, or long-term sustainability, primarily for personal satisfaction and profit. This behavior poses a threat to coastal resources and undermines their potential. The North Bengkulu Regency's coastal area spans approximately 115.9 km of coastline [2]. Coastal regions of North Bengkulu Regency have experienced degradation, mainly due to erosion, which threatens the economic development of communities. Large coastal waves cause sediment to be transported parallel to the shore [3]. Abrasion involves the coastline change due to more sediment being transported from the beach to the sea than from the sea to the beach [4]. Natural and human factors can cause abrasion. Natural factors are influenced by the hydrodynamics of the sea, including currents, waves, and wind [5]. The coastline is eroded by abrasion, resulting from an imbalance in the natural equilibrium of the coast [6]. Sulaiman et al. [7] reported that abrasion has shaped the beaches of North Bengkulu Regency, contributing to their current characteristics. Additionally, Farid (2014) reported that coastal erosion rates in this region range from 1.1 m/year to 5.8 m/year [8]. Located in the coastal region of North Bengkulu Regency, Bengkulu Province, Urai Village has experienced significant erosion, impacting the local population with recurring abrasion disasters. Providing residents with scientific information on abrasion and effective risk reduction measures is essential [10]. As shown in Figure 1, the abrasion disaster in Urai Village is both severe and spreading.

Figure 1. The road conditions in Urai village are broken due to abrasion.

Abrasion in coastal areas can cause three different impacts, including the loss of land that has either economic or ecological value. This loss can include beaches or other areas of similar importance. Additionally, the collapse of layers located on cliffs can occur due to this mechanism [11]. Every second, the waves relentlessly crash onto the shore, eroding the land as they drag soil and sand into the sea and mix it with grains of sand, causing the loss of land [12]. Analysis of natural vibrations in a specific area caused by local geological effects depends on the soil's dynamic characteristics or rock [13]. The characteristics of the soil layer significantly affect the vulnerability index and ground acceleration in a specific area [14]. The potential of liquefaction in areas prone to abrasion in North Bengkulu Regency has been discussed in many previous studies, but not much about the nature and structure of rocks up to a certain depth, known as stratigraphy. To understand the stratigraphy of rocks, it can interpret geophysical method measurements, such as the Multichannel Analysis of Surface Wave (MASW) method. The seismic technique known as MASW (Multichannel Analysis of Surface Wave) is one of the geophysical techniques that can be used to locate subsurface structures. Because the rock layer modeling used to construct the stratigraphy can produce a minimum misfit value, this technique is beneficial for viewing subsurface rock stratigraphy in detail [15].

In this research, the problem to be investigated is about abrasion or coastal erosion caused by subsurface conditions such as weak soil or unstable rock layers. Therefore, it is very important to understand the properties of the layers in the subsurface structure of the area using shear wave velocity values for disaster mitigation efforts. Multichannel Analysis of Surface Wave (MASW) is a non-destructive technique employed to infer images of Vs value from energy associated with surface waves. The method of MASW measurement uses the dispersion of Rayleigh waves to represent underground layers [16]. The MASW interpretation provides a Vs. profile for each depth and rock layer [17]. This study used the MASW method to obtain the Vs value to model the rock layers and produce stratigraphy. Based on the Vs. value, we can estimate the characteristics of each rock layer and the type of material that makes up the rock. Determining Vs can provide valuable insights into the subsurface dynamic conditions [18]. A similar study was conducted by (Refrizon et al, 2019) using the MASW method to analyze subsurface rock structures based on the analysis of Vs values [17]. The seismic vulnerability index is a parameter that can be used to determine an area's vulnerability level to the threat of abrasion risk [19]. The MASW method is therefore particularly suitable for assessing shear wave velocity (Vs), which directly reflects the stiffness and composition of the subsurface material. As soft soils and weak rock layers contribute to higher erosion risks, MASW provides important data to evaluate these risks.

In this research, the analysis of underground rock structures is based not only on shear wave velocity (Vs) but also on shear modulus, Young's modulus, and Poisson's ratio. The shear wave velocity, which reflects subsurface profiles to a depth of 30 meters [20], offers critical insights into the geological conditions beneath coastal abrasion areas. This information is valuable for understanding the underlying causes of coastal erosion and can benefit local communities affected by abrasion and researchers working in related fields. The findings from this study could serve as a reference for future geophysical, geochemical, and geological research, contributing to better management and mitigation strategies for coastal erosion in Urai Village, North Bengkulu Regency.

Theory and Calculation

Shear wave velocity (Vs)

Shear wave velocity (Vs) is important in determining soil dynamic conditions. Simply put, shear wave propagation through rock will be polarized (φ) into two parts when propagating through different medium structures, such as fractures. One method that can be used to evaluate Vs is to calculate the average Vs value based on the propagation time from the surface to a depth of 30 m [21]. Vs values are interpreted based on table 1 which is the data from previous study.

Table 1. Vs. values in various materials near the surface [22].

No	Geomaterial	Vs (m/s)
1	Crystalline rocks	2500-3500
2	Calcareous, fractured rocks	1000-1500
3	Soft rocks, very dense gravel	500-1000
4	Medium to dense gravel	400-800
5	Medium to dense sands	200-400
6	NC clays and silts	150-300
7	Very soft clays	50-100

Shear Modulus of the Rock

Shear modulus is a significant material quantity that represents the ratio of shear stress to shear strain. A higher shear modulus value means that the material is stiffer because a greater shear stress is required to achieve the same shear strain [23]. The shear modulus (G) value can be determined by obtaining field measurements of the Vs. The shear modulus is defined as the ratio of the applied shear stress to the applied shear strain. The value is influenced by various factors such as the type of soil, applied stresses, dynamic strain rate, degree of saturation, load frequency, and number of dynamic loading cycles [24]. The shear modulus (G) value can be determined by obtaining field measurements of the Vs. Obtaining the equation requires knowledge of the relationship between shear modulus (G) and stress-strain modulus (E) [25].

$$G = \rho.(Vs)^2 \quad (1)$$

Where:

G = Shear modulus (MPa)
ρ = Density (Kg/m^3)
Vs = Shear wave velocity (m/s)

Young's Modulus of the Rock

The sonelastic equipment measures the acoustic response resulting from mechanical impulses and determines Young's modulus through stress-strain curves. Young's modulus is influenced by rock characteristics such as petrographic structure, degree of weathering and alteration, void index, porosity, elastic and plastic properties [26]. The elastic modulus (Young's modulus) represents the relationship between normal stress and normal strain. The modulus of elasticity is the stress-to-axial strain ratio of the soil. Axial strain is the proportion of vertical deformation to initial height [24].

$$E = 2\ (\rho.(Vs)^2\ ))(1+\sigma) \quad (2)$$

Where:
E = Modulus of Elasticity (MPa)
ρ = Density (Kg/m^3)
Vs = Shear wave velocity (m/s)
σ = Poisson's ratio

Poisson's Ratio of the Rock

Poisson's ratio (σ) is an elastic constant found in every material. It can be used as a parameter to determine the condition of the material or soil in a particular area. If a force is applied to a material, the material will deform. Poisson's ratio (σ) is also known as the elastic property of rocks, and can indicate the degree of rock collapse. Poisson's Ratio (σ) values for various materials interpreted based on the classification by [27].

Methods

The study took place in 2024 and focused on the erosion area in the coastal region of Urai Village, located in the Ketahun District, North Bengkulu Regency. The geographical conditions in the area are formed by the Bintunan Formation lithological unit and the Alluvium unit, creating an undulating hilly plain facing the sea. The study recorded measurements at 10 distinct points within the erosion area, as shown in Figure 2, the red point are measurement points starting from the lowest point to the highest point, namely T1, T2, T3, T4, T5, T6, T7, T8, T9 and T10.

Figure 2. Research Area Map.

The nature and condition of subsurface rock layers can be determined by analyzing geophysical method measurements, such as the active seismic method, using a 24-channel seismograph with the MASW method. MASW interpretation provides profiles of Vs for each depth and rock layer.

The first research stages are survey of the research site, site survey was carried out to assess the eroded area's geological state and define the investigation's position. Then data acquisition involved utilizing a 24-channel Seismograph equipped with the Multichannel Analysis of Surface Wave (MASW) technique at 10 different measurement locations within the degraded region. After all the data is done, then data processing using WinMASW software to acquire shear wave velocity (Vs) values. In this studi, analyzed the shear wave velocity profile to interpret the data and establish the subsurface rock structure down to 30 meters. The identification of subsurface rock types relied on the shear wave velocity, shear modulus, Young's modulus, and Poisson's ratio values. The analysis of Rayleigh wave data recorded through retrieval and inversion leads to the creation of dispersion curves. The curve displays different colored lines, including pink, green, and blue. The pink line represents the retrieval results, the blue line is the best retrieval model, and the green line is the intermediate model between the best model and the mean model. The best model displays the Vs profile value, and the mean model is indicated by the point where the blue and red lines intersect. The misfit value is observed until it reaches a value close to zero indicating that the error in the retrieval process has been minimized. Following the acquisition of the Vs value and Poisson's Ratio value, the Shear Modulus and Young's Modulus values were calculated using equations (1) and (2). This study, analyzed the Vs profile to interpret the data and establish the subsurface rock structure down to 30 meters. The identification of subsurface rock types relied on the shear wave velocity, shear modulus, Young's modulus, and Poisson's ratio values. The research stages show in figure 3.

These values were then analyzed according to the classification of Vs values in different materials near the surface. The dispersion curve is generated by graphing the information that connects phase velocity to frequency and then picking out data points on the dispersion curve. After that, the inversion process is conducted to generate the 1-dimensional Vs. The MASW measurement data underwent processing to derive the Vs measurement. This measurement is utilized to assess the categorization of abrasion-prone land surface areas in Urai Beach according to [28]**.** Data processing is shown in Figure 4.

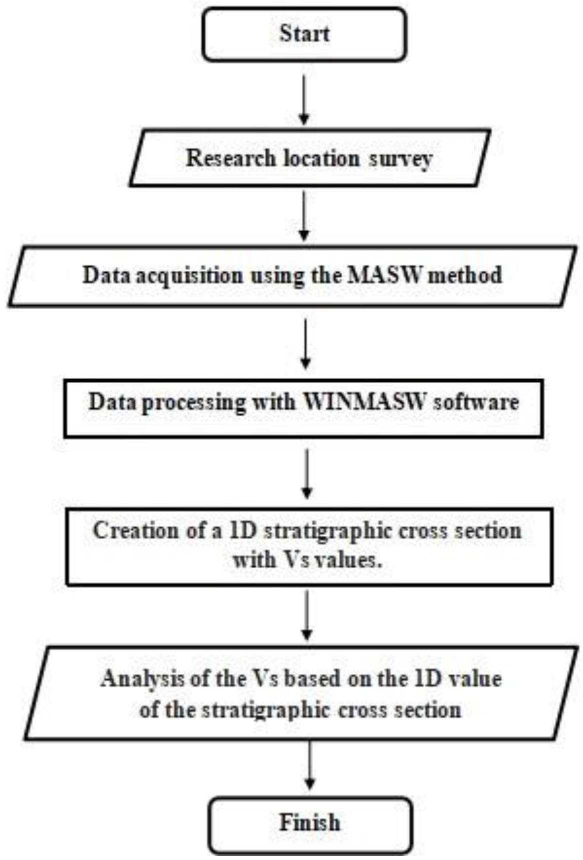
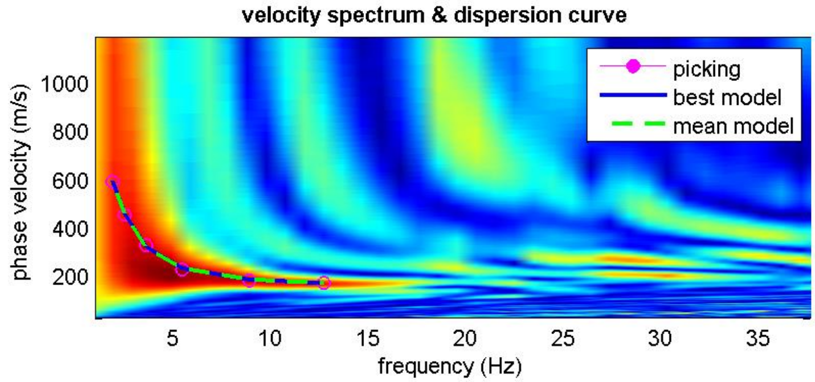
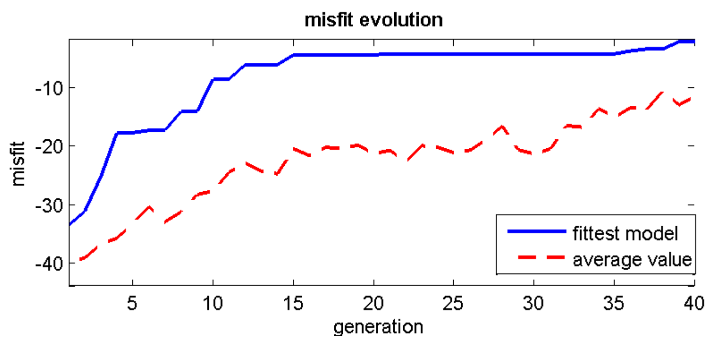


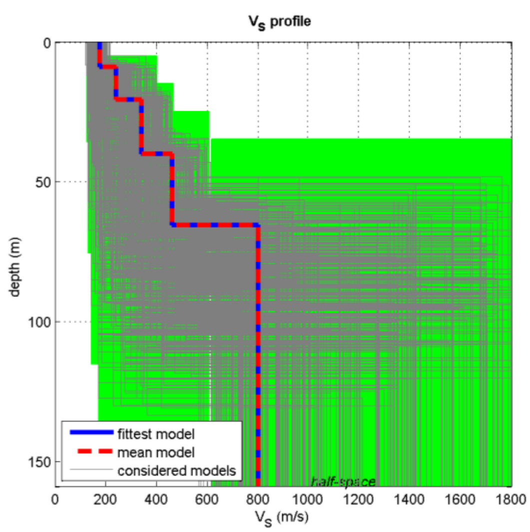
Figure 3. Research Stages flowchart.



(a)



(b)



(c)

Figure 4. (a) The dispersion curve shows the relationship between frequency and phase velocity, (b) Misfit Curve, (c) Vs Profile.

Result and Discussion

Vs profile at each research point

The best model is represented by the Vs profile value, while the point where the blue and red lines intersect indicates the average model as shown in Figure 5.

The Vs profile describes how the velocity of shear waves changes within a medium or along it. A physical of Vs profile describes how the shear wave propagation velocity changes in the medium being studied. Vs profile values are displayed for the best model, and the average model is represented by the point where the blue and red lines intersect. Each subsurface soil layer has a different degree of hardness, shown by the Vs values varying up to a depth of 30 meters. In the 1D modeling profile, different colors represent different soil densities and thicknesses for each layer. This means that for each Vs value, the average velocity of shear waves at a depth of 30 meters can be determined.

Values of Shear Wave Velocity, Shear Modulus, Young's Modulus and Poisson's Ratio

Each subsurface soil layer has a different level of hardness, indicated by the Vs values that vary up to a depth of 30 meters. The average Vs at a depth of 30 meters can be calculated for each Vs value. Table 2 shows the values of Vs, shear modulus, Young's modulus, and Poisson's ratio from the field data processing results. These values show the differences in each layer at the point of investigation. It can be seen that each survey point has different layers, some have 4 layers and some have 5 layers. This is also based on the conditions in the field, as can be seen in Figure 6-16 that each point has a different arrangement, so when processing the data it is adjusted to the location conditions of the measurement points in the field.

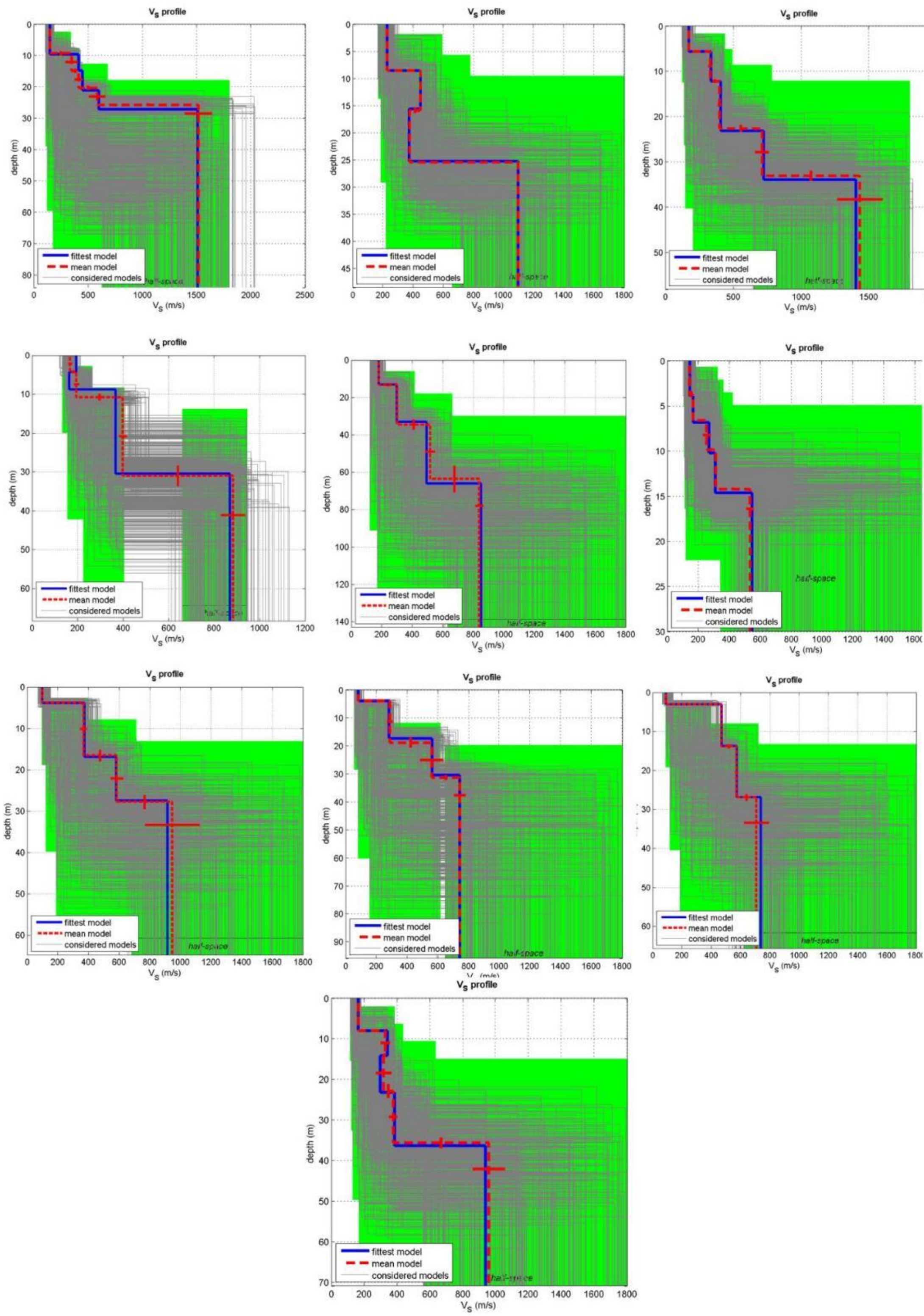


Figure 5. Vs profile at each research point are displayed for the best model, and the average model is represented by the point where the blue and red lines intersect.

Table 2. Table of Shear Wave Velocity, Shear Modulus, Young's Modulus, and Poisson's Ratio of each layer.

Research Point	Layer	Vs (m/s)	Shear Modulus (MPa)	Young's Modulus (MPa)	Poisson's Ratio
1	1	149	40	113	0.41
	2	347	241	680	0.41
	3	412	340	948	0.39
	4	583	714	1941	0.36
	5	1514	5272	14339	0.36
2	1	228	99	276	0.4
	2	447	400	1086	0.36
	3	376	282	758	0.34
	4	1095	2758	7501	0.36
3	1	172	53	148	0.39
	2	330	218	588	0.35
	3	399	318	866	0.36
	4	711	1112	3025	0.36
	5	1432	4716	12734	0.35
4	1	228	99	282	0.43
	2	447	400	1023	0.28
	3	376	282	729	0.29
	4	1095	2757	7446	0.35
5	1	180	62	173	0.41
	2	302	173	464	0.34
	3	517	561	1493	0.33
	4	839	1548	4212	0.36
6	1	143	37	105	0.42
	2	165	50	132	0.35
	3	253	122	333	0.37
	4	312	185	500	0.35

	5	532	595	1617	0.36
7	1	99	17	46	0.39
	2	368	271	737	0.36
	3	586	721	1947	0.35
	4	948	1977	5299	0.34
8	1	99	17	47	0.42
	2	368	271	721	0.33
	3	586	721	1933	0.34
	4	948	1977	5378	0.36
9	1	82	11	32	0.4
	2	287	157	426	0.36
	3	559	656	1785	0.36
	4	741	1208	3310	0.37
10	1	163	48	133	0.39
	2	328	215	590	0.37
	3	317	191	504	0.32
	4	375	281	765	0.36
	5	956	2010	5429	0.35

Table 3 shows the Vs30 value at each measurement point, where Vs30 refers to the value of the wave speed at a depth of 30 meters. The Vs30 value is obtained from the results of data processing using WINMASW software, which can be seen in the table below.

Table 3. Vs_{30} Value

Research Point	**Vs_{30} (m/s)**
1	288.83
2	358.46
3	311.02
4	358.46
5	146.34
6	297.10
7	603.34

8	316.44
9	226.59
10	218.98

1-Dimensional Stratigraphy of Shear Wave Velocity (Vs)

The 1D profile displays several colors representing different layers, and the 1D profile image consists of 4 to 5 layers. Each soil layer has a different Vs value up to a depth of 30 meters. Table 4 shows the range of shear wave velocity and lithology interpretation of each research point. The figure below illustrates a comparison of the Vs value of the 1D stratigraphic cross section with the condition of the abrasion site.

Table 4. Range of Shear wave Velocity and Lithology Interpretation

No	Classification	Range Shear Wave Velocity (m/s)	Lithology Interpretation
1	Low	< 447	Soil
2	Medium	287 - 447	Clay
3	High	517 - 711	Silt
4	Very High	>711	Napal

Each research point has different layers, which can be seen from the 1D stratigraphy at each point and the real conditions. The interpretation is based on the shear wave velocity value at each investigation point. T1 and T3 have 5 layers, namely soil, clay, clay, silt and marl. T2 has 4 layers of soil, clay, silt and marl. T4 has 4 layers of soil, clay, silt and marl. T5, T7, T8 and T9 consist of 4 layers of soil, clay, silt and marl. T6 consists of 5 layers, namely 3 layers of soil, clay and marl. While T10 consists of 5 layers, namely soil, 3 layers of clay and marl. At each point there are several layers that are doubled because the range of Vs values is not very different or still in one range and is adapted to the real conditions in the field. This can be seen in Figure 6-15.

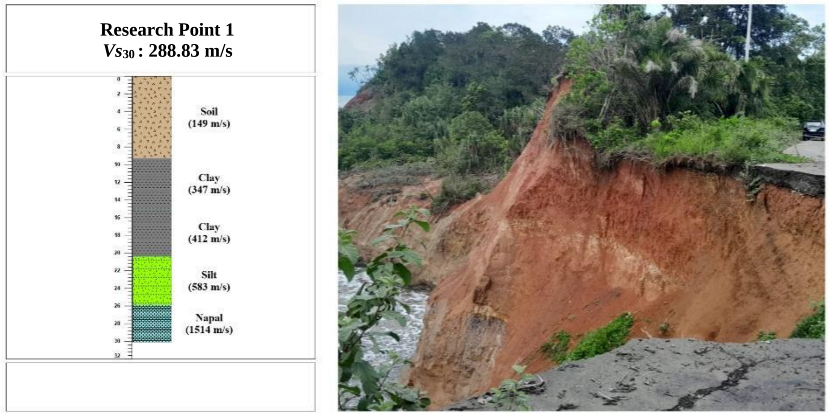


Figure 6. 1D stratigraphic of the Vs value at research point 1.

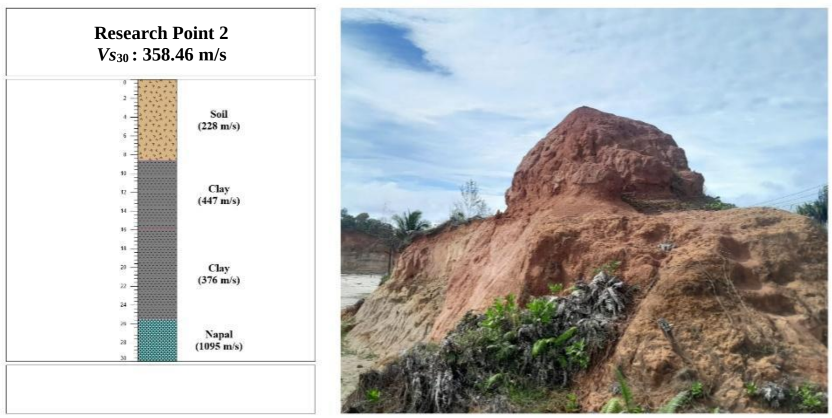


Figure 7. 1D stratigraphic of the Vs value at research point 2.

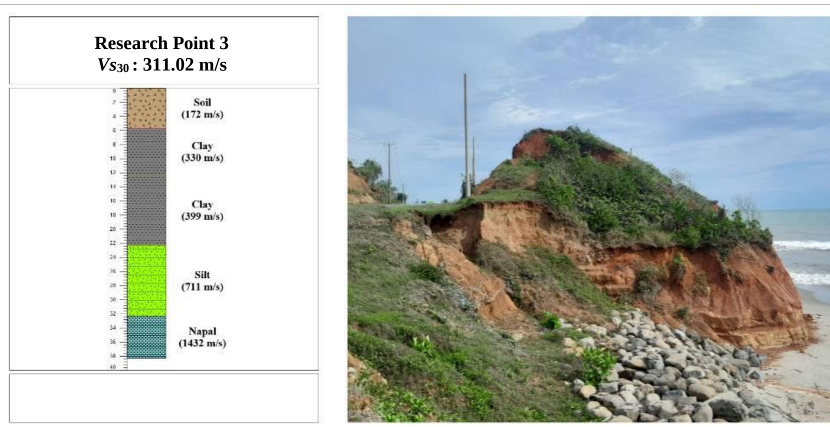


Figure 8. 1D stratigraphic of the Vs value at research point 3.

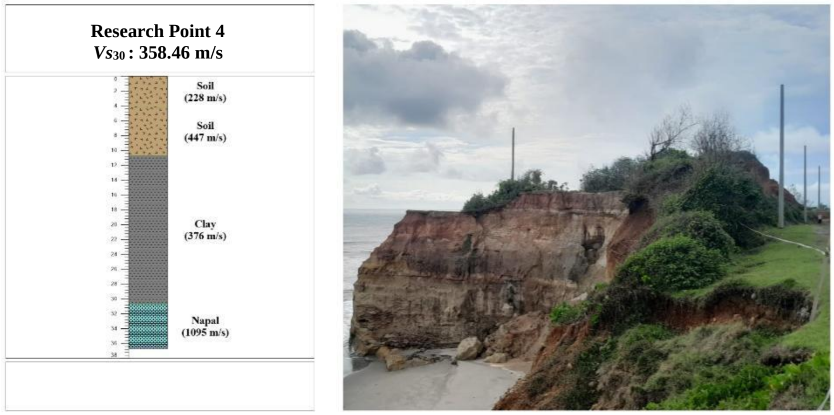


Figure 9. 1D stratigraphic of the Vs value at research point 4.

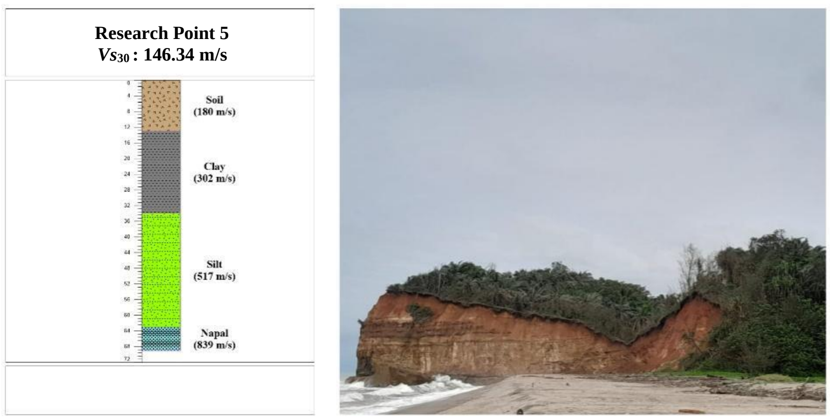


Figure 10. 1D stratigraphic of the Vs value at research point 5.

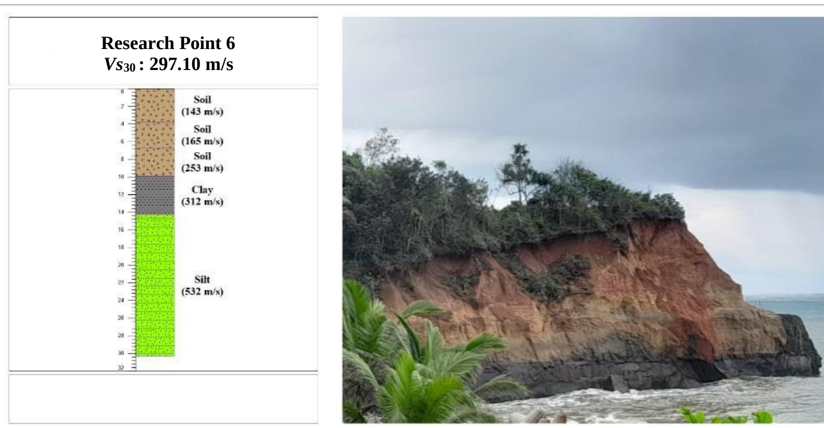


Figure 11. 1D stratigraphic of the Vs value at research point 6.

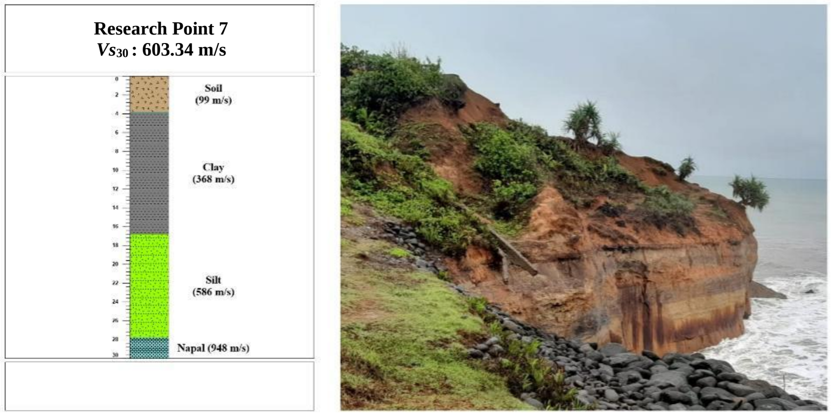


Figure 12. 1D stratigraphic of the Vs value at research point 7.

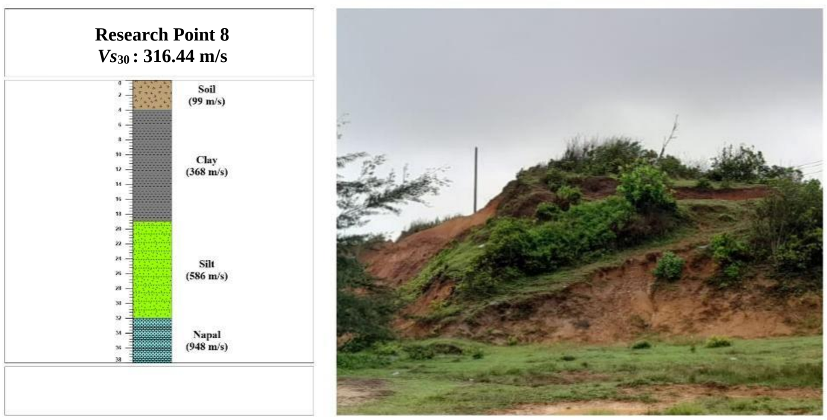


Figure 13. 1D stratigraphic of the Vs value at research point 8.

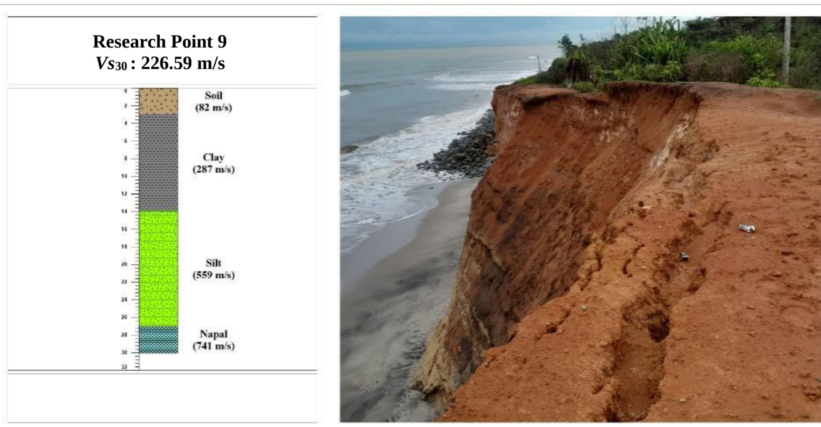


Figure 14. 1D stratigraphic of the Vs value at research point 9.

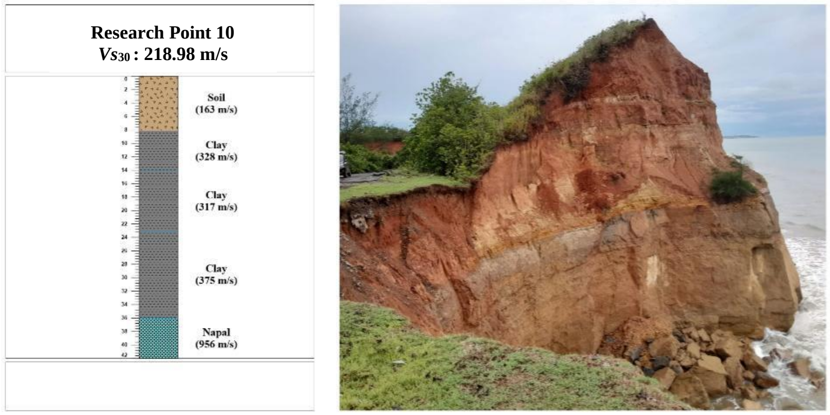
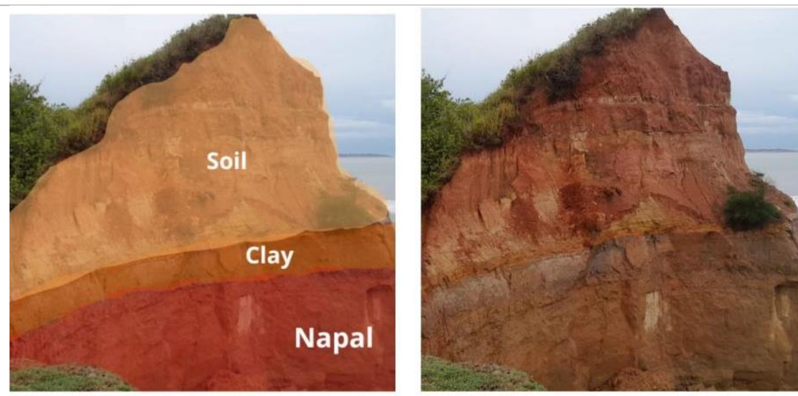


Figure 15. 1D stratigraphic of the Vs value at research point 10.



(a) (b)

Figure 16. The stratigraphy of the coastal area of Urai Beach (a) interpreted and (b) uninterpreted.

The figure (16) shows the interpretation result of the coastal area that has experienced abrasion. The interpretation shows that the area consists of three layers: soil, clay and marl. The first layer, which is most susceptible to weathering, is responsible for the abrasion.

Stratigraphy describes the rock layers vertically, while shear wave velocity indicates the nature of the subsurface rocks. The 1D model only provides information on Vs values interpreted to a depth of 30 meters from the surface. The Vs30 results range from 146 m/s to 603 m/s. Based on the findings of the Vs30 data, points T1, T3, T5, T6, T8, T9 and T10 all have fairly low Vs30 values, ranging from 175 to 350 m/s and according to [29] are included in the medium soil category. This is in line with previous research conducted by (Farid, 2024), in the coastal area of Central Bengkulu which shows that most of the coastal areas of Central Bengkulu have moderate soils, with Vs30 values ranging from 175 to 350 m/s [30]. This means the coastal area in Urai Village is vulnerable to various types of deformation when exposed to ocean waves. As a result, the coastal area in Desa Urai is prone to erosion.

The shear modulus and young modulus values depend on the shear wave velocity and density values. Higher shear wave velocity (Vs) and density values correspond to higher shear modulus and young modulus values, and vice versa. However, Poisson's ratio value is independent of shear wave velocity and density values. A higher shear wave velocity, shear modulus, Young's modulus, and Poisson's ratio value indicate that the rock is hard, while a lower shear wave velocity, shear modulus, Young's modulus, and Poisson's ratio value indicate that the rock is soft. Higher shear wave velocity indicates a higher elasticity value of the rock. Materials with less density and more tenuous structure have a lower elastic modulus compared to denser and more consolidated materials. Consequently, lower rock elasticity implies that the rock is more susceptible to abrasion.

Conclusion

The subsurface structure in Urai Village can be categorized as rigid soil. Rigid soils are generally more resistant to abrasion than softer soils and can influence shoreline shapes and wave patterns. When more complex soils form the coastal structure, they can modify water flow, impacting the abrasion process. However, the shear wave velocity (Vs) values indicate that lower elasticity is associated with lower Vs, suggesting softer layers in some parts of the area. Based on the shear wave velocity (Vs, Vs30), Poisson's ratio, shear modulus, and Young's modulus, it can be concluded that the coastal area of Urai Village is vulnerable to various types of deformation, making it susceptible to abrasion.

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