MARI

MULTIDISCIPLINARY APPLIED RESEARCH AND INNOVATION
e-ISSN: 2773-4773

Vol. 7 No. 3 (2026) 139-146
https://publisher.uthm.edu.my/periodicals/index.php/mari

Assessing the Influence of Undrained Shear Strength on Coastal Erosion at Muar Coastal Area

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DOI: https://doi.org/10.30880/mari.2026.07.03.017

Article Info

Received: 1 September 2026
Accepted: 15 October 2026
Available online: 01 December 2026

Keywords

Undrained shear strength, coastal erosion, coastal shoreline, shoreline changes, soil strength

Abstract

The natural process of coastal land being worn away, frequently because of wind, tides, waves and currents, is known as coastal erosion This study examines the influence of undrained shear strength, a measure of soil's ability to resist deformation, sliding, or movement under saturated conditions without drainage, on coastal erosion in the region. Field investigations in the Pantai Parit Kedondong, Muar, Johor area, which is severely affected by erosion, involve conducting tests such as the vane shear test (VST), moisture content, sieve analysis, and specific gravity. Satellite imagery is used to identify erosion patterns, while field data helps determine the shear strength of the shoreline soils. The relationship between undrained shear strength and erosion was examined to understand how variations in soil resistance under saturated and undrained conditions influence coastal erosion patterns and rates. The analysis showed that soils with lower undrained shear strength are more susceptible to faster and more severe erosion, as they offer less resistance to deforming forces such as waves and water currents. In contrast, soils with higher undrained shear strength tend to resist these forces more effectively, contributing to greater stability of coastal areas and reducing erosion rates. These findings highlight the critical role of soil properties in shaping coastal dynamics and underscore the importance of considering undrained shear strength when predicting erosion behavior and developing strategies for coastal protection and management.

1. Introduction

The natural process by which coastal land is worn away is known as coastal erosion, and it is frequently brought on by wind, tidal currents, wave action, and sea level rise. Human activities like urbanization, deforestation, and the building of seawalls or breakwaters, which alter sediment flow and reduce coastal resilience, hasten this process even more [1]. Beaches, cliffs, dunes, and other coastal features are lost due to coastal erosion, which has a major effect on ecosystems and local livelihoods. It happens when the water's force is greater than the shoreline soil's resistance, which causes the sediments to shift. Assessing erosion risks and preserving coastal stability requires an understanding of the function of undrained shear strength, which represents a soil's short-term resistance to shear stresses under rapid loading [2]. In Muar, where infrastructure development and mangrove degradation have diminished natural soil reinforcement, exposed sediments are more susceptible to tidal and

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wave forces, increasing the risk of erosion [3]. A key factor in coastal changes is the interaction between hydrodynamic forces and geotechnical features like undrained shear strength. This interaction is significant in areas with clayey soils because cyclic tidal and wave loads can weaken their undrained shear strength. Shoreline resistance has been further weakened in some places by the removal of mangroves, which are naturally occurring protectors of coastal soil [4]. The purpose of this study is to assess how erosion susceptibility along the Muar coast is influenced by differences in undrained shear strength among various soil types and geomorphological settings.

Effective erosion control strategies and the prioritization of high-risk areas depend on field inspections and laboratory analysis. By fostering a deeper comprehension of the physical and geotechnical processes involved, these studies support efforts to protect the coast [5]. Therefore, the impact of undrained shear strength on erosion processes needs to be addressed for Muar's coastal management to be study offers information for creating sustainable mitigation strategies, like revetments and mangrove replanting, by evaluating the connection between soil strength and sediment characteristics. In addition to preserving coastal stability, these initiatives are essential for the region's socioeconomic prosperity and environmental sustainability. The practical applications of this research, such as infrastructure planning and ecosystem conservation, are also significant. The risk of habitat loss, environmental degradation, and infrastructure damage can be decreased by identifying high-risk areas and putting targeted interventions into place [6].

2. Coastal Erosion

A worldwide problem, coastal erosion is brought on by both natural processes like storms, tidal currents, and wave action as well as man-made ones like shoreline development, sand mining, and land reclamation [6]. As a result of this process, shorelines are retreating inland, endangering communities, infrastructure, and ecosystems. Coastal regions are more susceptible to environmental and man-made hazards due to the increasing rate of erosion in many areas, which is primarily caused by anthropogenic factors [4]. Effective mitigation and management strategies are desperately needed because coastal erosion not only destroys habitats and diminishes biodiversity, but it also has an impact on local economies, particularly tourism, and raises the risk of disasters.

2.1 Coastal Erosion at Muar Johor

Coastal sustainability is significantly impacted by sea level rise, which is a result of climate change [7]. Both natural and man-made factors, such as sand mining and the destruction of mangroves, are contributing to the worsening of coastal erosion in Malaysia, particularly in Johor. Ecosystems, infrastructure, and livelihoods are all at risk due to erosion in Muar. A more comprehensive strategy is required despite mitigation initiatives like rock revetments and mangrove replanting [8]. As demonstrated in Batu Pahat, where changes to the coastline between 1985 and 2013 have affected flood-prone areas and community income, coastal areas which are essential to local economies face land loss and infrastructure damage [8].

2.2 Sediment characteristic

The way sediments move, and settle is influenced by their properties, including mineral content, sorting, and grain size [8]. Sand is coarse with good drainage, silt is smooth, gravel is big and heavy, and clay is extremely fine and sticky. While poorly sorted sediments suggest shifting environments, well-sorted sediments show stable conditions. Understanding erosion, transportation, and coastal stability all depend on these characteristics.

2.2.1 Clay

Particles smaller than 0.002 mm make up clay, a fine-grained sediment with flat, plate-like shapes that become sticky when wet. It is essential for soil fertility and plant growth because it efficiently holds onto water and nutrients. The three primary clay minerals kaolinite, montmorillonite, and elite have different characteristics. For instance, kaolinite forms in low weathering conditions, whereas montmorillonite expands when wet. Because clay has a low permeability, it can be used as a natural barrier in dams and landfills. It is useful in ceramics and pottery because of its plasticity, which also makes it easy to mold [9]. Clay deposits are found close to coastal areas all over the world.

2.2.2 Sand

Sand is a hard, resistant sediment that is primarily made up of quartz and has particle sizes ranging from 0.0625 to 2 mm. Depending on the travel distance, sand grains can be angular or rounded. Because of its good drainage, it is frequently found in deserts, rivers, and beaches and is used in filtration and construction. Energy levels affect grain size and sorting; high-energy shorelines have coarser, gritty sand, while calm areas have fine, soft sand. Sand composition and texture are influenced by wave strength [9].

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2.2.3 Gravel

The sediment particles that make up gravel are bigger than sand and range in diameter from 2 to 64 mm. It consists of stones, pebbles, and other rocks that are frequently found along high-energy shorelines where larger materials may be carried and deposited by waves. Pebbles on gravel beaches are frequently rounded or angular in shape due to wave action. These beaches, which are usually found close to river mouths, glacial deposits, or rocky coasts, drain water rapidly because of their coarse texture. Gravel is frequently found on beaches and is created by the erosion and movement of rocks and soil by water and waves [9].

3. Methodology

The main literature on coastal erosion at Kedondong Beach in Muar is reviewed in this chapter, with an emphasis on the different types of sediment and their impact on beach stability the stability of the beach. It illustrates the function of undrained shear strength in preventing erosion and describes the connection between sediment properties and erosion trends. This context aids in the interpretation and analysis of study results.

3.1 Research Site

A site visit was carried out to gather detailed data that considers the surrounding environment, including nearby houses, food stalls, and other features along the study area. The site was accurately identified, its function thoroughly assessed, and the topography analyzed using Google Earth Pro prior to the commencement of fieldwork. This tool was also used to pre-mark sampling points along the shoreline. Several reference images were taken during the initial survey in December 2024, which was the first of several visits that were part of the project.

3.2 Determination of Sampling Station

Pantai Parit Kedondong coastal area was divided into three zones, with two sampling points in each zone. Six (6) sample locations will be included in the coastline area, for a total of twelve sampling locations. The three (3) high tide places will be separated horizontally by about 118 meters, and the three (3) low tide positions were separated from the high tide by about 15 meters. The selection of sampling stations is influenced by accessibility to the sampling sample collection sites during high and low tide. Fig. 1 shows the location for the shoreline sampling at Pandai Parit Kedondong.



Fig. 1 *Location for shoreline sampling*

3.3 Laboratory Testing

Laboratory and field testing are essential for evaluating mechanical and physical properties of coastal sediments as these characteristics influence. Three laboratory tests of moisture content, sieve analysis, and specific gravity were employed in this investigation to examine materials more thoroughly. The amount of water in materials like soil, concrete, or wood is determined by moisture content testing. This is important because excessive moisture can reduce the strength and durability of structures; for example, excessive wet soil can cause instability in foundations, while excessive moisture in concrete or wood can cause cracks or decay [9]. Water loss by weight is calculated after the sample is oven dried. In contrast, sieve analysis uses a stack of sieves with progressively smaller mesh sizes to classify materials such as soil, gravel, or sand according to their particle size distribution. The retained materials are then weighed to determine the percentage distribution [4].

Assessing the undrained shear strength of coastal soils, which influences their resistance to erosion from tides, waves, and currents, requires field testing in addition to laboratory research. The Vane Shear Test (VST),

which involves driving a four-bladed vane into the ground and measuring the torque needed to cause shear failure, is a widely used technique for figuring out the in-situ strength of soil. Better erosion resistance is indicated by higher shear strength, whereas more susceptibility to slope failure and sediment loss is shown by lower values. Predictive models for coastal erosion under environmental stresses are improved, and erosion-prone locations are identified by mapping these values along the shore [10].

4. Result and Discussion

4.1 Shoreline and Coastline Change Analysis

Using aerial photos processed with Google Earth Pro and Global Mapper Pro, a thorough shoreline change analysis was conducted as part of the research of coastal erosion at Pantai Parit Kedondong. Stations A, B, and C are the three designated locations where visual inspections were carried out. Natural ecosystems and mangrove vegetation define Station A, which is situated on the left side of the research area. The presence of several tree roots, including those of mangrove and Ru trees, identifies Station B, which is in the center. The groin at Station C, on the right, was built to reduce coastal erosion. The software marked each coastline in a different color for each year, and overlapping shoreline photos from 2016 and 2021 were used to identify changes. According to this investigation, shoreline alterations differed depending on the location, which is consistent with the erratic, natural behavior of coasts. By splitting each station into 3-meter segments, the variations were measured and show in Fig. 2. The average coastline change was 11.882 meters at Station A, 9.392 meters at Station B, and 4.006 meters at Station C.



Fig. 2 *The overlapping image*

Based on the data from Global Mapper, the average shoreline changes at Pantai Parit Kedondong over a five-year period are approximately 8.43 meters. Due to the preventive mechanisms in place, Station C showed the least amount of change among the three zones, whereas Station A showed the highest. The research revealed that Pantai Parit Kedondong is extremely susceptible to coastal erosion, as evidenced by GPS data indicating a shoreline alteration exceeding 1.5 meters. It is anticipated that the erosion will continue and maybe get worse in the absence of efficient mitigating measures, endangering the infrastructure and ecosystem nearby. Table 1 shows the results highlight the dynamic character of coastal regions and the significance of ongoing management and monitoring initiatives to safeguard these susceptible areas [10].

Table 1 *Coastline changes in Pantai Parit Kedondong*

Zone	Average Shoreline Changes From 2016 to 2021 (m)	Coastline changes
A	11.882	8.43
B	9.392	8.43
C	4.006	8.43

4.2 Experimental Result

This study involved laboratory tests aimed at gaining insight into the soil characteristics from various zones using three primary methods: sieve analysis, specific gravity testing, and moisture content assessments. The sieve analysis in Fig. 3 (a) shows a clear variation in soil particle sizes across the sampling stations. With the largest median grain sizes, Zones C1 and C2 appear to have coarser soil. In the meantime, the soil in zones A1, A2, and B1

was significantly finer, featuring grain sizes of less than 1 mm. These variances may represent natural phenomena like erosion or sediment accumulation occurring differently in each area. Results of the specific gravity test in Fig. 3 (b) indicated that soil from B2 had the highest density, whereas soil from A1 had the lowest density. This might indicate that B2 contains more minerals. Regarding moisture content in Fig. 3 (c), the findings were remarkable A2 exhibited an extremely high moisture level exceeding 90%, which could be attributed to the fact that finer soils generally retain more water. In contrast, the soil in areas such as B2 and C1 was considerably drier. These tests contribute to a clearer understanding of the behavior of each area and provide useful indications of where erosion may be more probable. These tests help clarify the behavior of each area and offer valuable insights into potential erosion hotspots, as finer soils with higher moisture content are typically more susceptible to erosion.

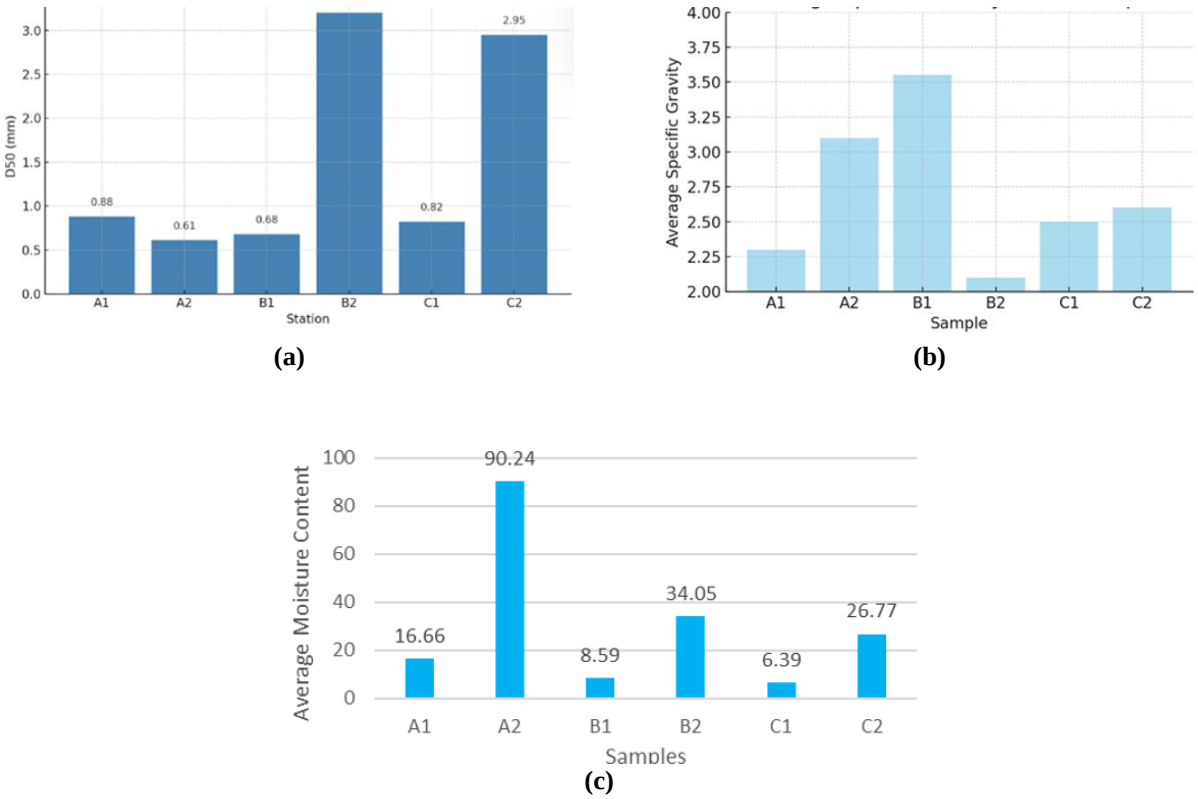

Fig. 3 *Result of sieve analysis (a) on different zones; (b) specific gravity; (c) moisture content*

4.2.1 Sieve Analysis

The sediment properties at Pantai Parit Kedondong are very significant between sites, according to the sieve analysis data gathered from six stations (A1, A2, B1, B2, C1, and C2). In A2, the median grain size (D50) was 0.61 mm, suggesting coarser sand; in B2 and C2, it was 3.20 mm and 2.95 mm, respectively, indicating fine gravel. While the sediments at B2 and C2 exhibit non-uniform and poorly graded compositions, indicating more dynamic depositional settings, the sediment at A2 is more uniform and poorly graded. Although they occasionally have higher grading, stations A1, B1, and C1 also show coarse sand. These results offer important insights into sediment dynamics and erosion potential throughout the coast by classifying the energy conditions and sediment texture at each site as shown in Fig. 4 (a).

4.2.2 Specific Gravity

A range of average specific gravity values were obtained from the analysis of six soil samples (A1, A2, B1, B2, C1, and C2) based on the specific gravity test findings. The average specific gravity of samples A1 and A2 was 2.40 and 3.16, respectively, while C1 and C2 had the highest and lowest specific gravities, 2.51 and 2.57, respectively. These differences point to different mineral densities and compositions in identifying zones of high risk and developing effective mitigation strategies based on specific geotechnical characteristics of the area of the samples; higher specific gravity values are generally linked to lighter, organic-rich soils or higher porosity, whereas higher values indicate denser or more metallic mineral content was shown in Fig. 4 (b).

4.2.3 Moisture

The average moisture content of six different soil samples (A1, A2, B1, B2, C1, and C2) is illustrated in the Fig. 4 (c). While the moisture content of sample A2 is 90.24%, that of sample C1 is only 6.39%. In general, Group A exhibits a broad variation between A1 (16.66%) and A2, while Groups B and C each contain one sample with low moisture content (B1 and C1) and one with higher levels (B2 and C2). These results suggest significant differences in soil properties both between and within the sample groups, possibly due to factors such as soil type, sampling location, or water absorption capacity.

4.3 Sediment properties result

At Pantai Parit Kedondong, this study investigated several important sediment parameters, such as specific gravity, shear strength, moisture content, median particle size (D50), and percentages of gravel, sand, silt, and clay in the sediment composition and it is toward better understanding of the mechanism causing coastal erosion through an examination of the strength of the soil to resist these exposures. Sediment properties differed considerably between sampling locations, as seen in Table 2. With the greatest D50 value of 2.95mm, gravel was the predominant coarse material, particularly at C2 (64.13%), suggesting a more active depositional environment. A2 on the other hand, which represents finer sediment buildup, had the highest moisture content (90.24%), the lowest median particle size (0.61 mm) and a preponderance of sand composition (86.93%). While gravel was more prevalent in B2 (74.77%) and C2, sand predominated at most sampling places, especially A1 (87.55%), B1 (94.06%), and C1 (90.77%). This suggests that the distribution of sediment on the beach varies spatially, ranging from fine to coarse textures.

The specific gravity values were 2.23 to 2.94, with A2 and B1 having the greatest values (2.94) and B2 having the lowest (2.23). These discrepancies are explained by the sediment's organic composition and mineralogical variances. According to the results of the Vane shear test, undrained shear strengths ranged from 0.8 to 1.3 kPa. The weaker, less stable soils were indicated by the lowest shear strengths (0.8 kPa) at A2 and B2, which correlated with increased moisture and finer particles. B1 and C1, on the other hand, displayed the highest shear strengths (1.3 kPa), indicating more solid and well-compacted sediments.

Table 2 *Summary of sediment properties at Pantai Parit Kedondong*

Coastal Areas		A1	A2	B1	B2	C1	C2
	Median Grain Size D50 (mm)	0.88	0.61	0.68	3.2	0.82	2.95
Percentage of Sediment Composition	Gravel (%)	11.87	9.29	5.18	74.77	9.22	64.13
	Sand (%)	87.55	86.93	94.06	24.59	90.77	35.22
	Silt and Clay (%)	0.58	2.94	0.76	0.64	0.8	0.35
	Specific Gravity	2.40	2.94	2.94	2.23	2.51	2.57
	Shear Strength (kPa)	1.0	0.8	1.38	0.8	1.3	1.0
	Moisture Content	16.66	90.24	8.59	34.05	6.39	26.77

4.4 Relationship between Undrained Shear Strengths and Erosion

At Pantai Parit Kedondong, the results from Fig. 4 (a) and (b) clearly demonstrate a correlation between the soil's undrained shear strength (CU) and the rate of shoreline erosion. Zone A had the lowest CU values (1.0 kPa and 0.8 kPa, respectively) and the greatest alteration of the coastline (11.882 m) in both sets of zones (A1–C1 and A2–C2). Zone C, on the other hand, exhibits comparatively higher CU values (1.3 kPa and 1.0 kPa) despite recording the least amount of coastline alteration (4.006 m). This implies that while poorer soils (lower CU) erode more quickly, places with stronger soils (higher CU) are more resistant to erosion.A weak negative correlation (R^2 = 0.3623) between soil shear strength (Cu) and shoreline change is demonstrated in Fig. 4(a) and Fig. 4(b), suggesting that in high-tide areas, where the forces of waves and currents frequently surpass the soil's resistance, increases in Cu have minimal effects on shoreline stability. Additionally, it is affected by elements like soft soil composition and human disturbances. Conversely, Fig. 4 (c) and Fig. 4 (d) show a considerably stronger negative correlation (R^2 = 0.9044), indicating that in low-tide areas characterized by reduced wave energy, a higher soil shear strength significantly diminishes shoreline change. As a result, the results illustrated in Fig. 4 (c) and Fig. 4 (d) are deemed more trustworthy and represent a better basis for this research. The opposite relationship suggests that one of the main factors affecting coastal erosion is undrained shear strength. Low Cu soils are more susceptible to erosion and shoreline retreat because they are less able to withstand the impacts of waves and currents. Thus, enhancing or preserving soil shear strength by vegetation, soil fortification, or structural measures may aid in reducing erosion in coastal management. In conclusion, the rate of erosion in each area increases with decreasing soil shear strength.

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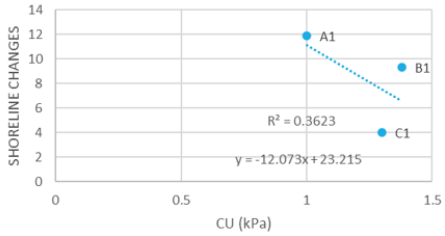
Zone	A1	B1	C1
Average Shoreline Changes	11.882	9.392	4.006
Cu (kPa)	1.0	1.38	1.3

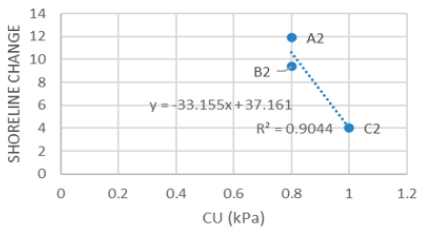
(a)

Zone	A2	B2	C2
Average Shoreline Changes	11.882	9.392	4.006
Cu (kPa)	0.8	0.8	1.1.0

(b)



(c)



(d)

Fig. 4 *The correlation of soil (a) shear strength on shoreline changes for high tide zone; (b) shear strength on shoreline changes for low tide zone; (c) shear strength on shoreline changes graph for high tide zone; (d) shear strength on shoreline changes graph for low tide zone*

A weak negative correlation (R^2 = 0.3623) between soil shear strength (Cu) and shoreline change is demonstrated in Fig. 4 (a) and Fig. 4 (b), suggesting that in high-tide areas, where the forces of waves and currents frequently surpass the soil's resistance, increases in Cu have minimal effects on shoreline stability. Additionally, it is affected by elements like soft soil composition and human disturbances. Conversely, Fig. 4 (c) and Fig. 4 (d) show a considerably stronger negative correlation (R^2 = 0.9044), indicating that in low-tide areas characterized by reduced wave energy, a higher soil shear strength significantly diminishes shoreline change. As a result, the results illustrated in Fig. 4 (c) and Fig. 4 (d) are deemed more trustworthy and represent a better basis for this research. The opposite relationship suggests that one of the main factors affecting coastal erosion is undrained shear strength. Low Cu soils are more susceptible to erosion and shoreline retreat because they are less able to withstand the impacts of waves and currents. Thus, enhancing or preserving soil shear strength by vegetation, soil fortification, or structural measures may aid in reducing erosion in coastal management. In conclusion, the rate of erosion in each area increases with decreasing soil shear strength.

5. Conclusions

The study at Pantai Parit Kedondong demonstrated that the coastal area is experiencing notable shoreline changes, particularly in Zone A, which recorded the highest erosion rate from 2016 to 2021. This erosion indicates that the region is highly susceptible to coastal retreat and environmental instability. Sediment analysis showed a varied distribution of soil types, with sand being the dominant component in most zones, while some areas contained higher gravel content, contributing to better soil stability and drainage. Moisture content and specific gravity varied across locations, influencing the soil's structural properties. Based on the data, Zone A recorded the highest average shoreline change of 11.882 meters between 2016 and 2021, while Zone C had the lowest at 4.006 meters. This pattern is consistent with the vane shear test results, which confirmed that Zone A had the lowest shear strength, indicating weak soil with high water content. In contrast, Zone C exhibited stronger and more stable soil conditions. The significant erosion observed in Zone A can therefore be linked to its poor soil strength, making it more vulnerable to coastal erosion. These findings highlight the importance of understanding site-specific soil behavior for effective coastal planning and management.

Acknowledgement

This research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through Multidisciplinary Research Grant (MDR) (vot Q696) and Geran Penyelidikan Pascasiswazah (GPPS) (vot Q664). The authors would also like to thank the Centre for Diploma Studies, Universiti Tun Hussein Onn Malaysia for its support.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** Mohammad Syazwan Syakir Mawadin, Nurhusna Ilyani Zakaria, Muhammad Fariz Darwish Aron and Mardiha Mokhtar*;* ***data collection:*** Mohammad Syazwan Syakir Mawadin, Nurhusna Ilyani Zakaria and Muhammad Fariz Darwish Aron; ***analysis and interpretation of results:*** *Mohammad Syazwan Syakir Mawadin, Nurhusna Ilyani Zakaria and Muhammad Fariz Darwish Aron;* ***draft manuscript preparation:*** *Mohammad Syazwan Syakir Mawadin, Nurhusna Ilyani Zakaria, Muhammad Fariz Darwish Aron and Mardiha Mokhtar. All authors reviewed the results and approved the final version of the manuscript. The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.*

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