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Coastal Abrasion Vulnerability of the Southern Seluma Regency, Bengkulu, Based on Seismic Properties and Parameters Elasticity

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Abstract - Geophysical investigations were conducted in the coastal area of Seluma Regency using Multi-Channel Analysis of Surface Waves (MASW) to determine subsurface geology, material stiffness, and potential weak zones to a depth of approximately 30 m. This study aims to identify and map the susceptible areas to abrasion in Seluma Regency coastal region and to analyze the causal factors associated with parameters elasticity of subsurface rocks. Data acquisition, processing, and inversion have been parameterized and selected to produce shear wave velocities representing actual subsurface conditions using Win-MASW 5.0 Professional software. The shear wave velocity analysis shows that the coastal area of Seluma Regency has the potential for high and moderate ground deformation which is vulnerable to abrasion. The area with high deformation potential is the Air Periukan Sub-Regency, Seluma Regency, Indonesia.

Keywords: Abrasion, Win-MASW 5.0, Poisson Ratio, Shear Modulus, Young Modulus, Shear Wave Velocity, Reyleigh Wave Velocity

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Introduction

Most regencies in Bengkulu Province directly border the coast (BPS, 2022). One of the regencies that border directly the coast is Seluma Regency. The coast, as a transition area between land and sea in Seluma Regency, has great potential for natural disasters, one of which is abrasion. The existence of this coast makes that regency as an area prone to abrasion. Abrasion is a natural disaster that needs to be seriously monitored. Coastal abrasion is resulted from an imbalance between oceanographic and geological factors. Oceanographic factors include ocean currents, waves, and tides, while geological factors pertain to the rocks that make up the coastal area and the beach morphology. Therefore, abrasion occurs when oceanographic factors overpower geological factors, whereas sedimentation occurs when geological factors dominate over oceanographic factors (Morton, 2003).

Research on abrasion along the coast of Bengkulu Province has been carried out by several researchers, including Suwarsono *et al*. (2011), Oktami (2016), Supiyati *et al*. (2017), Hasanudin and Kusmanto (2018), Refrizon *et al*. (2019), Lubis *et al*. (2021), Maulana *et al*. (2021), and Lubis *et al*. (2022). The rate of abrasion in several locations in Bengkulu Province, particularly in North Bengkulu, is approximately 2.5 m/year

(Suwarsono *et al*., 2011). This is supported by findings indicating that the stratigraphy in the abrasion-prone areas of North Bengkulu consists of weak soil types susceptible to abrasion (Refrizon *et al*., 2019). The presence of abrasion in North Bengkulu is also confirmed by a research from Lubis *et al*. (2022), showing that longshore currents are one of the causes of abrasion in this area. Additionally, high sea waves can accelerate the abrasion process (Lubis *et al*., 2021). In contrast, based on the results from Maulana *et al*. (2021), the abrasion rate in Bengkulu City was 2.823 m/year, caused by an intensive wave action at the base of coastal cliffs and high rainfalls (Hasanudin and Kusmanto, 2018). In the southern part of Bengkulu, abrasion rates range from 6.19 to 9.59 m/year (Oktami, 2016). In Kaur Regency, over the past ten years, the abrasion rate has ranged from 12.63 to 18.48 m/year (Supiyati *et al.*, 2017).

Previous research has shown that almost all regencies located on the coastal Bengkulu Province are prone to abrasion, with significant rates of abrasion in several key locations. However, a research on the potential for abrasion along the coast of Seluma Regency has not been conducted. Based on survey results, the coastal area in Seluma Regency is utilized by the surrounding community for tourism, settlements, rice fields, oil palm plantations, and other activities that are essential for meeting their daily needs. The coast, as a transitional area, significantly affects the regions bordering it (Lokollo *et al*., 2020). The utilization of coastal areas by human activities changes their morphological vulnerability, increasing the potential for abrasion.

Seluma Regency, intersected by the Sumatran Fault, has various rock formations. In the onshore area, there is the oldest Tertiary rock type comprising the Hulu Simpang Formation, which consists of lava, volcanic breccia, and tuffs. Additionally, the onshore area is occupied by Quaternary volcanic rocks, Bintunan Formation consisting of volcanic rock, the Seblat Formation comprising claystone and mudstone, limestone, and sandstone, and the Lemau Formation composed of claystone, calcareous claystone, coal seams, sandstone, and conglomerate. In another location, the offshore area consists of alluvium terraces, alluvium, swamp deposits, and the Bintunan Formation (Panggabean and Haryanto, 2009).

The offshore area in Seluma Regency is a vital zone that needs to be studied. In coastal areas, if the offshore zone has weak rock conditions and the oceanographic factors are substantial, it is prone to abrasion. To mitigate the disaster in Seluma Regency, one of the steps to discover the subsurface conditions of potential abrasion areas is to analyze the elasticity parameters. Fundamentally, an area is prone to abrasion if the elasticity of the subsurface rock is low, as it will easily deform.

Further analysis of the subsurface lithology is needed to determine the abrasion potential. Therefore, to obtain a comprehensive analysis, rock site classification (SNI 1726:2019, 2019) is linked to the determination of subsurface lithology based on a table of rock mass density values (Telford *et al*., 1931). Additionally, rock site classification and the table of rock mass density values are correlated with the geological conditions of the subsurface rock to obtain accurate results. Based on these correlations, the elasticity parameter is determined. This parameter reflects the force exerted on a material that causes a change in shape (Zanetta *et al*., 2021). In this study, the elasticity parameters used include shear modulus, Young's modulus, and Poisson's ratio for each subsurface rock lithology along the coast of Seluma Regency.

The research was conducted on the coast of Seluma Regency, with the research locations depicted in Figure 1. The initial stage of this research involved a field survey to determine specific measurement points, with five points selected to represent each type of rock found along the coast of Seluma Regency.

Methods and Materials

One of the geophysical methods that can be used to determine subsurface elasticity param-

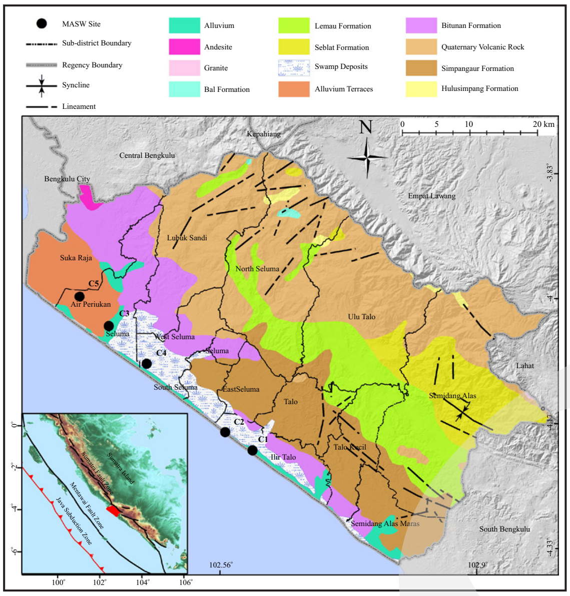

Figure 1. Geological map of the study area (Gafoer *et al.,* 2007).

eters is the Multichannel Analysis of Surface Waves (MASW) as illustrated in Figure 2. This method can determine seismic properties and their influence on abrasion on the coast of Seluma Regency by analyzing subsurface structure and stratigraphy. In addition, MASW accurately determines the dispersion curve of field data (Craig and Hayashi, 2015) and can transform field data from the time-space (t-x) domain to the frequency-velocity (f-v) domain (Park *et al*., 1998).

MASW utilizes Rayleigh waves that propagate below the surface generated by hammer blows and anvils. These waves depend on the medium's properties, wave frequency, and the distance between the source and the ground motion detector (Yeluru, 2013). The waves generated by the hammer and anvil are detected by geophones, allowing measurement of wave travel times through each subsurface soil medium. MASW leverages the interaction between P waves (primary waves, which arrive first and have the highest speed) and S waves (secondary waves, arriving after P waves) to analyze particle motion and wave propagation characteristics (Crice, 2002). In this research, a Seismograph 24 Channels PASI Model 16S24P with a 2-meter spacing and 5-meter offset was used. Field data collected were processed using Win-MASW software (see Figure 3). Data processing involved inputting field data into Win-MASW 5.2 Professional software. The next steps included wave picking to isolate recorded waves from noise (Figure 3.a), velocity spectrum determination, and dispersion curve analysis using the fundamental node (Figure 3.c) (Eliosoft, 2012).

Theoretical dispersion curves were computed assuming an elastic, homogeneous, and isotropic layered earth model. Initial models assigned physical properties such as Vs, Poisson's ratio, and layer thickness, with the bottom layer modeled as a half-space. The best-fit theoretical dispersion curve was iteratively updated using Genetic Algorithms (Gas) based on L2-norm objective function evaluation (Dal Moro *et al*., 2007). The f-v spectrum of the dispersion curve extracted from Win-MASW was inverted to estimate subsoil properties (Figure 3.b). Dispersion curves represent phase velocities at specific frequencies, primarily from Rayleigh waves that contribute predominantly to the vertical components of noise. The estimation process involved proposing maximum and minimum velocity and frequency limits to develop a 1D shear wave velocity profile based on empirical data (Eliosoft, 2012). The Rayleigh wave velocity profile was derived from the Vs profile. Vp classification

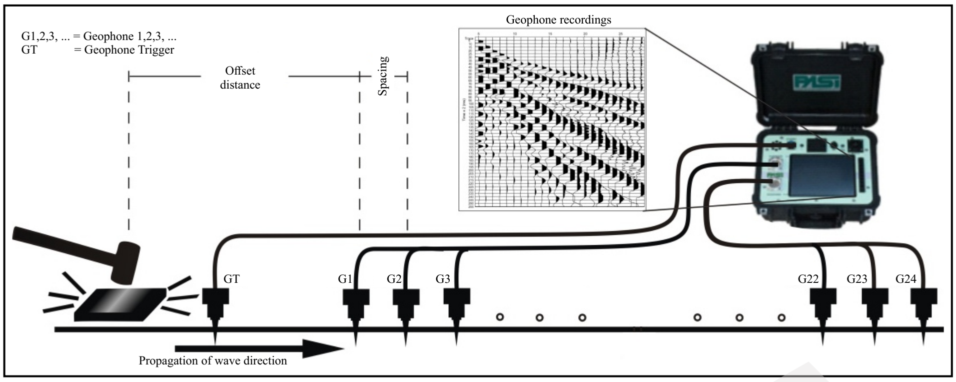

Figure 2. MASW data measurement configuration in the field using Seismograph PASI Mod. 16S24-P s.n. 121217044 (modified from (Rusydy *et al.,* 2016).

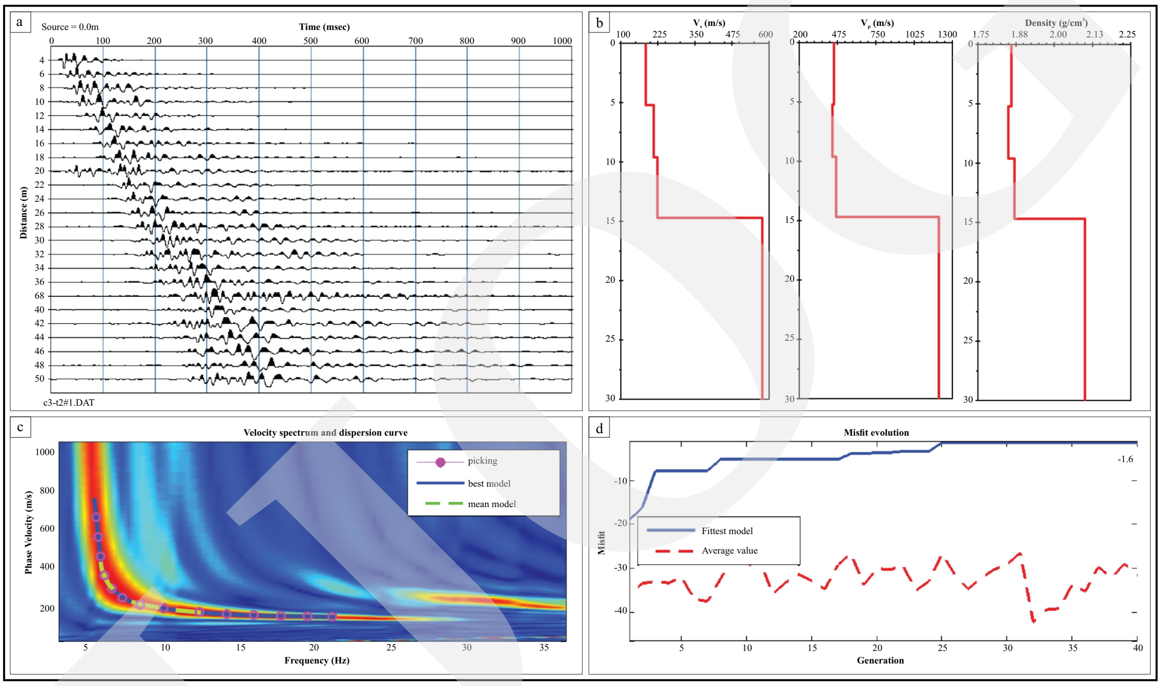

Figure 3. C1 data processing. a). Seismic recording of 24 channels MASW method with 2 m distance between geophones and 5 m offset; b). 1-D subsurface model with Vs, density, and layer thickness value; c). The velocity spectrum and dispersion curve; d) The results of picking the dispersion curve with the minimum RMSE and best misfit.

in this study followed Hadi's (2019) findings. Additionally, Win-MASW processing provided elasticity parameter values such as density, shear modulus, Young's modulus, and Poisson's ratio specific to the study site.

Results and Discussion

This study utilized five measurement points (Figure 1). Measurements were conducted at each point five times, and the best measurement result from each point was processed using Win-MASW 5.0 Professional software.

The 1-D results of data processing using Win-MASW 5.0 Professional software are shown in Figure 4. In this study, each point contains values of Vs (m/s), density (g/cm³), and thickness (m). Additionally, all 1-D data were interpolated into a single map, with each map consisting of 4 layers extending to a maximum depth of 30 meters. The use of 4 layers aimed to achieve the lowest

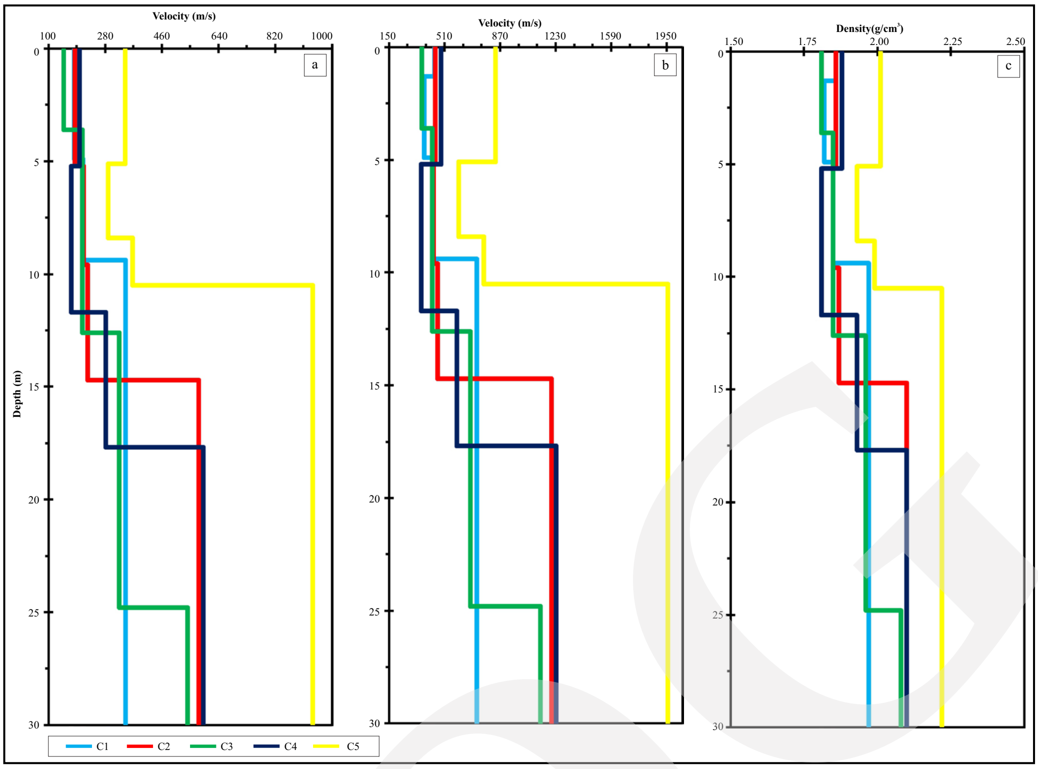

Figure 4. 1-D Profile of a). Vs; b). Vp; and c). Density 5 measurement points in the coast of Seluma Regency.

standard deviation and misfit. Each layer was visualized as a cross-section using ArcGIS Desktop ArcMap 10.8.2 software to illustrate the distribution of seismic properties and subsurface rock elasticity parameters along the coast of Seluma Regency. Detailed results of seismic property values and rock elasticity parameters for each parameter are presented in Table 1.

Shear Wave Velocity (Vs)

The determination of Vs describes the type of soil at a location, classified into five groups according to SNI-1726:2019: >1500 m/s indicates hard rock, 750-1500 m/s indicates rock, 350-750 m/s indicates hard soil, very dense and soft rock, 175-350 m/s indicates medium soil, and <175 m/s indicates soft soil. These classifications are based on the average Vs values down to a depth of 30 meters.

Based on Figure 5, layers (a), (b), and (c) are predominantly classified as medium soil. In layer (a), C4 exhibits a lower classification, indicating soft soil. In layer (b), C3 shows a lower classification. Furthermore, point C5 in layers (c) and (d) has a higher classification compared to the dominant classification of the layer: C5 in layer (c) consists of hard, very dense soil and soft rock, while C5 in layer (d) consists of hard rock.

Primary Wave Velocity (Vp)

The Primary wave classification is based on Hadi (2019), which categorizes subsurface conditions into five groups based on rock types. These classifications are: <300 m/s for soft soil types, 300-500 m/s for medium soil types, 500-1000 m/s for complex, very dense soil and soft rock, 1000-2500 m/s for rock, and >2500 m/s for hard rock. Figure 6 shows that the density values along the coast of Seluma Regency increase with depth. Layers (a) and (b) are predominantly classified as medium soil, layer (c) is dominated by complex, very dense soil and soft rock, and layer (d) is dominated by rock. Layers (a) and (b) exhibit anomalies where C5 shows different classifications, namely hard soil, very dense, and soft rock. Additionally, there is an anomaly in layer (d) at point C1, classified as lower, namely hard soil, very dense, and soft rock.

Table 1. Seismic Property Values and Rock Elasticity Parameters in the Coastal Area of Seluma Regency in Each Layer

Point	Layer	Thickness (m)	Vs (m/s)	Vp (m/s)	Density (g/cm^3)	Poisson Ratio	Shear Modulus (MPa)	Young Modulus (MPa)
C1	1	0 - 1.3	183	448	1.86	0.40	62	173.61
	2	1.4 - 5	182	379	1.82	0.35	60	161.96
	3	5.1 - 9.6	210	437	1.85	0.35	82	221.35
	4	9.7 - 30.0	346	720	1.97	0.35	236	637.05
C2	1	0 - 5.2	184	451	1.86	0.40	63	176.41
	2	5.3 - 9.7	211	439	1.85	0.35	83	224.04
	3	9.8 - 14.9	224	466	1.87	0.35	94	253.74
	4	15.0 - 30.0	578	1203	2.10	0.35	701	1892.26
C3	1	0 - 3.6	148	363	1.81	0.40	40	112.00
	2	3.7 - 12.7	208	433	1.85	0.35	80	215.95
	3	12.8 - 25.0	325	677	1.96	0.35	207	558.77
	4	25.1 - 30.0	543	1130	2.08	0.35	614	165.42
C4	1	0 - 5.2	199	487	1.88	0.40	74	207.21
	2	5.3 - 11.8	173	360	1.81	0.35	54	145.77
	3	11.9 - 17.8	283	589	1.93	0.35	154	415.70
	4	17.9 - 30.0	592	1232	2.10	0.35	738	199.14
C5	1	0 - 5.1	343	840	2.01	0.40	237	663.62
	2	5.2 - 8.5	289	602	1.93	0.35	161	434.60
	3	8.5 - 10.6	367	764	1.99	0.35	268	723.43
	4	10.7 - 30.0	939	1955	2.22	0.35	1955	5277.28

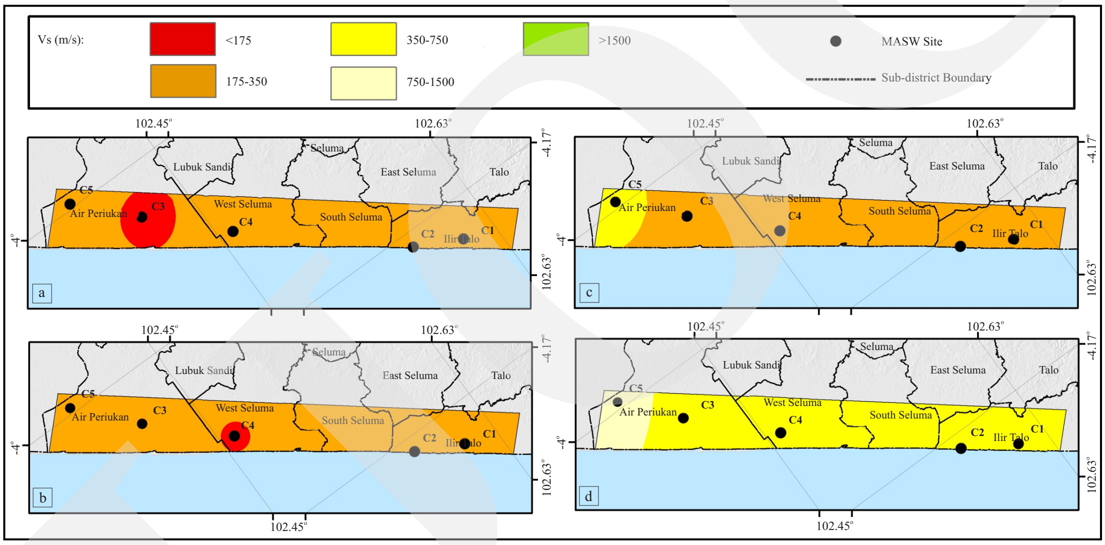

Figure 5. Distribution of Vs in each layer in Seluma regency coastal area. (a) Vs result in the first layer; (b) Vs result in the second layer; (c) Vs result in the third layer; and (d Vs result in the fourth layer.

Density (ρ)

Density is a physical property influenced by mineralogy and porosity differences among various rock types, providing valuable insights into subsurface geological conditions (Gordon *et al*., 1984). According to Figure 7, the density values along the coast of Seluma Regency increase with depth. Layers (a) and (b) are characterized by a consistent density value of <1.86 g/cm^3, indicating a soft soil structure. However, at point C5 in layer (b), a moderate soil structure is observed. Layer (c) exhibits varying classifications: C1 is composed of soft soil, C2, C3, and C4 are medium soil, and C5 consists of hard, very dense soil and soft rock. Layer (d) is dominated by density values ranging from 2.08 to 2.30 g/cm^3, indicative of rock types, except at point C1 where complex, very dense, and soft rock types are identified.

Poisson Ratio

Poisson's ratio is defined as the negative ratio of transverse strain to axial strain in an isotropic material under uniaxial stress (Poisson, 1829;

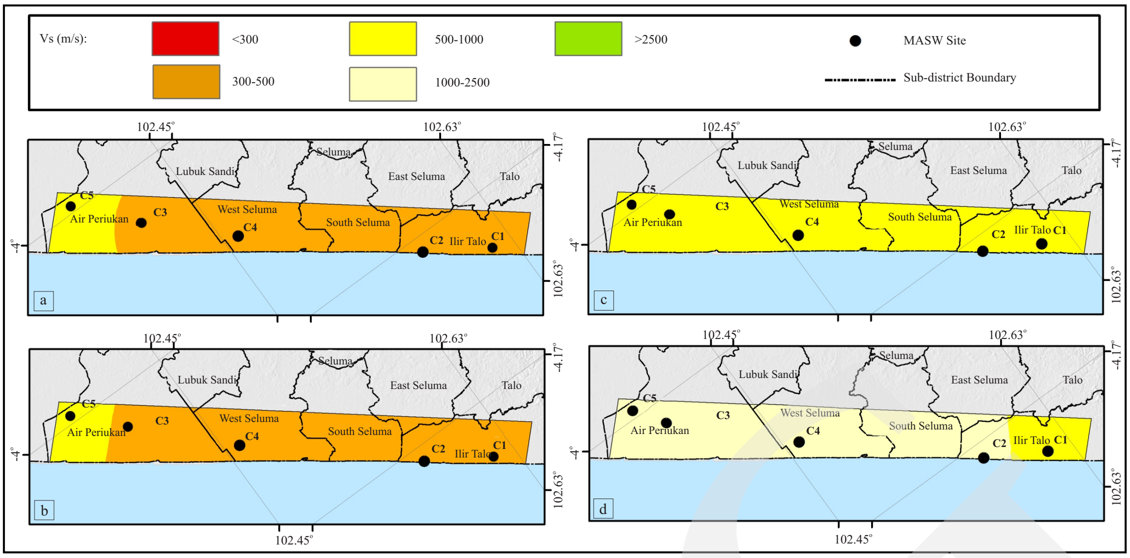

Figure 6. Distribution of Vp in each layer in Seluma regency coastal area. (a) Vp result in the first layer; (b) Vp result in the second layer; (c) Vp result s in the third layer; and (d) Vp result in the fourth layer.

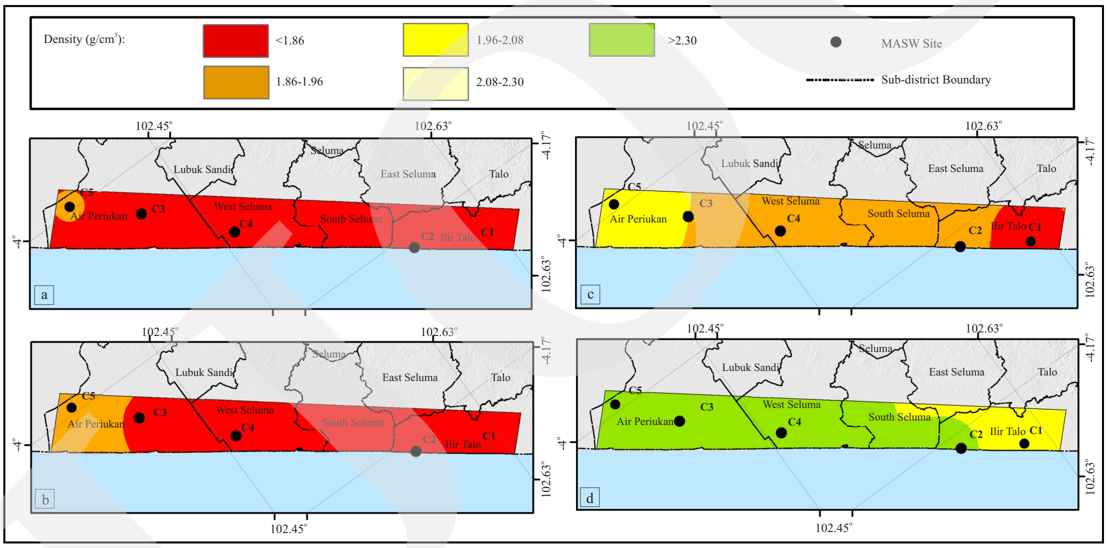

Figure 7. Distribution of density in each layer in Seluma regency coastal area. (a) Density result in the first layer; (b) Density result in the second layer; (c) Density result in the third layer; and (d) Density result in the fourth layer

Timoshenko, 1970; Christensen, 1996; Wang *et al*., 2005; Gercek, 2007). According to Nakamura *et al*. (2014), the Poisson ratio classification states that a ratio of 0.4 indicates surface soil with a clay loam structure, while a ratio of 0.3 typically denotes sand and gravel. Two Poisson ratio values were identified along the coast of Seluma Regency (Figure 8). Layer (a) corresponds to surface soil with a clay loam structure, whereas layers (b), (c), and (d) exhibit characteristics typical of sand and gravel.

Young Modulus (E)

The elastic modulus is determined as the slope of the linear portion of the stress-strain relationship (Xu and Dai, 2018). The Young's modulus of rock is an important parameter for assessing the strength, deformation, and stability of rock engineering structures (Ghasemi *et al*., 2018). According to Figure 9, layers (a) and (b) exhibit similar classifications, predominantly <250 MPa, indicating soft soil types, with point C5 showing a medium soil type. In contrast, layer (c) is domi-

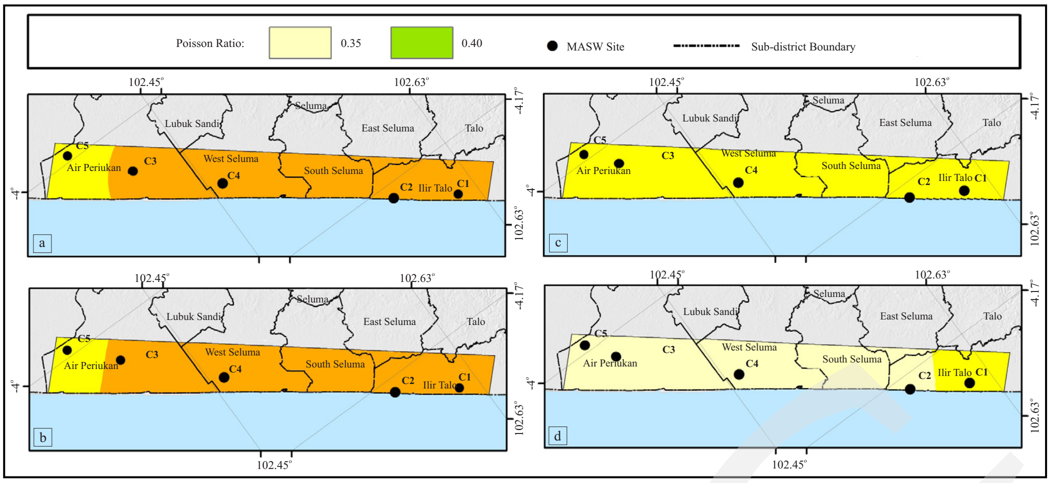

Figure 8. Distribution of Poisson Ratio in each layer in Seluma regency coastal area. (a) Poisson Ratio result in the first layer; (b) Poisson Ratio result in the second layer; (c) Poisson Ratio result in the third layer; and (d) Poisson Ratio result in the fourth layer.

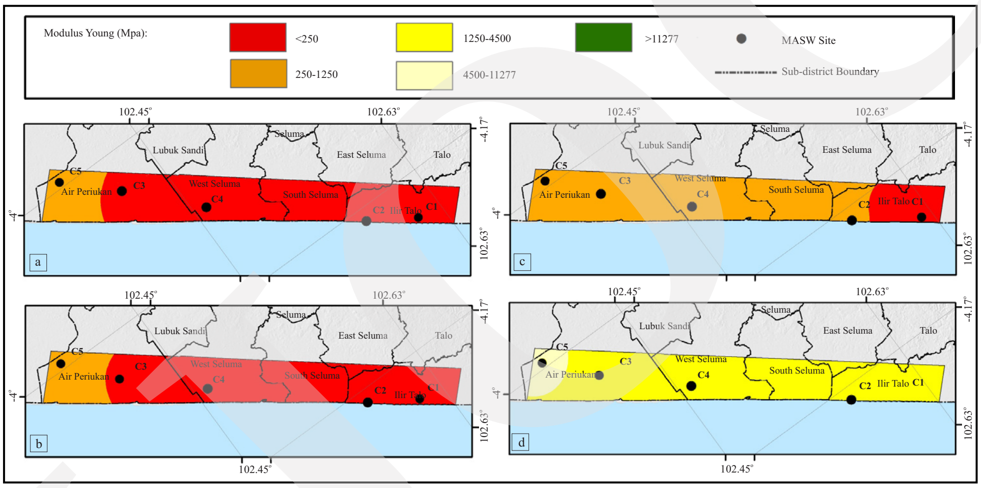

Figure 9. Distribution of Young Modulus in each layer in Seluma regency coastal area. (a) Young Modulus result in the first layer; (b) Young Modulus result in the second layer; (c) Young Modulus result in the third layer; and (d) Young Modulus result in the fourth layer.

nated by medium soil, while point C1 in this layer consists of soft soil. Layer (d) is characterized by values ranging from 1250 to 4500 MPa, indicating complex, very dense, and soft rock soil types.

Shear Modulus (G)

Shear modulus represents the relationship between shear stress and strain (Xu and Dai, 2018; Okewale, 2020). It is a crucial parameter for determining the fundamental stiffness of soil and is essential in the design and analysis of geotechnical structures, as well as in studies of seismic engineering (Kramer, 1996; Cavallaro *et al.*, 2016; Castelli *et al.*, 2016; Chen *et al.*, 2019). According to Figure 10, layers (a) and (b) exhibit the same classification, predominantly <100 MPa, indicating soft soil types, with a difference noted at point C5, which shows a medium soil type. Layer (c) is characterized by classifications ranging from 100 to 500 MPa, predominantly with soft soil types, and points C1 and C2 are identified as soft soil types. Layer (d) displays various classification types, dominated by hard soil, very dense, and soft rock. However, in layer (d), point C5 is categorized as rock type, while point C1 shows a moderate soil type.

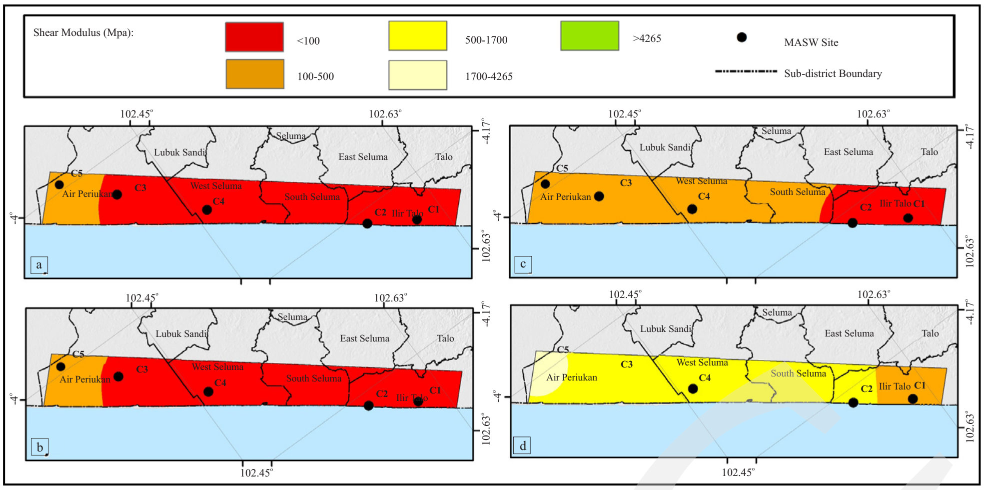

Figure 10. Distribution of Shear Modulus in each layer in Seluma regency coastal area. (a) Shear Modulus result in the first layer; (b) Shear Modulus result in the second layer; (c) Shear Modulus result in the third layer; and (d) Shear Modulus result in the fourth layer.

Based on the regional geological conditions, the coastal area of Seluma Regency primarily consists of alluvium, alluvial terraces, and swamp deposits (Gafoer *et al*., 2007), indicating a soft soil structure. This research focuses on specific points along the coast of Seluma Regency: points C1 and C2 in Ilir Talo Sub-district, C3 in West Seluma Sub-district, and C4 and C5 in Air Periukan Sub-district. This study employs seismic velocity parameters including Vs (shear wave velocity) and Vp (compressional wave velocity). Vs values are determined according to the rock site classification specified in SNI 1726:2019, while Vp classification is based on research by Capizzi and Martorana (2014). As depicted in Figure 5, each layer exhibits distinct Vs values that generally increase with depth, reflecting variations in lithology within each rock layer (Rizqulloh and Riyanto, 2021).

Vs and Vp exhibit a linear relationship (Sabrian *et al*., 2018). Figures 5 and 6 illustrate that point C5 has higher Vp and Vs values compared to other points, indicating a rock structure in Air Periukan Sub-district that is highly vulnerable to abrasion. The vulnerability to abrasion in Air Periukan Sub-district is further supported by elasticity parameters. Density results (Figure 7) show an anomaly at point C5, while points C1, C2, C3, and C4 exhibit similar density values. Layers three (Figure 7c) and four (Figure 5d) show a decrease in density from point C5 to C1, suggesting decreasing vulnerability to abrasion towards the southeast coast of Seluma Regency.

Young's modulus and shear modulus values, based on research by Cevasco *et al*. (2018) and Hadi (2019) respectively, also indicate patterns consistent with elasticity parameters across different layers (Figures 9 and 10). These parameters highlight that point C5 in Air Periukan Sub-district is more susceptible to abrasion due to its softer rock structure compared to other points. Additionally, Poisson ratio values, based on research by Nakamura *et al*. (2014), reveal higher values in the first layer (Figure 8.a) compared to the second to fourth layers (Figures 8b, 8c, and 8d). This suggests that the first layer is more prone to abrasion, whereas the subsequent layers are more resistant.

In summary, this study integrates various geological and seismic parameters to assess abrasion vulnerability along the coast of Seluma Regency, highlighting specific areas such as Air Periukan Sub-district as more susceptible to this natural hazard.

Conclusions

Our research indicates that Seluma Regency exhibits high to moderate potential for abrasion. Analysis of shear wave velocity (Vs) reveals an increase in Vs values with depth. The seismic properties and elasticity parameters highlight that point C5, or Air Periukan Sub-district, is more vulnerable to abrasion compared to other areas. Conversely, density, Young's modulus, and shear modulus suggest that the southeastern coast of Seluma Regency experiences lower levels of abrasion vulnerability. In contrast, based on Poisson's ratio, the first layer of the coastal Seluma Regency is susceptible to abrasion, whereas the second to fourth layers are more resistant.

The elastic parameter estimates obtained from this study provide a dynamic approach to characterizing each subgrade layer, offering detailed information crucial for engineering structures' foundation design. While geotechnical methods are effective in assessing subgrade strength, seismic methods provide depth-related stiffness shear strength parameters across broader survey areas at a lower cost compared to point tests typically used in geotechnical methods. This approach proves advantageous in its ability to cover extensive areas economically, making it a preferable option for assessing subgrade conditions prior to construction.

Acknowledgments

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