Ocean Systems Engineering, *Vol. 16, No. 2 (2026) 115-128*
https://doi.org/10.12989/ose.2026.16.2.115

Techno-Press

Sediment grain size in the swash zones of Alue Naga and Kuala Gigieng, Aceh Regency, Indonesia

Ichsan Setiawan*[1], Rafwan Hidayat[1], Syahrul Purnawan[1], Syarifah Meurah Yuni[2], Makwiyah A. Chaliluddin[3], Said Ali Akbar[4]

[1]*Department of Marine Sciences, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia*
[2]*Department of Mathematics, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia*
[3]*Laboratory of Fishing Technology, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia*
[4]*Department of Aquaculture, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia*

(Received July 20, 2025, Revised February 3, 2026, Accepted March 26, 2026)

Abstract. This research investigates seasonal variations in sediments of the swash zones at Alue Naga and Kuala Gigieng, Indonesia, by measuring mean grain size, sorting, skewness, kurtosis, slope of the beach, and height of waves. Sediment samples were collected during May and July 2022 using core sampling to a depth of 15 cm from the swash zones of Alue Naga and Kuala Gigieng. In May, mean grain size (Mz) values ranged from 0.89–1.99 φ at Alue Naga and 1.40–2.16 φ at Kuala Gigieng, both locations being dominated by medium and fine sands. In July, the sediments had changed to predominantly coarser sediments, the Mz values of both locations changed to 0.73–1.99 φ for Alue Naga and 0.71–2.06 φ for Kuala Gigieng; however, gravel content increased at both locations to 9.93% and 14.34%, respectively. It was found that the sorting had improved at Alue Naga (σ = 0.35–0.88 φ) while the sorting was highly variable at Kuala Gigieng (σ = 0.08–2.06 φ). Skewness was predominantly coarse skewed at both locations, indicating a predominance of strong hydrodynamic forcing at both study locations. Kurtosis values showed a range from very platykurtic (at 0.20 φ) and later a very leptokurtic (at 2.43 φ). Seasonal increases in wave energy, likely influenced by monsoon weather patterns, impact sediment structure and distribution. Regular observations of sediments in the swash zones provide important information to support coastal management in response to the impacts of natural processes and human activities that affect the coastline.

Keywords: coastal management; grain size; sediment; swash zone

1. Introduction

The different sediment properties found in coastal areas will reflect how the physical and biological activity of the coastal area has changed over time. Consequently, this type of analysis serves as a record of changes in environmental processes from the past to the present, and provides a baseline for future changes. Sediment analysis typically utilises statistical parameters to analyse present and past depositional conditions, including mean grain size, sorting, skewness and kurtosis, amongst other environmental parameters [1-3]. Mean grain size is one of the primary parameters in sediment studies, as it provides valuable information related to processes that transport sediments and the amount of energy available to deposit or accumulate sediments. The research in

*Corresponding author, Ph.D., E-mail: ichsansetiawan@usk.ac.id

http://www.techno-press.org/ose/5

ISSN: 2093-6702 (Print), 2093-677X (Online)

the Aceh region suggests that different hydrodynamic environments will have different sediment distribution patterns within the Kuala Gigieng Estuary due to the processes controlling sediment deposition [4-7]. Not only does the classification of sediments provide an understanding of sediment characteristics at present, but it also assists in reconstructing marine and coastal processes from the past; thus, by examining sediment types, geologists can interpret sedimentological history, determine the source of sediments and assess both anthropogenic and natural impacts on nearshore and marine environments [8-11]. Through the study of sediment grain characteristics in coastal settings, we can enhance our understanding of beach morphodynamics and coastal management; in addition, we will expand our knowledge of Earth Sciences and Environmental Sciences, therefore making these types of studies critical for the continued sustainability and protection of the changing coastal ecosystems.

The swash zones are important locations for mixing sediments and determining how coastlines develop over time because they are where most of the sediment being mixed along coastlines gets mixed [12-15]. This zone is defined by the uppermost limit reached by rising waves and the lowermost boundary of falling waves, marking the area most frequently reworked by wave action [16-18]. Sediment transport within the swash zones occurs based on the type of wave, the size of particles of sediment, and the slope of the beach. Waves that are moving to the beach at different angles create sediment movement towards and away from the beach based on the slope of the beach, causing further redistribution of sediment. Sediments from higher energy waves will generally move further out towards the sea than sediments from waves with lower energy, thus moving towards land as well [19-21]. Due to the differing forces operating the swash zone, sediment sizes vary widely. Variations due to wave energy and physical characteristics of locations can have an influence over how sediments are influenced. By observing these active processes, we can learn about their patterns of movement so that we may be able to manage coastal areas more efficiently as well as anticipate both natural and anthropogenic changes to sediment transport.

The Alue Naga area is at the eastern border of Banda Aceh, Indonesia, in Syiah Kuala subdistrict on the Malacca Strait and has coordinates of longitude E95°21.25" to 5°35.00"; and latitude N5°20.25" to S5°35.60". The Alue Naga coastline features a highly dynamic marine environment compared to the area of Kuala Gigieng, located within Baitussalam subdistrict in Aceh Province, which is situated in a delta formed by where the rivers named Lambada Lhok, Lamnga and Baro combine. The hydrologically connected to the Malacca Strait and the Krueng Neuheun River, both of which are adjacent to Alue Naga, possess distinct sedimentation characteristics resulting from the interaction of the hydrodynamic processes occurring in both locations. The objective of this research is analyze the mean grain size of sediments found at Alue Naga and Kuala Gigieng as an indicator of sediment dynamics in the swash zone. Although earlier research has established general trends for sediment distribution between (and within) coastal and estuarine environments throughout the study region, there is still insufficient knowledge of how coastal morphology and wave energy can influence sediment properties in active swash zones. The results of this research provide important insights into sediment movement in coastal ecosystem transition zones leading to improved sediment behavior prediction models that can be used by planners and managers of sustainable coastal development, while maintaining ecological functions during periods of environmental change.

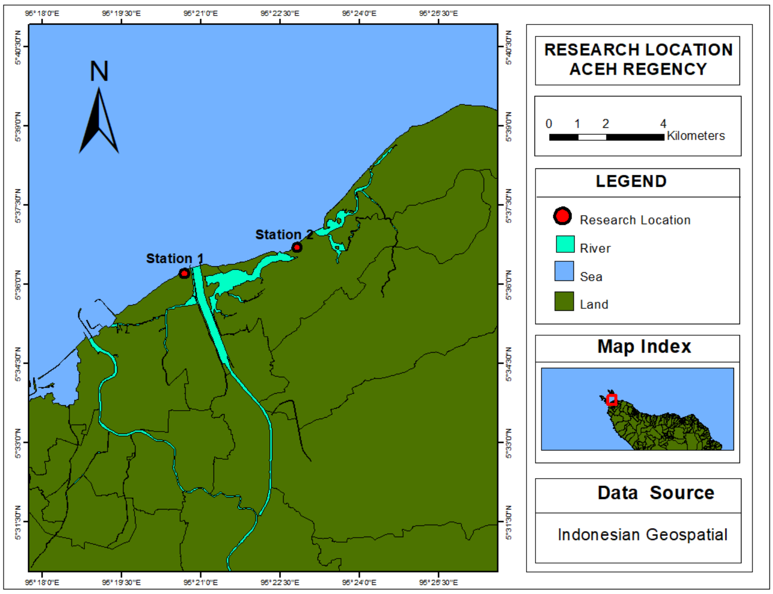

Figure 1. Research locations for Alue Naga (Station 1) and Kuala Gigieng (Station 2) swash

2. Research methods

2.1 Study area

The research was conducted in two areas; the Alue Naga, Banda Aceh City, and Kuala Gigieng swash zone, Aceh Regency, in May 2022 and July 2022 (Fig. 1). The research included direct data collection of sediment samples, coastline slope, and incoming sea wave height in the field, and then the samples were analyzed at the Marine and Fisheries Laboratory of Universitas Syiah Kuala (USK), Indonesia.

2.2 Sediment sampling procedure

Sediment collection was carried out based on the coring method by sinking a tube core with a diameter of 2.5 in and a length of 15 cm perpendicular to a depth of 15 cm divided into 7.5 cm upper layer and 7.5 cm lower layer [21]. Sediment sampling was conducted in the area bounded by the highest limit of rising waves (flood swash zone) and the lowest limit of falling waves (ebb swash zone) on the beach (intertidal zone). The sample was then taken to the laboratory for analysis. The sampling was performed twice in May and July 2022.

2.3 Laboratory analysis

The weight percentage of sediment determined from each sediment fraction was calculated using Eq. (1).

$$\text{Weight percent (\%)} = \frac{\text{fraction weight } i}{\text{total weight of sample}} \text{ x } 100\ \% \tag{1}$$

where the fraction weight i and total weight of the sample are the weight of each grain size fraction and number of grain size fractions in grams, respectively. The weight percentage of sediment for each data point was classified using Folk's triangle to determine the sediment type [22].

2.4 Statistical analysis of grain size

The sediment means grain size (M_Z) was obtained based on the graphical method [3], following Eq. (2).

$$M_Z = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3} \tag{2}$$

Then, the statistical parameters namely sorting (σ_I), skewness (Sk_I), and kurtosis (K_G) are also based on the graphical method using Eqs. (3)-(5), respectively.

$$\sigma_I = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6} \tag{3}$$

$$Sk_I = \frac{\phi_{16} + \phi_{84} - 2(\phi_{50})}{2(\phi_{84} - \phi_{16})} + \frac{\phi_5 + \phi_{95} - 2(\phi_{50})}{2(\phi_{95} - \phi_5)} \tag{4}$$

$$K_G = \frac{\phi_{95} - \phi_5}{2.44(\phi_{75} - \phi_{25})} \tag{5}$$

where, ϕ is $-\log_2 d$, parameter d is the sediment grain diameter in millimeters.

3. Results

3.1 Weight percentage and type of sediment

Tables 1 and 2 report the percentage of sediment weight in each grain-size fraction at Alue Naga (Station 1) and Kuala Gigieng (Station 2) during May and July 2022. Grain-size classes follow the phi scale: 2 mm = gravel, 0.063–1 mm = sand, and 0.038 mm = mud. Between May and July 2022, both Alue Naga (Station 1) and Kuala Gigieng (Station 2) experienced a clear coarsening of their swash-zone sediments (Table 3). In May, gravel (2 mm) was virtually absent in most layers ranging from just 0.01 % to 7.09% by weight and sand (0.063–1 mm) overwhelmingly dominated across flood and ebb layers, while mud (< 0.038 mm) remained below 0.4 %. By contrast, July saw gravel rise markedly to 1.26 %–9.93 % at Station 1 and 3.05%–14.34 % at Station 2, even as sand still comprised the bulk (85 %–96.87 %), and mud decreased only slightly (0.08 %–0.13 %). This shift indicates that coarser particles were more prevalent in July, likely due to changes in hydrodynamic energy or sediment supply between the two sampling periods.

3.2 Statistical parameters of sediment grain size

The results of the statistical parameters, mean grain size (M_Z), sorting (σ_I), skewness (Sk_I), and kurtosis (K_G) are shown in Table 4. The appearance of this statistical parameter is considered to

Table 1. Percentage of sediment weight based on weight fraction at Alue Naga and Kuala Gigieng swash zone in May 2022

Month	Diameter	Fraction	Sediment weight percentage (%)			
May	(mm)		USF	LSF	USE	LSE
	2	Gravel	0.08	0.02	7.09	2.16
	1		0.41	0.31	13.53	6.61
	0.5		9.37	8.92	26.86	13.04
St 1	0.25	Sand	56.61	49.40	22.91	15.16
	0.125		28.56	37.65	18.09	47.52
	0.063		4.96	3.60	11.29	15.34
	0.038	Mud	0.02	0.10	0.23	0.18
	Total		100.00	100.00	100.00	100.00
	2	Gravel	1.55	0.01	0.85	0.03
	1		9.55	0.322	2.35	0.31
St 2	0.5		25.04	2.05	6.98	3.08
	0.25	Sand	28.15	25.39	24.30	24.53
	0.125		32.03	66.11	58.85	64.95
	0.063		3.51	5.88	6.32	6.74
	0.038	Mud	0.25	0.24	0.34	0.36
	Total		100.00	100.00	100.00	100.00

Where:
USF=Upper sediment layer in the flood swash zone
LSF=Lower sediment layer in the flood swash zone
USE=Upper sediment layer in the ebb swash zone
LSE=Lower sediment layer in the ebb swash zone
St= Station

reflect the representativeness and dominance of sediments in the swash zone of Alue Naga (Station 1) and Kuala Gigieng (Station 2). In May, the inclusive graphic mean grain size (M_Z) at Alue Naga (Station 1) ranged from 0.89 φ (coarse sand) in the flood zone to 1.99 φ (medium sand) in the ebb zone. At Kuala Gigieng (Station 2), M_Z values fell between 1.40 φ and 2.16 φ, spanning medium to fine sand. In July, Station 1 M_Z values shifted slightly coarser overall (0.73–1.99 φ), with the flood layer coarser (0.73–0.88 φ) and the ebb layer similar to May (1.96–1.99 φ). Station 2 in July produced M_Z = 0.71 φ (coarse sand) in the flood zone, 1.43–1.44 φ (medium sand) in the lower flood and upper ebb, and 2.06 φ (fine sand) in the ebb lower. Thus, July's swash sediments were, on average, coarser than those in May, consistent with a decrease in M_Z from May to July (Fig. 2).

May's sorting (σ) at Station 1 varied between 0.89 φ (moderately sorted) and 1.99 φ (poorly sorted), while Station 2 spanned 0.322 φ (well sorted) up to 0.66 φ (moderately well sorted). In July, Station 1 σ tightened to 0.35–0.88 φ (very well to moderately sorted), whereas Station 2 broadened to 0.08 φ (extremely well sorted) up to 2.06 φ (extremely poorly sorted). In other words, July saw Station 1 become more uniformly sorted, but Station 2 experienced a wider range from very uniform to very mixed sediments. For skewness, May's Station 1 yielded both coarse-skewed and near-symmetrical values, and Station 2 ranged from fine-skewed through very coarse-skewed. In July, Station 1 skewness ranged from very fine-skewed to very coarse-skewed and near symmetrical, while Station 2 fell between coarse-skewed and very coarse-skewed. As for kurtosis, May samples at both stations covered very platykurtic through very leptokurtic (0.20–2.43 φ),

Table 2. Percentage of sediment weight based on weight fraction at Alue Naga and Kuala Gigieng swash zone in July 2022

Month	Diameter	Fraction	Sediment weight percentage (%)			
July	(mm)		USF	May	(mm)	
St 1	2	Gravel	4.56	9.93	6.63	1.26
	1		12.91	14.64	10.96	1.26
	0.5		19.27	14.56	17.05	6.37
	0.25	Sand	25.84	21.12	29.26	42.42
	0.125		32.99	34.40	31.95	45.03
	0.063		4.07	4.83	3.94	3.63
	0.038	Mud	0.35	0.53	0.21	0.30
	Total		100.00	100.00	100.00	100.00
St 2	2	Gravel	4.67	3.05	14.34	5.88
	1		8.17	5.78	14.59	5.85
	0.5		15.46	12.73	19.95	17.80
	0.25	Sand	33.23	53.38	28.98	52.97
	0.125		34.95	23.08	20.53	16.66
	0.063		3.38	1.90	1.56	0.84
	0.038	Mud	0.13	0.08	0.04	0.02
	Total		100.00	100.00	100.00	100.00

Table 3. Sediment types at Alue Naga and Kuala Gigieng swash zone in May and July

Month	Sampling Point	Sediment Layer	% Gravel	% Sand	% Mud	Total (%)	Sediment type
May	St 1	USF	0.08	99.90	0.02	100.00	Slightly gravelly sand
		LSF	0.02	99.89	0.1	100.00	Slightly gravelly sand
		USE	7.09	92.67	0.23	100.00	Gravelly sand
		LSE	2.16	97.67	0.18	100.00	Slightly gravelly sand
	St 2	USF	1.55	98.20	0.25	100.00	Slightly gravelly sand
		LSF	0.01	99.74	0.24	100.00	Slightly gravelly sand
		USE	0.85	99.81	0.34	100.00	Slightly gravelly sand
		LSE	0.03	99.61	0.36	100.00	Slightly gravelly sand
July	St 1	USF	4.56	95.09	0.35	100.00	Slightly gravelly sand
		LSF	9.93	89.54	1.53	100.00	Gravelly sand
		USE	6.63	93.16	0.23	100.00	Gravelly sand
		LSE	1.26	98.72	0.3	100.00	Slightly gravelly sand
	St 2	USF	4.67	95.15	0.13	100.00	Slightly gravelly sand
		LSF	3.05	96.87	0.08	100.00	Slightly gravelly sand
		USE	14.34	85.61	0.04	100.00	Gravelly sand
		LSE	5.88	94.11	0.02	100.00	Slightly gravelly sand

whereas July's kurtosis likewise spanned all classifications but with a slight shift toward higher values in the flood layers (indicating more peaked, well-sorted central modes). Together, these precise values confirm that July's sediments were overall coarser, exhibited more variable sorting

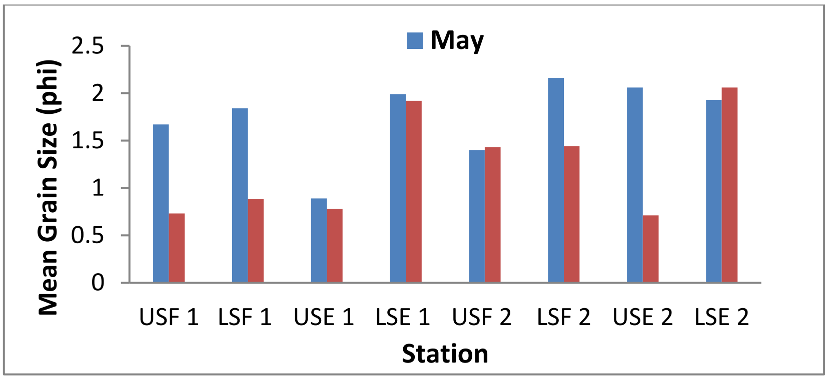

Figure 2. Comparison of M_Z values for May and July

Table 4. Calculation Results of Statistical Parameters for Sediment Grain Size for May and July 2022 in ϕ

Month	St	Sediment Layer	M_Z	Classification	σ_I	Classification	Sk_I	Classification	K_G	Classification
	1	USF	1.67	Medium sand	0.71	Moderately sorted	0.09	Coarse skewed	1.04	Mesokurtic
		LSF	1.84	Medium sand	0.75	Moderately sorted	0.02	Coarse skewed	0.20	Very platykurtic
May		USE	0.89	Coarse sand	1.74	Poorly sorted	0.26	Coarse skewed	0.81	Platykurtic
		LSE	1.99	Medium sand	0.97	Moderately sorted	0.14	Near symmetrical	1.20	Leptokurtic
	2	USF	1.40	Medium sand	0.67	Moderately sorted	0.27	Fine skewed	0.94	Mesokurtic
		LSF	2.16	Fine sand	0.39	Well sorted	0.15	Near symmetrical	1.90	Very leptokurtic
		USE	2.06	Fine sand	0.86	Moderately sorted	0.30	Very coarse skewed	1.16	Leptokurtic
		LSE	1.93	Medium sand	1.32	Very well sorted	0.41	Very coarse skewed	1.45	Leptokurtic
	1	USF	1.96	Medium sand	1.71	Moderately sorted	0.34	Very coarse skewed	0.81	Platykurtic
		LSF	0.88	Coarse sand	0.31	Very well sorted	0.44	Very fine skewed	0.37	Very platykurtic
July		USE	0.73	Coarse sand	0.80	Moderately sorted	0.45	Very fine skewed	0.84	Platykurtic
		LSE	1.92	Medium sand	0.78	Moderately sorted	0.13	Coarse skewed	1.16	Leptokurtic
	2	USF	1.43	Medium sand	7.24	Extremely poor sorted	0.26	Coarse skewed	2.43	Very leptokurtic
		LSF	1.44	Medium sand	1.05	Poorly sorted	0.39	Very coarse skewed	1.65	Very leptokurtic
		USE	0.71	Coarse sand	1.41	Poorly sorted	0.57	Very fine skewed	0.44	Very platykurtic
		LSE	2.06	Fine sand	1.03	Very well sorted	2.27	Very fine skewed	0.26	Very platykurtic

at Kuala Gigieng, and maintained mixed distribution shapes in skewness and kurtosis compared to May.

Table 5. Average values of slope, wave, and mean grain size in the swash zone

Month	Station	Slope (%)	Wave height (cm)	M_Z (ϕ)
May	1	3.30	100	1.75
	2	2.65	83	1.78
July	1	3.87	67	0.80
	2	2.33	126	1.43

3.3 The relationship between mean grain size, slope and waves

The beach slope is an important parameter in determining the mean grain size of the sediment because the steeper the beach slope, the coarser the grain size. The Alue Naga and Kuala Gigieng swash zones had the same slope percentages. The slope classification at Alue Naga was 3.30% at Station 1 in May, 2.65% at Station 2 in May, while at Kuala Gigieng it was 3.87% at Station 1 in July and 2.33% at Station 2 in July. Therefore, the slope classification of these two swash zones was included in the low-slope category. Sea waves are significantly influenced by various oceanographic and atmospheric conditions. Beach waves are created by the force of the blowing wind. As you enter sailing waters, ocean waves increase in size. This is because the bottom of the wave experiences pressure due to contact with the bottom of the water. In May, the wave height was 100 cm at Station 1 and 83 cm at Station 2. In July 2022, the wave height was 67 cm at Station 1 and 126 cm at Station 2 (Table 5).

4. Discussion

The sediment dynamics of Alue Naga and Kuala Gigieng swash zones in May reflect transitional coastal systems that have moderate hydrodynamic forcing. At Alue Naga (station 1), Mz ranged between 0.89 φ (flood, coarse sand) to 1.99 φ (ebbs, medium sand). This indicates an onshore-offshore sorting gradient created by fluctuations in wave energy. In Kuala Gigieng (Station 2), sediments generally exhibit finer grain size characteristics, with a grain size range between 1.40 and 2.16 φ. The presence of fine sand (2.16 φ) in the ebb layer indicates that the local depositional environment was influenced by sediment supply from the Krueng Neuheun estuary. These differences in characteristics are also reflected in the sorting patterns at both stations. Station 1 exhibits a higher degree of sorting variability, ranging from moderate to poor sorting, reflecting the influence of high-energy conditions that cause sediment instability. Station 2 exhibits a relatively more uniform sorting pattern, ranging from well to moderate sorting, indicating a more stable depositional process [23]. Sediment skewness analysis, which is generally coarse and approaching symmetry, indicates that the fine sediment fraction is still being transported through erosion processes. This condition is most evident at Station 2, which has a higher percentage of fine material than the other stations. The kurtosis values obtained vary from highly platykurtic (0.20 φ) to highly leptokurtic (2.43 φ), which reflects the presence of sharp distribution peaks and a wide grain size range due to sediment mixing. This indicates that the waves and currents causing the transport of material have not been consistent [24], [25]. Therefore, these characteristics of the data suggest that there has been an intricate interplay between the energy of the waves and the environment within the estuaries along with sediment inputs, leading to the development of May profiles for the swash zone, while bringing to light new information on spatial variability of these processes over the section of coast studied within the Malacca Strait.

The differences in the characteristics of sediments within the swash zone observed at both study locations are directly correlated to the seasonal fluctuations that occur in coastal sediment transport due to variations in hydrodynamic forces. For example, the dramatic increase in the mean grain size (Mz) observed at both study locations for the month of July shows a significant increase of 0.73–0.88 φ (coarse sand) at Station 1 and 0.71–2.06 φ at Station 2, which indicates an increase in wave intensity. It should be noted that the substantial increase in wave height at Station 2 (up to 126 cm) likely caused an increase in sediment movement, which facilitated the movement of fine sediments off of the beach, whereas the same increased wave intensity helped retain the coarser fractions of sediment in the swash zone at Station 2. The results also indicate that at Station 1, increased sediment sorting occurs from having "very well sorted" to "moderately sorted," which suggests that at Station 1, there is a consistent and steady winnowing process occurring due to extended wave energy during the high-energy month of July. However, the increase in the diversity of sorting at Station 2 from "very well sorted" to "extreme poor sorting" indicates a more complex depositional pattern. The fluctuations in sorting are a result of alternating periods of high energy and low-energy waves, as well as local estuarine influences, and variable wave generate sediment layers that have multiple grain-size distributions [26]. Patterns of skewness provide further evidence of the aforementioned dynamic processes. The prevalence of both coarse skewed and very coarse skewed sediments represents the removal of fine sediments due to high hydrodynamic forces during July across both stations. In contrast to this generalised removal of the finer sediment, areas of fine skewed sediments were identified at one of the study locations (Station 1) where it is likely that these sediments have been deposited during short duration, low energy events (depositional events). The relationship between wave energy, sediment sorting, and skewness indicates how sensitive swash zone sedimentary structures are to both episodic high energy events, as well as ongoing variability in hydrodynamic conditions [27], [28]. The results presented here add to the existing body of knowledge regarding sediment transport mechanisms in monsoon-influenced coastal environments and demonstrate the importance of monitoring sediment dynamics temporally to assess how they respond to the gradual change of environmental factors.

Kurtosis measurements from May and July indicate that sedimentary processes in the swash zone are highly influenced by their complexity as a result of combined wave and current activity. In May, kurtosis values were very platykurtic (0.20 φ) and very leptokurtic (2.43 φ); they contained both poorly sorted broad populations of sediment and well-sorted layers exhibiting narrow-selected grain sizes. Variability in these kurtosis values indicates that during this period sediment was subjected to a mixed-energy regime where continuous wave and current action frequently modified sediment structure. By the end of July, kurtosis measurements displayed similar variation across the whole range of kurtosis measurements. However, a significant change is that flood sediment layers displayed greater peakedness (more leptokurtic values) in their grain-size frequency distributions due to long-term winnowing action (when wave energy continually sorts sediment) and increased strength of the wave-driven sorting process. Conversely, ebb sediment layers retained more diverse platykurtic kurtosis patterns, indicating episodic reworking and deposition due to transient energy events, for example, storms or shifts in wave pattern behaviour [25], [26]. The appearance of both platykurtic and leptokurtic forms in the swath zones is evidence for the continuously changing or shifting processes responsible for sediment transport. In this instance, sediment transport through the swash zones can be considered a product of multiple interactions of energy influenced by wave action during storm conditions. The ability of sediment to either develop complex layers or remain uniform during varying levels of wave action reinforces the necessity of detailed temporal data collection. Single-time data points are unable to provide a complete picture of how sedimentary processes will dictate beach morphology and stability within these areas [27], [28].

The differences between July and May show that in July, coarser sediments were deposited in the swash zone at all locations, as shown by the lower mean grain size (Mz) of July sediments. This increase in coarseness suggests an increase in hydrodynamic energy; either as a result of seasonal monsoon-induced wave intensity, or an increase in sediment coming from rivers. Sediments from Station 1 are relatively uniform in their sorting in July, which reflects that they have gone through continued removal of the finer grain sizes due to continuously applied wave energy at Station 1. In contrast, sediments from Station 2 were more variable in their sorting category, ranging from very well sorted to extremely poorly sorted. This indicates that Station 2 sediments have been affected by both high and low periods of energy, as well as riverine inputs and the complexities of nearshore circulation. The persistence of coarse skewness at both stations in July indicates the prevalence of processes that preferentially removed finer grain sizes [29]. The presence of pockets of fine skewness and the full spectrum of kurtosis values, including platykurtic formats, indicates that the presence of episodic low-energy events that contribute to sediment structure was also significant in July. However, the fact that fine-skimmed pockets are present and that all values of kurtosis exist (including platykurtic), indicates that low-energy episodic events have had an effect on sediment structure [30]. This suggests that even though the environment during July was dominated by larger energy forces, the sedimentary environment was very dynamic and responded to both continuous processes as well as event-based processes. Understanding how they interact is important to predicting the behaviour of sediment within a monsoon effect coastal area and developing adaptive coastal management solutions.

Wind and wave energy combine to create an important mechanism for influencing the characteristics of sediments within the swash zone of this coastal geomorphic system. High-energy wind-generated waves, especially in combination with high-energy onshore winds, have the potential to create substantial turbulence within the nearshore zone and to create enhanced sediment transport and sorting. Based on the skewness data collected from samples, it can be reasonably concluded that hydrodynamic forces were the primary processes driving the transport and sorting of sediments during the sampling period. The strong onshore winds were likely responsible for removing fine-sized sediments from the nearshore zone, thereby resulting in the coarse skewed grain size distributions observed [31]. Conversely, sediment that is transported by aeolian processes is typically very fine skewed or symmetrical in nature. This finding indicates a limited contribution from wind-deposited dust or material originating from the surrounding dunes. It appears these aeolian deposits were localized, likely affecting backshore/interdune areas rather than primarily foreshore sediment bodies. As an example, the presence of these minor detectable aeolian contributions (derived largely from wind) on top of the predominant wave contributions shows how complicated the interactions between coastal sediment movement via wind and waves can be particularly in areas of dynamic monsoon weather patterns.

The combined grain-size metrics indicate that the coastal habitat is quite dynamic, with large changes in wave energy and a broad range of local topographical features affecting the sediment size distributions. The high concentration of poorly sorted sediment indicates that the region experiences many high-energy events (e.g., storm waves) that can move and redeposit large particles and simultaneously remove small particles from the system. Some fine sediment does accumulate during calmer periods, but the vast majority of the sediment remains coarsely skewed (high concentrations of coarse material). Evidence for this dynamic system can also be found in the beach slope angle measurements: steeper slopes correlate with coarser, better-sorted sands due to rapid energy dissipation, whereas flatter profiles retain relatively finer sediments. Skewness and kurtosis metrics further strengthen the interpretation of coarse-grained slope dominance, while leptokurtic kurtosis values reflect ongoing filtering and periodic sediment reworking. These conditions indicate active depositional dynamics, with sediments continually being re-selected by hydrodynamic processes.

The slope of the beach is affected directly by increased wave energy. Higher energy conditions tend to create steeper beach profiles. When there is greater strength and frequency of wave action, sediment is sorted more rapidly because finer-grained particles are moved into the vertical air column and pushed offshore while coarser-grained particles remain in the swash zone. Continued wave action at locations where hydrodynamic forces are present will display this effect more noticeably. Therefore, it can be concluded that coarser-sized sediment was found in July during the high-wave period because of wave-induced erosion, intensified hydrodynamic activity, and shape changes of the sedimentary structure. Additionally, sediment grain size distribution indicates that the wave action predominately influences transport of sediments along this shoreline and that secondary but significant contributions are made by the dominant wind and topographic variation. These findings generally support the theory that a high energy beach under mixed wave conditions is defined as the interaction of wave action and beach morphology, which ultimately governs sediment dynamics.

5. Conclusions

The dynamic nature of sediment transport and distribution under various seasonal hydrodynamic conditions in the swash zones of Alue Naga and Kuala Gigieng, Indonesia, is highlighted in this research. There are noticeable differences in the characteristics of the sediment between May and July, which are caused by modifications in coastal processes. Medium to fine sands predominated in the sediments in May, with mean grain sizes (Mz) ranging from 0.89–1.99 φ at Alue Naga and 1.40–2.16 φ at Kuala Gigieng. In July, coarser sediments were more common; Mz dropped to 0.73–1.99 φ and 0.71–2.06 φ, respectively, while the gravel content significantly increased to 9.93% and 14.34%. A more consistent winnowing regime is indicated by improved sorting at Alue Naga (σ = 0.35–0.88 φ), while alternating energetic and calm periods are reflected in the wider sorting range at Kuala Gigieng (σ = 0.08–2.06 φ). The influence of strong wave action interspersed with episodic low-energy deposition is further highlighted by persistent coarse skewness and a broad range of kurtosis values (0.20–2.43 φ) across both locations. The correlation between wave height which reached peaks of up to 126 cm with coastal slope and sediment characteristics confirms the high sensitivity of swash zone sediments to seasonal monsoon forcing.

Overall, the results of this study indicate that the coastal system is highly responsive to a combination of episodic events and ongoing hydrodynamic processes. These findings have important implications for coastal management and policy formulation, particularly in emphasizing the importance of routine monitoring of sediment dynamics to anticipate and mitigate the impacts of natural variability and human-induced changes on shoreline stability and coastal ecosystem health in monsoon-affected areas.

Acknowledgements

The author would like to thank the Institute for Research and Community Service at Universitas Syiah Kuala (USK) and Ministry of Education, Culture, Research, and Technology, Indonesia.

References

1. Christensen, D.F., Hughes, M.G., Aagaard, T. (2019). Wave period and grain size controls on short-wave suspended sediment transport under shoaling and breaking waves. Journal of Geophysical Research: Earth Surface, 124(12), 3124-3142. https://doi.org/10.1029/2019JF005168.
2. Lagarde, S., Dietze, M., Gimbert, F., Laronne, J.B., Turowski, J.M., Halfi, E. (2021). Grain-size distribution and propagation effects on seismic signals generated by bedload transport. Water Resources Research, 57(4), e2020WR028700. https://doi.org/10.1029/2020WR028700.
3. Su, M., Luo, K., Fang, Y., Kuang, Z., Yang, C., Liang, J., Liang, C., Chen, H., Lin, Z., Wang, C., Lei, Y., Liu, S., Stow, D.A.V. (2021). Grain-size characteristics of fine-grained sediments and association with gas hydrate saturation in Shenhu Area, northern South China Sea. Ore Geology Reviews, 129, 103889. https://doi.org/10.1016/j.oregeorev.2020.103889.
4. Hasanah, M., Syamsuddin, F., Safitri, R., Fadhli, Z., Karmel, M.E.R., Syukri, M. (2024). Analysis of gravity anomaly data for identification of mineral distribution prospects in the Kuta Cot Glie area, Aceh Besar. IOP Conference Series: Earth and Environmental Science, 1356(1), 012118. https://doi.org/10.1088/1755-1315/1356/1/012118.
5. Ismail, N., Yanis, M., Asyqari, A. (2023). The use of magnetic and geoelectrical methods to locate buried ancient artificial canals and wells around the cultural heritage of Indrapatra Fort, Aceh, Indonesia. Geosciences Journal, 27(1), 67-76. https://doi.org/10.1007/s12303-022-0025-y.
6. Roodhiyah, L.Y., Nurhasan, Tiffany, Pratomo, P.M., Susilawati, A., Supriyadi, Ogawa, Y., Sugiyanto, D., Sutarno, D., Srigutomo, W. (2024). Interpretation of a 3D magnetotellurics model of the Aceh and Seulimeum segments of the Sumatran fault zone. Applied Sciences, 14(23). https://doi.org/10.3390/app142311335.
7. Surya, R. A., Abdullah, F., Darisma, D., Yanis, M., Ismail, N. (2019). Sedimentation process in Kuala Gigieng Coast, Aceh Besar based on magnetic and gravity surveys. IOP Conference Series: Earth and Environmental Science, 348(1), 012040. https://doi.org/10.1088/1755-1315/348/1/012040.
8. Cui, X., Yang, F., Wang, X., Ai, B., Luo, Y., Ma, D. (2021). Deep learning model for seabed sediment classification based on fuzzy ranking feature optimization. Marine Geology, 432, 106390. https://doi.org/10.1016/j.margeo.2020.106390.
9. Ji, X., Yang, B., Tang, Q. (2020). Seabed sediment classification using multibeam backscatter data based on the selecting optimal random forest model. Applied Acoustics, 167, 107387. https://doi.org/10.1016/j.apacoust.2020.107387.
10. Kairouani, H., Zaghloul, M.N., Abbassi, A., Micheletti, F., Fornelli, A., El Mourabet, M., Piccoli, F., Criniti, S., Critelli, S. (2023). Provenance and source-to-sink of lower-middle Jurassic sediments from hinterland mounts to NW-Gondwana hyper-extended passive margin (Prerif sub-domain, External Rif, Morocco): First evidence from sedimentary petrology and detrital Zircon geochronology. Marine and Petroleum Geology, 157, 106492. https://doi.org/10.1016/j.marpetgeo.2023.106492.
11. Setiawan, B., Antonie, S., Adhiperdana, B.G. (2019). Grain-size characteristics of Aceh's coastal deposits. IOP Conference Series: Materials Science and Engineering, 523(1), 012082. https://doi.org/10.1088/1757-899X/523/1/012082.
12. Chen, W., van der Werf, J.J., Hulscher, S.J.M.H. (2023). A review of practical models of sand transport in the swash zone. Earth-Science Reviews, 238, 104355. https://doi.org/10.1016/j.earscirev.2023.104355.

13. Chen, W., van der Werf, J.J., Hulscher, S.J.M.H. (2024). Practical modelling of sand transport and beach profile evolution in the swash zone. Coastal Engineering, 191, 104514. https://doi.org/10.1016/j.coastaleng.2024.104514.
14. Suzuki, T., Tomoki, H., Gelfi, M. (2025). Field study of sediment transport dynamics in swash zone using fluorescent sand tracers. Coastal Engineering Journal, 67(2), 350-362. https://doi.org/10.1080/21664250.2025.2485606.
15. Tazaki, T., Eiji, H., Gotoh, H. (2023). Grain-scale investigation of swash zone sediment transport on a gravel beach using DEM-MPS coupled scheme. Coastal Engineering Journal, 65(2), 347-368. https://doi.org/10.1080/21664250.2023.2202958.
16. Brocchini, M. (2020). Wave-forced dynamics in the nearshore river mouths, and swash zones. Earth Surface Processes and Landforms, 45(1), 75-95. https://doi.org/10.1002/esp.4699.
17. Deng, B., Zhang, W., Tang, H.S., Jiang, C.B., Liu, X.J. (2022). An experimental study on hydrodynamic process, beach profile, and sand migration in swash zone under action of dam-break bore. Applied Ocean Research, 129, 103391. https://doi.org/10.1016/j.apor.2022.103391.
18. Li, S., Li, W., Shi, H., Guan, X. (2024). Hydrodynamics and sediment transport under solitary waves in the swash zone. Journal of Marine Science and Engineering, 12(9). https://doi.org/10.3390/jmse12091686.
19. Aagaard, T., Brinkkemper, J., Christensen, D.F., Hughes, M.G., Ruessink, G. (2021). Surf zone turbulence and suspended sediment dynamics—a review. Journal of Marine Science and Engineering, 9(11). https://doi.org/10.3390/jmse9111300.
20. Anthony, E.J., Aagaard, T. (2020). The lower shoreface: Morphodynamics and sediment connectivity with the upper shoreface and beach. Earth-Science Reviews, 210, 103334. https://doi.org/10.1016/j.earscirev.2020.103334.
21. Rodríguez-Padilla, I., Castelle, B., Marieu, V., Bonneton, P., Mouragues, A., Martins, K., Morichon, D. (2021). Wave-filtered surf zone circulation under high-energy waves derived from video-based optical systems. Remote Sensing, 13(10). https://doi.org/10.3390/rs13101874.
22. Singh, R., Kumar, R., Bahuguna, I.M., Kumar, R. (2020). Grain size analysis of dune and bar sediments of the Shyok River between Khalsar and Hunder Village, Karakoram Range, Ladakh, India. Journal of the Geological Society of India, 95(2), 183-189. https://doi.org/10.1007/s12594-020-1408-1.
23. Wengrove, M.E., de Schipper, M.A., Lippmann, T.C., Foster, D.L. (2022). Surfzone bedform migration and sediment flux implications to large scale morphologic evolution. Geomorphology, 410, 108246. https://doi.org/10.1016/j.geomorph.2022.108246.
24. Chubarenko, I., Efimova, I., Bagaeva, M., Bagaev, A., Isachenko, I. (2020). On mechanical fragmentation of single-use plastics in the sea swash zone with different types of bottom sediments: Insights from laboratory experiments. Marine Pollution Bulletin, 150, 110726. https://doi.org/10.1016/j.marpolbul.2019.110726.
25. Pilarczyk, J.E., Sawai, Y., Matsumoto, D., Namegaya, Y., Nishida, N., Ikehara, K., Fujiwara, O., Gouramanis, C., Dura, T., Horton, B.P. (2020). Constraining sediment provenance for tsunami deposits using distributions of grain size and foraminifera from the Kujukuri coastline and shelf, Japan. Sedimentology, 67(3), 1373–1392. https://doi.org/10.1111/sed.12591.
26. Vermeiren, P., Lercari, D., Muñoz, C.C., Ikejima, K., Celentano, E., Jorge-Romero, G., Defeo, O. (2021). Sediment grain size determines microplastic exposure landscapes for sandy beach macroinfauna. Environmental Pollution, 286, 117308. https://doi.org/10.1016/j.envpol.2021.117308.
27. Soloy, A., Turki, I., Fournier, M., Costa, S., Peuziat, B., Lecoq, N. (2020). A deep learning-based method for quantifying and mapping the grain size on pebble beaches. Remote Sensing, 12(21). https://doi.org/10.3390/rs12213659.
28. Stark, N., Mewis, P., Reeve, B., Florence, M., Piller, J., Simon, J. (2022). Vertical pore pressure variations and geotechnical sediment properties at a sandy beach. Coastal Engineering, 172, 104058. https://doi.org/10.1016/j.coastaleng.2021.104058.
29. Guest, T.B., Hay, A.E. (2021). Small-scale morpho-sedimentary dynamics in the swash zone of a megatidal mixed sand–gravel beach. Journal of Marine Science and Engineering, 9(4).

https://doi.org/10.3390/jmse9040413.
30. Bayle, P.M., Blenkinsopp, C.E., Martins, K., Kaminsky, G.M., Weiner, H.M., Cottrell, D. (2023). Swash-by-swash morphology change on a dynamic cobble berm revetment: High-resolution cross-shore measurements. Coastal Engineering, 184, 104341. https://doi.org/10.1016/j.coastaleng.2023.104341.
31. Bauer, B.O., Wakes, S.J. (2022). CFD simulations of wind flow across scarped foredunes: Implications for sediment pathways and beach–dune recovery after storms. Earth Surface Processes and Landforms, 47(12), 2989-3015. https://doi.org/10.1002/esp.5439.