https://doi.org/10.48048/tis.2024.7544

The Combination of Hvsr and Masw Methods with Landsat 8 Imagery to Assess the Changing Shoreline along the Coastal Area of Central Bengkulu

Muchammad Farid[1,2,*], Arif Ismul Hadi[1,2], Refrizon[1], Hery Suhartoyo[3], Litman[4], Darmawan Ikhlas Fadli[1,2] and Eli Putriani[5]

[1]Department of Geophysics, Faculty of Mathematics and Natural Sciences, University of Bengkulu, Bengkulu 38371, Indonesia
[2]Center of Disaster Mitigation Studies, University of Bengkulu, Bengkulu 38371, Indonesia
[3]Department of Forestry, Faculty of Agriculture, University of Bengkulu, Bengkulu 38371, Indonesia
[3]Department of Forestry, Faculty of Agriculture, University of Bengkulu, Bengkulu 38371, Indonesia
[4]Agency for Meteorology, Climatology, and Geophysics, Geophysical Station Grade III, Kepahiang 39372, Indonesia
[5]Department of Geosciences, National Taiwan University, Taipe 106319, Taiwan

(*Corresponding author's e-mail: mfarid@unib.ac.id)

Received: 29 September 2023, Revised: 8 December 2023, Accepted: 15 December 2023, Published: 15 March 2024

Abstract

The Central Bengkulu Regency possesses a coastline measuring 21.8 km, situated in direct proximity to the Indian Ocean. The heightened wave and ocean current dynamics possess the capacity to induce detrimental effects in the form of coastal abrasion along the coastline. This study conducted an examination of the rate of shoreline changes resulting from coastal abrasion in Central Bengkulu Regency, Bengkulu, Indonesia. Horizontal-to-vertical spectral ratio (HVSR) analysis, multichannel analysis of surface waves (MASW), and Landsat-8 remote sensing were all used in the current investigation. The project gets started with conducting field investigations and measurements of geophysical techniques, including the collection of Landsat-8 satellite imagery spanning the period from 1990 to 2020. Additionally, an examination was conducted on the rate at which the shoreline undergoes changes in velocity. In order to determine the increase in change that occurs along coastlines over a period of several decades, a study was carried out during which Landsat-8 satellite images were analyzed. This study investigates the application of the HVSR technique for assessing the seismic vulnerability of the ground and, additionally, the MASW technique for measuring the shear wave velocity of the coastline's soil. Both of these methodologies are compared and contrasted with one another in this research. The findings indicated that the mean pace of coastline change in Central Bengkulu Regency was 1.5 m/yr, with the maximum velocity recorded at 4.1 m/yr. This high velocity of shoreline change is correlated with the *Vs30* value of MASW measurement and *Kg* of HVSR measurement, where the subsurface soil structure along the coast of Central Bengkulu Regency from *Vs30* measurement shows that it is dominated by stiff soil structure that is susceptible to erosion. Outcomes from the study can inform decision-making processes about safeguards and preventative measures to prevent further coastal degradation.

Keywords: Central Bengkulu regency, HVSR method, Landsat-8, MASW method, Shoreline change

Introduction

Among of the several regencies in Bengkulu Province, Central Bengkulu Regency represents one of the regencies that's practically near to the Indian Ocean. According to Rostika *et al.* [1] and Pratama *et al.* [2], this ocean is frequently subjected to waves of a significant magnitude. These ocean waves cause coastal erosion in various regions directly facing it [1-3] including Central Bengkulu Regency. They hit the beaches and the cliffs. Central Bengkulu Regency has of 21.8 km of coastline [4]. This marine area causes Central Bengkulu Regency to be bordered by coastal areas dominated by cliffed beaches that have experienced erosion and are prone to abrasion (**Figure 1**). The abrasion condition in this regency is also exacerbated by the development of shrimp ponds that affect the vulnerability of the land around the coast. Coastal areas that experience abrasion for an extended period will cause disruption of local sediment dynamics [5] caused by nature and humans [6]. Abrasion, a global problem [7,8] is caused by highintensity waves and currents [9]. In order to effectively manage coastal assets, ecosystems, navigation, and economic growth, alongside coastal area development [10], it is critical to protect coastlines that are prone to erosion and high ocean waves [11].

Figure 1 Coastal conditions in one area of Central Bengkulu Regency.

Previous research on coastline and coastal erosion has been conducted by Lubis *et al.* [12] in North Bengkulu Regency, which shows the average velocity of coastline change in Padang Betuah is 19.4 m/yr, Lais is 19.9 m/yr, Serangai is 19.5 m/yr, Ketahun is 15.9 m/yr, and in PT Firman Port with a velocity of 15.7 m/yr. Maulana *et al.* [13] showed that the abrasion velocity in Bengkulu City was 2.8 m/yr. Furthermore, the abrasion velocity in Southern Bengkulu covers 6.2 - 9.6 m/yr [14]. In Kaur Regency, the abrasion velocity covers 12.6 - 18.5 m/yr [15]. Research by Lubis *et al.* [12]; Maulana *et al.* [13]; Oktami [14]; and Supiyati *et al.* [15] showed that the abrasion velocity around Central Bengkulu Regency had experienced abrasion with significant shoreline changes. However, based on the studies conducted, research has yet to discuss changes in the coastline throughout Central Bengkulu Regency. However, based on existing field conditions, coastal erosion in Central Bengkulu Regency is included in severe coastal erosion. Therefore, it is necessary to mitigate coastal erosion disasters in Central Bengkulu Regency. These mitigation efforts are carried out for coastal area management, understanding of coastal dynamics, and development in coastal areas [16-18]. Utilization of data derived from satellite images makes it possible to ascertain the rate of change that is occurring along coastlines. For the purpose of this study, the satellite images were analyzed using a technique recognized as the Modified Normalized Difference Water Index (MNDWI). The MNDWI method has been successfully used by several researchers on shoreline-related studies [19-21]. This method can determine object-based classification and segmentation in coastline regions [21]. Because this technique has the ability to differentiate between wetlands and vacant land with a precision rating of 99.85 % [22], it is particularly useful for determining the rate at which coastline changes occur along the coastline of the Central Bengkulu Regency.

After this, the outcomes of the MNDWI are combined with the findings of active seismic methods like the Multichannel Analysis of Surface Wave (MASW) to attempt to determine the velocity of shear waves (*Vs30*), in addition to the results of passive seismic methods like the Horizontal-to-Vertical Spectral Ratio (HVSR). At the location of the research, the MASW approach is utilized so that the velocity of the shear wave profile may be determined. The Rayleigh wave dispersion principle may be derived from this method simply through the reference to the correlation that exists among phase velocity and frequency, as Park *et al.* [23], Xia *et al.* [24] have previously explained. Horizontal-to-vertical Spectrum The approach is known as the HVSR [25]. This method has been utilized on a massive scale worldwide to map high-risk locations for earthquake-related disasters [26-28]. This study also uses seismic vulnerability index (K_g) statistics, calculated utilizing natural frequencies and amplification factors and based on the HVSR approach. In-ground motion site effect studies Anderson *et al.* [29], Park and Elrick [30] were conducted in the coastal Central Bengkulu Regency, and this Vs30 data is considered an important parameter. By analyzing the characteristics of the soil dynamics in the research region and basing that analysis on the seismic vulnerability value (K_g), we can reduce the likelihood that an earthquake will cause significant damage. In addition, it is anticipated that the findings obtained from the integration of MNDWI, active seismic, and passive seismic in the coastal area of Central Bengkulu Regency will make a significant contribution to the efforts made to develop policies and management strategies and spatial planning in the coastal area of Central Bengkulu Regency in order to mitigate the adverse effects of natural disasters.

Geological setting of study area

The west coast of Bengkulu, Indonesia, on the coastal part to the hills, are generally formed by sedimentary deposits of Quaternary age with layers of silty-clay sand, silt, and sand that can reach thicknesses ranging from 5 m to up to 40 m. In addition, the Bengkulu coastal area reflects beach ridge deposits, swamp deposits, and alluvial deposits [31] (see **Figure 2**). According to the outcomes of a study that was conducted by Gafoer *et al.* [32], the stratigraphy in the region where the study was conducted is generally made up of units of rocks and formations ranging from the Tertiary to the Quaternary, with composite rocks being generated by volcanic products. The Bintunan Formation, also known as QTb, is what makes up the Tertiary geologic unit. Alluvium (abbreviated as Qa) and Alluvium Terraces (abbreviated as Qat) are the types of rock units that make up the Quaternary strata. Alluvium (Qa) comprises boulders, pebbles, mud, and clays. The Bintunan Formation (QTb) consists of tuffaceous sandstone, polymictic conglomerate, and tuff & tuffaceous claystone. According to Gafoer *et al.* [32], the Alluvium Terraces (Qat) are composed of semiconsolidated gravels, sands, and mud clays. In addition, geology interprets the various kinds of rock that make up the coast as substrates for erosion. The relative hardness of the minerals that make up the kind of rock is what determines how easily erosion may occur on that particular rock. According to Sandhyavitri *et al.* [33], several geological forms can be found in coastal environments, including rocks, sediments, erosive deposits, and coral reefs. Those coastlines most resistant to the effects of seawater erosion are those with elastic strata. In comparison, strands that include sediments that are easily moved are more likely to be eroded by the ocean.

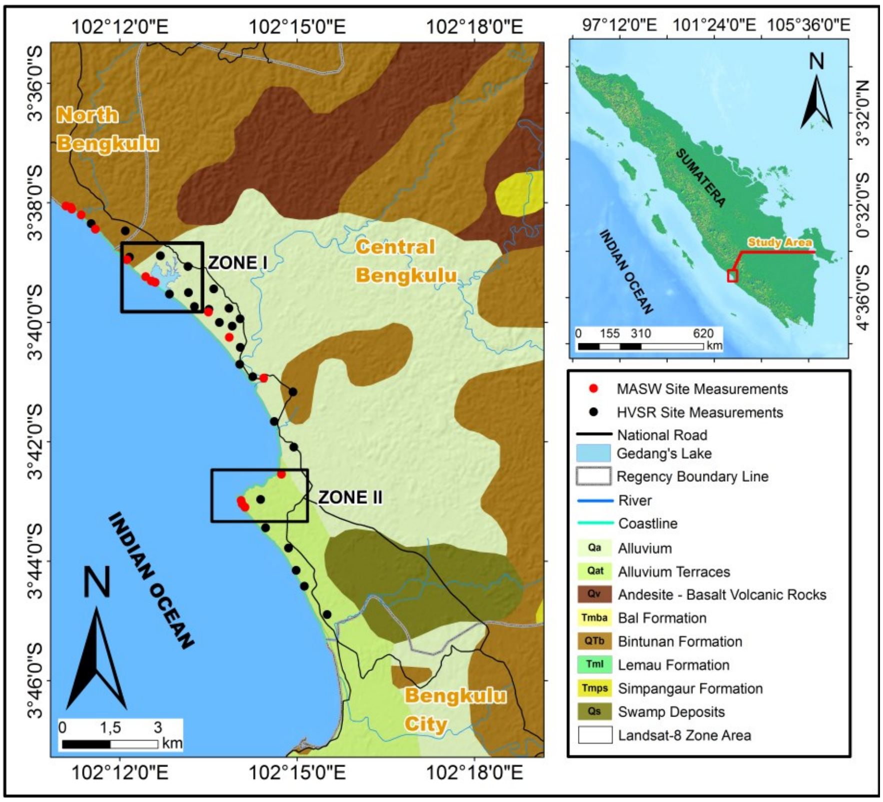

Figure 2 The Geological setting map and site measurements (HVSR and MASW) (adjustment from [32]).

Materials and methods

According to the data provided by the Central Bureau of Statistics in 2023, the Central Bengkulu Regency possesses a coastline of roughly 21.8 km (refer to **Figure 2**). Three methods were used to figure out how fast the shoreline was changing in the research area: Landsat-8 satellite imagery analysis in 2 different zones, active seismic measurements at 16 specific sites, and passive seismic measurements at 27 specific sites.

Landsat-8 imagery

The Landsat-8 satellite was used to acquire imagery for this investigation, and the investigation covered the years 1990 through 2022. Landsat-8 is a satellite that delivers worldwide georeferenced imagery as well as data processing abilities. NASA and the USGS are in charge of managing it. It is an operational land imager, and it covers an array of fields, including mapping, the use of land, forestry, coastal region observing, and managing flood risks [34]. Thermal infrared sensor equipment is also supported by this device. It had a resolution of 30 m and a width of 185 km, and it was equipped with an optical image that could identify things from the obvious to the near-infrared spectrum. According to the results published by Marangoz *et al.* [35], the overall precision of the Landsat-8 classification was reported to be 75.6 % for the classifications of bare ground, forest, human settlement, ecosystems, and water. The data were obtained from the official site of Landsat-8 data, which can be accessed at https://earthexplorer.usgs.gov. This website was used to collect the data for this study. The first step in the process of analyzing satellite imagery is to construct the MNDWI. Second, several stages were carried out in data processing, namely, image cropping, to obtain the focus of the research area. Furthermore, geometric corrections are carried out to improve the position of objects in the image so that they match the actual coordinates using QGIS (https://www.qgis.org/en/site/) Third, the data is processed using the MNDWI method [22]. MNDWI effectively distinguishes water and urban areas in satellite imagery [36]. This method is stable in describing water from land [37], so it is suitable for separating land and sea objects in satellite imagery data. According to Xu [22], this technique makes use of the obvious green (GREEN) and shortwave infrared 1 (SWIR1) spectrum bands. Although the outcomes of various other groups ranged from tighter intervals, the aqueous-related indices (NDWI and MNDWI) were more successful (particularly the MNDWI) in improving water characteristics. The differences in each index that were brought about by the watery land use class resulted in the discovery of weakened relationships among each index. In terms of statistics, the majority of varieties of land cover are separated from each other; at present, when different forms of greenery that have various water content are compared, analogues can be observed in some cases. According to Szabó *et al.* [38], MNDWI was determined to be the best approach for emphasizing lakes and rivers.

Active and passive seismic

Two stages of the survey were carried out. Namely, the first phase involved an active seismic survey in evaluating the thickness of the coastal sediments and shear wave velocity (V_s) at each case study location. The second phase involves passive seismic surveys, investigating the propagation of natural seismic waves (ambient noise) contributing to vertical and horizontal vibrations along the coastal environment. From these data, soil models were developed and used to evaluate the performance of active and passive seismic surveys in identifying the velocity of change of the coastline. The methodological performance of active and passive seismic engineering, including field procedures, instrument configurations, and settings, was tested at various coastal sites, following beach features, sediment grain sizes, and bedrock geology (bedrock stratigraphy) to assess their suitability. This study used passive seismic methods to observe subsurface structures in coastal erosion-prone areas in Central Bengkulu Regency. This research was conducted at as many as 27 site measurements spread along the coast in areas prone to coastal erosion, Central Bengkulu Regency. Data from 3 component waves (North-South, East-West, and Up-Down) were recorded for 30 min using the PASI Mod Seismoter Short Period tool. Gemini 2 with a sampling rate of 5 ms (200 Hz) at each measurement point. At the same time, the active seismic method is used to measure the speed of shear waves on subsurface structures in parts of the Central Bengkulu Regency that are vulnerable to coastal erosion. The tool used is the PASI Mod seismograph. 16S24P carried out as many as 16 site measurements. This tool has 24 geophone channels with an offset of 5 m, a spacing between geophones of 2 meters, and a sampling rate of 125 μs.

Horizontal-to-Vertical Spectral Ratio (HVSR) is an approach technique adopted by Nogoshi and Igarashi [39]; Nakamura [40] to look at passive seismic data and figure out the way site effects three-component noise in the environment recordings. The processes for processing the data were carried out utilizing the Geopsy application [41], and they were carried out in accordance with the recommendations that were presented in the SESAME project [42]. A period window duration of 15 s was chosen for the analysis. Additionally, a cosine taper width of 10 % was permitted in the analysis. Furthermore, Konno and Ohmachi [43] implemented a smoothing factor for every window, with a smoothing value of b = 40. The deformation amount in the ground depends on the frequency and amplitude of the seismic wave. In order to properly conduct soil mechanics analysis investigations, it is necessary to determine the potential deformation values that could occur after a quake [44,45]. In this regard, Nakamura [46,47] estimated the potential damage that could occur during an incident by using a vulnerability index (K_g) that depended on transverse deformation. According to Szabó *et al.* [38] categorised the seismic vulnerability index data into 4 classes: Low (< 3), moderate (3 - 5), high (5 - 10) and very high (> 10).

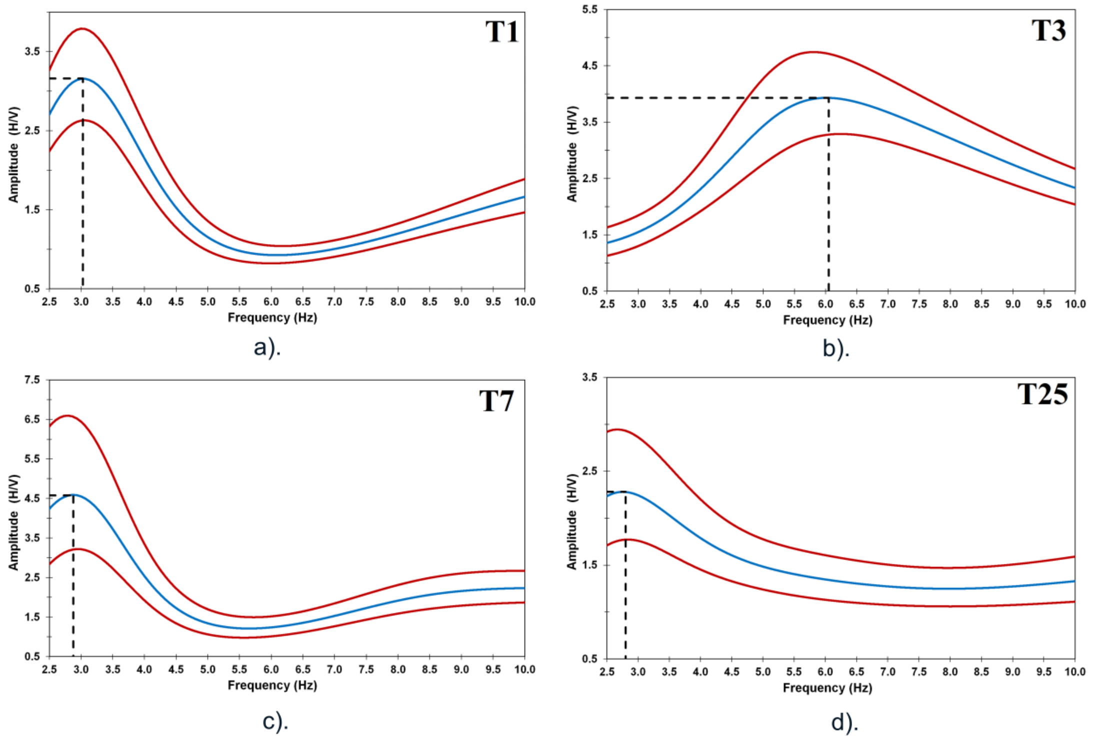

Figure 3 HVSR curves from several site measurement data; (a) T1, $A_0 = 3.2$, $f_0 = 3.0$, (b) T3, $A_0 = 3.9$, $f_0 = 6.1$, (c) T7, $A_0 = 4.6$, $f_0 = 2.9$, and (d) T25, $A_0 = 2.3$, $f_0 = 2.8$.

During active seismic fieldwork, we utilized the MASW geophysical approach. The MASW methodology has many benefits above other seismic methods since it is able to detect slow layers or zones that are below fast layers or zones in contrasting geology [48]. This is an enormous benefit. MASW data were processed with WinMASW 5.0 Professional. The analysis begins with the upload of the data collected into the WinMASW software in the format of.dat file formats. After that, the software adds the geometry metadata to the seismic records before producing dispersion curves from the Rayleigh wave windows it had previously observed. With the goal of producing the velocity of the shear wave profile, you will first need to pick the dispersion curve, then create the initial launching model, and then execute the inversion method. Recent studies and applications have efficiently used this method to calculate shear wave velocity (V_s30) distributions in soils and rocks [49] and correspondingly near-surface geological sites. In addition, it has been shown that the class can be estimated. Guides best practices in real-world projects [50]. The evaluation of the technical features of soils necessitates the consideration of shear wave velocity as a crucial element [51]. The variety of soil characteristics each produce their own unique set of velocity values for shear waves in the soil matrix. As a result, it is possible to connect it with various aspects of the soil, and it is also possible to use it as a crucial variable in usages such as the identification of the soil and the evaluation of its technical behavior [52].

Table 1 Site classification for seismic design from Badan Standarisasi Nasional [53].

Shear wave velocities (m/s)	< 175	175 - 350	350 - 750	750 - 1500	> 1500
Site classification	SE	SD	SC	SB	SA

Note: SE (Soft soil); SD (Stiff soil); SC (Very dense soil and soft rock); SB (Rock); SA (Hard rock) adapted from [53].

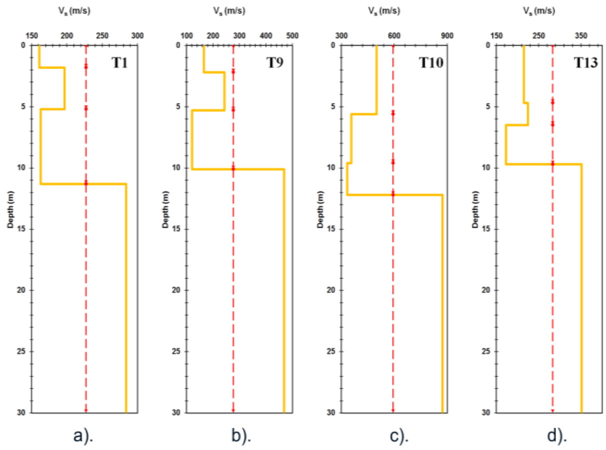

Figure 4 Shear Wave Velocity (*Vs*) curves from several site measurement data (Orange line is V_s and red dotted line is V_s30).

Results and discussion

Landsat-8 imagery measurement

One of the most stunning, peaceful, and alluring beaches in the area is located in Zone I and is referred to as Gedang Lake. This beach attracts a lot of tourists every year because of its incredible natural splendor and picturesque surroundings. The majority of the beach, which is located adjacent to the lake, is made up of sand. In general, the beaches surrounding Gedang Lake undergo seasonal variations due to deposition and erosion throughout the year. In Zone II, Sungai Suci Beach and Wahana Surya are also among the beautiful, attractive beaches in the region. Many tourists visit this beach to enjoy the scenery, beauty, and games available. The beach is primarily sandy and has been developed by the private sector and the government as one of the official tourist attractions. In general, the beach is also experiencing changes in the form of erosion. Using the Geographic Information System (GIS) along the coast of Central Bengkulu, imagery was taken from satellite images (Landsat-8 OLI) that showed changes in the shoreline. This coastline undergoes a lot because of both natural and human-made activities, including neighborhood drainage systems, disposal of solid waste, building with concrete, etc. Because of this, the placement of the coast changes every time. Furthermore, the shoreline changes all the time because sediments move across the shore and along the beach in the coastal zone. This is because the surface of the water at the coast constantly changes due to things like winds, tides, groundwater, storm surges, high tides, etc. [54]. **Figure 5** shows how the coast changed throughout the years.

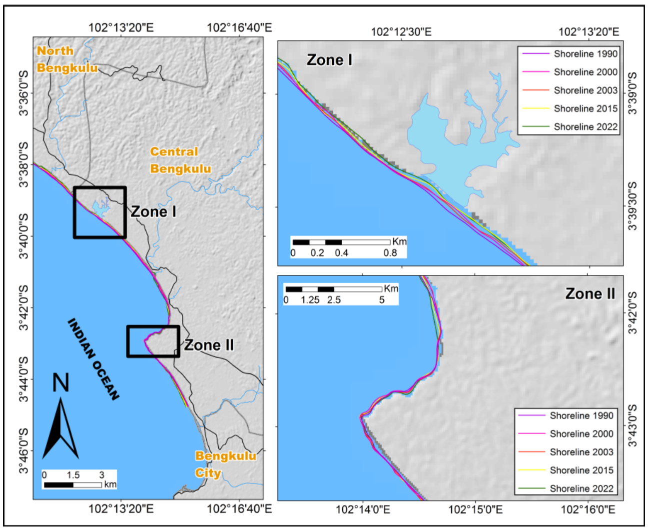

Figure 5 The shoreline of Central Bengkulu changes as one progresses along the coast. Gedang Lake is in Zone I. Sungai Suci and Wahana Surya coastlines are in Zone II.

Based on the data processing results using the MNDWI method, the velocity of shoreline change in Central Bengkulu Regency is obtained based on Net Shoreline Movement (NSM). This study used shoreline velocity data from 1990 - 2022 with NSM generated in this study as many as 102 transects. The results of NSM in each transect were then calculated with the basic velocity formula to obtain changes in shoreline velocity for 32 years. The velocity map of shoreline change in Central Bengkulu Regency can be seen in **Figure 5**, and the value of each transect can be seen in **Table 2**.

Table 2 Velocity of shoreline change from 1990 - 2022 along the Central Bengkulu coastline.

Transect	Distance (m)	Time (yr)	Velocity (m/yr)	Transect	Distance (m)	Time (yr)	Velocity (m/yr)
T1	33.46	32	1.05	T52	37.39	32	1.17
T2	42.05	32	1.31	T53	41.77	32	1.31
T3	46.88	32	1.47	T54	42.11	32	1.32
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
T49	62.40	32	1.95	T100	0.37	32	0.01
T50	41.87	32	1.31	T101	10.42	32	0.33
T51	31.32	32	0.98	T102	4.51	32	0.14
Average Velocity (m/yr)						1.53	

Active and passive seismic measurement

Together with the fundamental frequency, the H/V spectra from passive seismic recordings made at a total of 27 sites were used to figure out the factor of amplification. There was an extensive spectrum of acceptable values for the factor of amplification, which ranged from 0.59 to 4.58. The values of the fundamental frequency ranged from 2.58 to 8.62 Hz, as shown in **Figures 6(a)** and **6(b)**. When viewing the K_g map (**Figure 6(c)**), it is feasible to observe that the values for the K_g range ranged from 0.05 to 7.28. This study classified *Kg* values according to Akkaya [26]. The area closest to Gedang Lake and in the border part with North Bengkulu has a relatively high K_g value (**Figure 6(c)**). High K_g values indicate that the area consists of weak soils. On the other hand, in the coastal size from Gedang Lake to the border of Bengkulu City, K_g values decrease (**Figure 6(c)**). The results indicate that structural damage is likely to occur in locations with K_g values > 5.

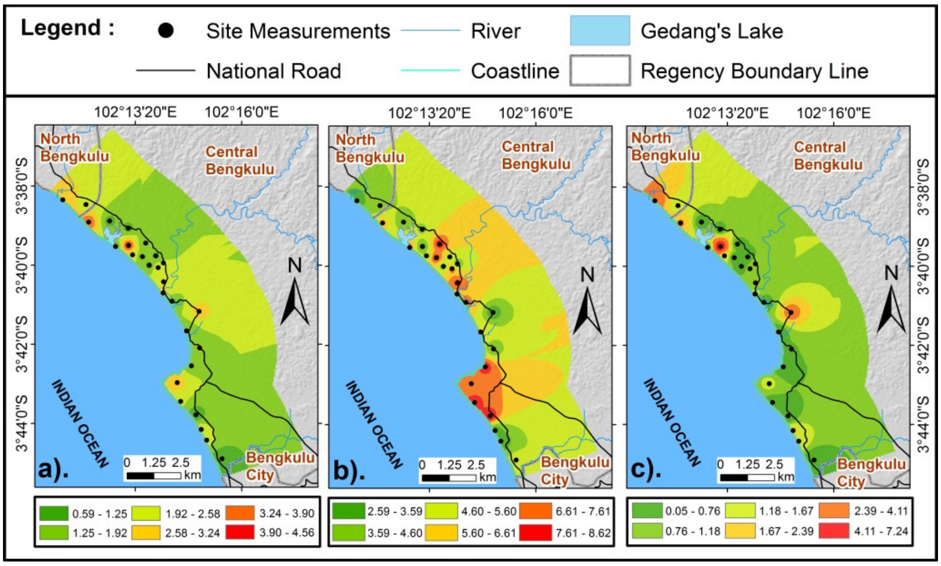

Figure 6 Spatial distributions of site effect along coastal Central Bengkulu. (a) Amplification factor distribution, (b) Fundamental frequency distribution, and (c) Distribution of SVI (K_g).

The investigation involved the utilization of the active seismic method (MASW) to obtain measurements, which were subsequently used to construct 1-D velocity profiles. Then each 1-D velocity profile was divided into 4 soil layers. The *Vs* values in the first layer ranged from 144 - 674 m/s. The *Vs* values in the second layer went from 131 - 583 m/s. The *Vs* Values in the third layer ranged from 121 - 484 m/s. The *Vs* Matter in the fourth layer ranged from 284 - 1800 m/s. The site class along the coast of Central Bengkulu, according to SNI 1726:2019 classification [53], is divided into 5 soil classes, namely Soft Soil, Stiff Soil, Very Dense Soil, Rock, and Hard rock (see **Figures 7(a) - 7(d)**). In the coastal region of Central Bengkulu, observations of the average velocity of shear waves were acquired up to a depth of 30 meters (**Figure 7(e)**). V_s30 values ranged from 227 to 1235 m/s. These values were compared with SNI 1726:2019 soil characterization for site category guidelines [53]. According to the *Vs30* map, the soil in the coastal region of Central Bengkulu can be classified into one of 3 categories: Rock, Very Dense Soil, and Stiff Soil. Rock is the most hazardous classification.

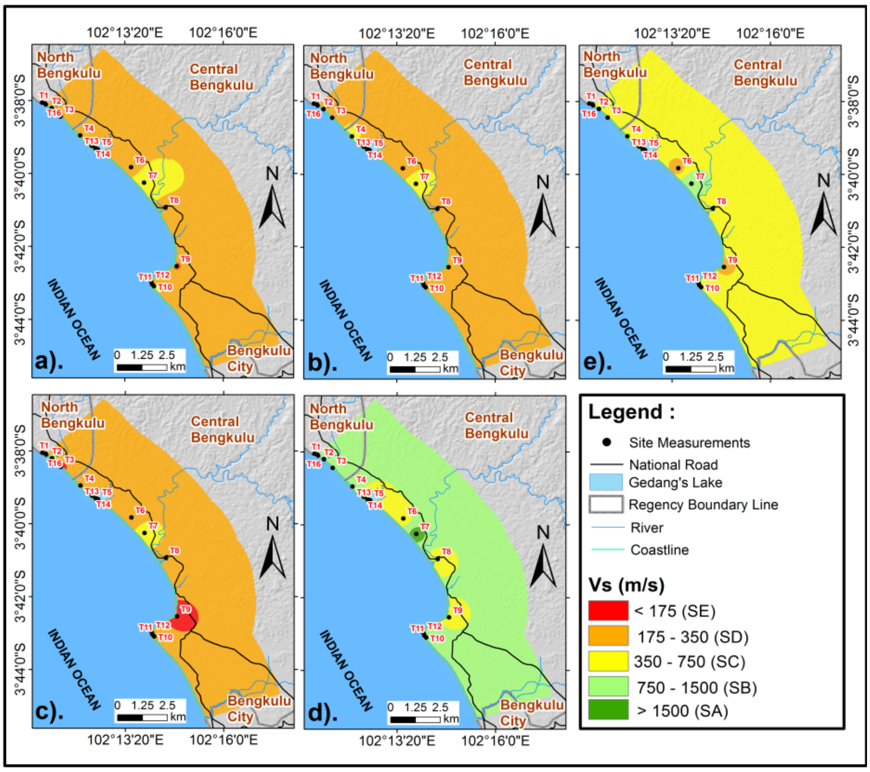

Figure 7 Spatial distributions of shear wave velocity (V_s) along coastal Central Bengkulu. (a). V_s layer one distribution, (b). V_s layer 2 distribution, (c). V_s layer 3 distribution, (d). V_s layer 4 distribution, and (e). V_s 30 distribution.

Discussion

Shoreline changes in Central Bengkulu Regency are caused by several factors, one of which is the geological conditions in the research area. The research area comprises Bintunan Formation, Alluvium, and Alluvium Terraces Formations [32]. Therefore, the rock formations in this area become one of the main controlling factors when changes in the coastline occur in Central Bengkulu Regency. Based on the results of satellite image data using the MNDWI method, from 1990 to 2022, the average velocity of shoreline change was 1.53 m/yr (see **Table 2**). The rate of shoreline change in Central Bengkulu Regency results in 2 events: Sedimentation and erosion. Coastal erosion, on the other hand, is the most significant phenomenon along the coastline of the Central Bengkulu Regency.

The velocity of shoreline change in Central Bengkulu Regency erodes some parts of the coastline in Central Bengkulu Regency. The results also show that the most significant rate of shoreline change occurs in T6 at a velocity of 4.06 m/yr with a reduction in land area of 130.11 m. The removal of land area around T6 is also relatively large, with the velocity of shoreline change occurring around 3 - 4 m/yr. Based on satellite image observations, the area around T6 is also very vulnerable to coastal erosion. The velocity of shoreline change is then correlated with the passive seismic method (HVSR) to determine the subsurface structure in Central Bengkulu Regency. Based on the passive seismic way, the K_g values obtained range from 0.05 to 7.28. The highest K_g value is around Gedang Lake, indicating that the area has a softer soil type than other areas with lower K_g values. Conversely, the low K_g value in the southern area along the coast indicates that the soil structure is more complex than in other areas. Based on the results of the K_g value shows that the area around Gedang Lake is an area that is prone and vulnerable to coastal erosion compared to other areas.

In addition to that, the active seismic method (MASW) was used in this investigation, and the results gave the velocity of shear waves measured at a depth of thirty meters. The results for V_s30 ranged from 227 to 1235 meters per second. According to the findings of the Vs30 data, the points T5, T13, T14, T6, and T9 have all received fairly low V_s30 values, ranging from 175 to 350 m/s. According to the categorization provided by SNI 1726:2019 [53], the region is categorized due to stiff soil. Based on the site class value, it shows that the location has a type of soil that is easily eroded by coastal waves, making it easier to experience coastal erosion. Various strategies exist to address coastal erosion. Typical interventions taken in response to coastal erosion include the construction of seawalls, breakwaters, land reclamation, and the conservation or relocation of reefs (Cooper and Pilkey 2012; French 2001; Nordstrom 2014).

Conclusions

It is required, in order to plan and put into practice relevant mitigation measures, to first have a comprehension of the conditions that lead to changes in shorelines and to carry out continual monitoring of these changes, particularly in regions that have been degraded. Only then can appropriate mitigation be planned and put into action. Based on the results, Central Bengkulu Regency experienced significant shoreline changes from 1990 - 2022. The average shoreline change velocity in Central Bengkulu Regency is 1.5 m/yr, with the highest velocity of 4.1 m/yr. This high shoreline change velocity is correlated with the V_s30 and Kg values, where the subsurface soil structure along the coast of Central Bengkulu Regency from V_s30 measurement shows that it is dominated by stiff soil structure that is susceptible to erosion. The shoreline change analysis that results from this study can provide stakeholders, policymakers, and scientists with assistance whenever it pertains to making decisions surrounding the continuation of coastal development activities along the coastline of Central Bengkulu.

Acknowledgements

Data acquisition was made possible by a Grant research from The Office of Research and Community Service, University of Bengkulu, Indonesia (2880/UN30.15/LT/2022). Laboratory of Physics kindly provided the survey's Seismograph 24-Channel (PASI Mod.16S24P) and Short Period Seismometer (PASI Mod. Gemini-2). We also thank the Farid Research Group (FRG) Team for its help in data acquisition.

References

[1] R Rostika, NP Purba, M Lutfi, J Kelvin and I Silalahi. The managing plan for abrasion in coastal area of Garut Regency. *Procedia Environ. Sci*. 2016; **33**, 512-9.
[2] DND Pratama, N Khakhim, A Wicaksono, A Musthofa and W Lazuardi. Spatio-temporal analysis of abrasion susceptibility effect on land cover in the coastal area of Bantul Regency, Yogyakarta, Indonesia. *Int. J. Geoinformatics* 2021; **17**, 109-26.
[3] UJ Wisha, R Dhiauddin, K Ondara, WA Gemilang and GA Rahmawan. Assessing urban development impacts in the Padang Coastline City, West Sumatra Indonesia; coastline changes and coastal vulnerability. *Geoplanning* 2022; **9**, 73-88.
[4] Statistics of Bengkulu Tengah Regency. *Bengkulu Tengah Regency in figures 2023*. Statistics of Bengkulu Tengah Regency, Bengkulu, Indonesia, 2023.
[5] P Vinayaraj, G Johnson, GD Udhaba, CS Philip, VS Kumar and R Gowthaman. Quantitative estimation of coastal changes along selected locations of Karnataka, India: A GIS and remote sensing approach. *Int. J. Geosci*. 2011; **2**, 385-93.
[6] A Gracia, N Rangel-Buitrago, JA Oakley and AT Williams. Use of ecosystems in coastal erosion management. *Ocean Coast Manag*. 2018; **156**, 77-89.
[7] LCV Rijn. Coastal erosion and control. *Ocean Coast Manag*. 2011; **54**, 67-87.
[8] DH Prasad and ND Kumar. Coastal erosion studies - a review. *Int. J. Geosci*. 2014; **5**, 341-5.
[9] N Moursy. Hazards and risk assessments of coastal erosion. *J. Coast. Zone Manag*. 2022; **25**, 1000505.

[10] SGMD Hashmi and SR Ahmad. GIS-based analysis and modeling of coastline erosion and accretion along the Coast of Sindh Pakistan. *J. Coast. Zone Manag*. 2018; **21**, 1000455.
[11] HA Banumathi and SP Jeyapriya. *A numerical study on hydrodynamic and liquefaction analysis of coastline protected with geotubes*. *In*: K Muthukkumaran, R Ayothiraman and S Kolathayar (Eds.). Soil dynamics, earthquake and computational geotechnical engineering IGC 2021 lecture notes in civil engineering. Vol 300. Springer, Singapore, 2023.
[12] AM Lubis, R Hanapi, J Sinaga, R Samdara and B Harlianto. Estimating shoreline changes at coastal region of North Bengkulu Regency using unmanned aerial vehicle (UAV). *Majalah Ilmiah Globë* 2022; **24**, 81-9.
[13] FA Maulana, K Amri and B Besperi. Prediksi perubahan garis pantai Bengkulu (Studi kasus pantai Zakat Kota Bengkulu). *Jurnal Peradaban Sains, Rekayasa dan Teknologi* 2021; **9**, 15-22.
[14] R Oktami. 2016, Changes in beach area in Southern Bengkulu Province using landsat satellite image data. Bachelor Thesis. University of Bengkulu, Bengkulu, Indonesia.
[15] Supiyati, B Sulistyo and R Oktami. Analisis perubahan garis pantai Kabupaten Kaur Provinsi Bengkulu selama 10 tahun (2006 - 2016). *Prosiding Seminar Nasional Fisika (E-Journal)* 2017; **6**, SNF2017-EPA.
[16] DJ Sherman and BO Bauer. Coastal geomorphology through the looking glass. *Geomorphology* 1993; **7**, 225-49.
[17] PJ Zuzek, RB Nairn and SJ Thieme. Spatial and temporal considerations for calculating shoreline change rates in the Great Lakes Basin. *J. Coast. Res*. 2003; **38**, 125-46.
[18] R Gens. Remote sensing of coastlines: Detection, extraction and monitoring. *Int. J. Remote Sens*. 2010; **31**, 19-36.
[19] N Adebisi, AL Balogun, M Mahdianpari and TH Min. Assessing the impacts of rising sea level on coastal morpho-dynamics with automated high-frequency shoreline mapping using multi-sensor optical satellites. *Remote Sens*. 2021; **13**, 3587.
[20] DN Quang, VH Ngan, HS Tam, NT Viet, NX Tinh and H Tanaka. Long-term shoreline evolution using dsas technique: A case study of Quang Nam Province, Vietnam. *J. Mar. Sci. Eng*. 2021; **9**, 1124.
[21] AY Yiğit, Y Kaya and IH Şenol. Monitoring the change of Turkey's tourism city Antalya's Konyaaltı shoreline with multi-source satellite and meteorological data. *Appl. Geomatics* 2022; **14**, 223-36.
[22] H Xu. Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery. *Int. J. Remote Sens*. 2006; **27**, 3025-33.
[23] CB Park, RD Miller and J Xia. Multi-channel analysis of surface waves using Vibroseis (MASWV). *SEG Tech. Program Expanded Abstr.* 1996, https://doi.org/10.1190/1.1826742.
[24] J Xia, R Cakir, RD Miller, C Zeng and Y Luo. Estimation of near-surface shear-wave velocity by inversion of Love waves. *In*: Proceedings of the 79th Society of Exploration Geophysicists International Exposition and Annual Meeting, Texas, USA. 2009, p. 1390-5.
[25] Y Nakamura. Real time information systems for seismic hazards mitigation UrEDAS, HERAS, PIC. *Q Rep. Railw. Tech. Res. Inst*. 1996; **37**, 112-27.
[26] I Akkaya. Availability of seismic vulnerability index (K_g) in the assessment of building damage in Van, Eastern Turkey. *Earthquake Eng. Eng. Vib*. 2020; **19**, 189-204.
[27] AM Al-Amri, K Abdelrahman and MS Fnais. Evaluation of seismic vulnerability index in Makkah Al-Mukarramah Urban Area, Saudi Arabia, using microtremor measurements. *Arab. J. Geosci*. 2022; **15**, 1350.
[28] MMR Bhuiya and W Shao. Perceptions of earthquake risks and knowledge about earthquake response among movement challenged persons in Dhaka City of Bangladesh. *Int. J. Disaster Risk Reduct*. 2022;**70**, 102743.
[29] JG Anderson, Y Lee, Y Zeng and S Day. Control of strong motion by the upper 30 meters. *Bull. Seismol. Soc. Am.* 1996; **86**, 1749-59.
[30] S Park and S Elrick. Predictions of shear-wave velocities in Southern California using surface geology. *Bull. Seismol. Soc. Am*. 1998; **88**, 677-85.
[31] E Soebowo, D Sarah and A Tohari. Geologi Bawah permukaan kaitannya dengan potensi likuifaksi di daerah Bengkulu. *In*: Proceedings of the Pertemuan Ilmiah Tahunan Iagi Ke-37, Bandung, Indonesia. 2008.
[32] S Gafoer, TC Amin and R Pardede. *Geological map of the Bengkulu Quadrangle, Sumatera*. Pusat Penelitian dan Pengembangan Geologi, Bandung, Indonesia, 2012.
[33] A Sandhyavitri, F Fatnanta, RR Husaini and I Suprayogi. Combination of a coastal vulnerability

index (CVI) and social economic approaches in prioritizing the development of Riau Coastlines, Indonesia. *MATEC Web Conf.* 2019; **276**, 02006.
[34] HM Miller. *Users and uses of landsat 8 satellite imagery-2014 survey results*. United States Geological Survey, Washington DC, USA, 2016.
[35] AM Marangoz, A Sekertekin and HAkçin. Analysis of land use land cover classification results derived from sentinel-2 image. *In*: Proceedings of the 17th International Multidisciplinary Scientific GeoConference, Albena, Bulgaria. 2017, p. 25-32.
[36] J Laonamsai, P Julphunthong, T Saprathet, B Kimmany, T Ganchanasuragit, P Chomcheawchan and N Tomun. Utilizing NDWI, MNDWI, SAVI, WRI, and AWEI for estimating erosion and deposition in Ping River in Thailand. *Hydrology* 2023; **10,** 70.
[37] C Huang, Y Chen, S Zhang and J Wu. Detecting, extracting, and monitoring surface water from space using optical sensors: A review. *Rev. Geophys*. 2018; **56**, 33-60.
[38] S Szabó, Z Gácsi and B Balázs. Specific features of NDVI, NDWI and MNDWI as reflected in land cover categories. *Landsc. Environ*. 2016; **10**, 194-202.
[39] M Nogoshi and T Igarashi. On the propagation characteristics of microtremor. *J. Seismol. Soc. Jpn*. 1970; **23**, 64-80.
[40] Y Nakamura. A method for dynamic characteristics estimation of subsurface using micrometers on the ground surface. *Railw. Tech. Res. Inst. Q. Rep.* 1989; **30**, 25-33.
[41] M Wathelet, JL Chatelain, C Cornou, GD Giulio, B Guillier, M Ohrnberger and A Savvaidis. Geopsy: A user-friendly open-source tool set for ambient vibration processing. *Seismol. Res. Lett*. 2020; **91**, 1878-89.
[42] SESAME. *Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations-measurements, processing and interpretations*. SESAME European Research Project WP12, 2004, p. 1-64.
[43] K Konno and T Ohmachi. Ground-motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremor. *Bull. Seismol. Soc. Am*. 1998; **88**, 228-41.
[44] E Pamuk, T Gönenç, ÖC Özdağ and M Akgün. 3D bedrock structure of bornova plain and its surroundings (İzmir/Western Turkey). *Pure Appl. Geophys*. 2018; **175**, 325-40.
[45] E Pamuk, ÖC Özdağ, A Tunçel, Ş Özyalın and M Akgün. Local site effects evaluation for Aliağa/İzmir using HVSR (Nakamura technique) and MASW methods. *Nat. Hazards* 2018; **90**, 87-99.
[46] Y Nakamura. Seismic vulnerability indices for ground and structures using microtremor. *In*: Proceedings of the World Congress on Railway Research, Firenze, Italy. 1997.
[47] Y Nakamura. Clear identification of fundamental idea of nakamura's technique and its applications. *In*: Proceedings of the 12th World Conference on Earthquake Engineering, New Zealand. 2000.
[48] TF Abdallatif, AA Khozym and AA Ghandour. Determination of seismic site class and potential geologic hazards using multi-channel analysis of surface waves (MASW) at the industrial city of Abu Dhabi, UAE. *NRIAG J. Astron. Geophys*. 2022; **11**, 193-209.
[49] MAM Ashraf, NS Kumar, R Yusoh, ZAM Hazreek and M Aziman. Site classification using multichannel channel analysis of surface wave (MASW) method on soft and hard ground. *J. Phys. Conf. Ser.* 2018; **995**, 012108.
[50] S Foti, F Hollender, F Garofalo, D Albarello, M Asten, PY Bard, C Comina, C Cornou, B Cox, GD Giulio, T Forbriger, K Hayashi, E Lunedei, A Martin, D Mercerat, M Ohrnberger, V Poggi, F Renalier, D Sicilia and V Socco. Guidelines for the good practice of surface wave analysis: A product of the InterPACIFIC project. *Bull. Earthquake Eng*. 2018; **16**, 367-420.
[51] G Cao, W Wang, G Yin and Z Wei. Experimental study of shear wave velocity in unsaturated tailings soil with variant grain size distribution. *Constr. Build. Mater*. 2019; **228**, 116744.
[52] W Duan, G Cai, S Liu and AJ Puppala. Correlations between shear wave velocity and geotechnical parameters for Jiangsu Clays of China. *Pure Appl. Geophys*. 2019; **176**, 69-84.
[53] Badan Standarisasi Nasional. Tata cara perencanaan ketahanan gempa untuk struktur bangunan gedung dan nongedung. Badan Standarisasi Nasional, Jakarta, Indonesia, 2019.
[54] EH Boak and IL Turner. Shoreline definition and detection: A review. *J. Coast Res*. 2005; **214**, 688-703.
[55] PW French. *Coastal defences: Processes, problems and solutions*. Routledge, London, 2001.
[56] JAG Cooper and OH Pilkey. *Pitfalls of shoreline stabilization: Selected case studies*. Springer, Dordrecht, Western Netherlands, 2012.
[57] KF Nordstrom. Living with shore protection structures: A review. *Estuar. Coast. Shelf Sci.* 2014; **150**, 11-23.