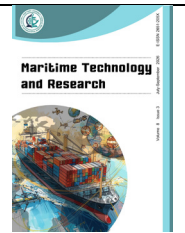




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Research Article

Morphodynamic classification and coastal structure interactions in monsoonal coastal systems: Implications for sustainable coastal management

Aminah Ismailluddin¹, Faerah Nasir¹, Lee Shin Yun¹, Siti Nur Hanani Zainuddin²,
Muhammad Rizal Razali^{2,3}, Muhammad Zahir Ramli⁴, Mohd Azhafiz Abdullah⁵ and
Effi Helmy Ariffin^{2,*}

¹Faculty of Science and Marine Environment, Universiti Malaysia Terengganu, Kuala Nerus, Terengganu 21030, Malaysia

²Institute of Oceanography and Environment, Universiti Malaysia Terengganu, Kuala Nerus, Terengganu 21030, Malaysia

³National Water Research Institute of Malaysia, Ministry of Energy Transition and Water Transformation, Seri Kembangan, Selangor 43300, Malaysia

⁴Department of Marine Science, Kulliyah of Science, International Islamic University Malaysia, Jalan Sultan Ahmad Shah, Kuantan, Pahang 25200, Malaysia

⁵Faculty of Maritime Studies, Universiti Malaysia Terengganu, Kuala Nerus, Terengganu 21030, Malaysia

*Corresponding author's e-mail address: effihelmy@umt.edu.my

Article information	Abstract
Received: January 10, 2026 Revision: March 27, 2026 Accepted: April 30, 2026	Coastal erosion has intensified coastal hazards, prompting widespread use of coastal protection structures to mitigate it. While effective, these interventions can alter natural shoreline dynamics, leading to unintended degradation. This study aims to advance understanding of beach morphodynamics under structural influence within monsoonal coastal systems. Field measurements of beach morphology and sediment characteristics were conducted across six sites during peak monsoon season, complemented by hydrodynamic simulations using MIKE 21-SW. Findings reveal distinct morphodynamic states between high-energy and low-energy environments. Energetic sites with coarser sediments and steep beach slope correspond to intermediate beach states, whereas calmer sites with finer sediments and gentle beach slope align with dissipative beach states. This study contributes to the existing body of knowledge by critically exploring the relationship between beach morphodynamics and coastal protection design discourse by cluster analysis and multidimensional scaling. Three main beach groups were identified, reflecting varying natural dynamics and designs of coastal structure. Importantly, the study emphasizes the need for region-specific management strategies, prioritising conservation in dynamic intermediate beaches and restoration in structurally constrained dissipative beaches. The research offers a repeatable and adaptable framework for assessing coastal systems shaped by both natural processes and human interventions, as well as supporting sustainable and site-specific coastal management.
Keywords Beach morphodynamic classification; Cluster analysis; Coastal management; Coastal protection structure; Monsoonal coastal system	

1. Introduction

Coastal erosion is a major problem around the world with its threats to coastal societies, infrastructure and ecosystems (Dong et al., 2023). Climate change has led to the increased vulnerability of coastal areas as a result of rising sea levels and the intensification of storms

(Ranasinghe et al., 2023; Basnayake et al., 2026). To combat erosion in response, coastal defense structures, e.g., seawalls, groynes, and breakwaters, are commonly applied (Sanitwong-Na-Ayutthaya et al., 2022; Saengsupavanich et al., 2024). Nevertheless, as much as their main role is protection, these structures usually interfere with natural sediment transportation, cause changes to nearshore hydrodynamics, and make morphological changes of a complex nature (Dong et al., 2023; Saengsupavanich et al., 2024). The changes have unintended effects, such as localized erosion, downdrift sediment deficit, and geomorphological instability in the long term (Charoenlerkthawin et al., 2025; Angnuureng et al., 2025).

In this scenario, morphodynamic beach classification has traditionally been a fundamental reference point to characterize the issue of coastal behavior as a result of the combined activity of hydrodynamic forcing, sediment characteristics, and morphological feedback (Castelle & Masselink, 2023). A simplified but powerful description of beach conditions has been created in the widely used reflective-intermediate-dissipative continuum parameterized by the Dean parameter (Ω) (Ariffin et al., 2018a, 2019; Korzinin and Leont'yev, 2024; Liu et al., 2024). The framework has been shown to be highly applicable in a range of coastal environments, including the characterization of site-specific processes (Ding & Cheng, 2020), the prediction of coastal hazards, including erosion and the occurrence of rip currents (Vousdoukas et al., 2012; Hamsan & Ramli, 2021), and the guidance of ecological evaluation and coastal management decisions (Castelle & Masselink, 2023).

However, irrespective of its universal use, the traditional paradigm of morphodynamic classifications is largely formed on, as well as tested in, natural or minimally perturbed coastal systems (Ariffin et al., 2018a). Its extrapolation to anthropogenically altered coastline has not been sufficiently restricted. According to world coastal assessments, coastal structures currently influence an estimated 33 % of the world's global coasts, essentially changing the local hydrodynamic regime and sediment budget (Athanasίου et al., 2024; Nawarat et al., 2024). This demonstrates that, while most coastlines remain without hard structures, certain densely populated or industrialized regions rely heavily on seawalls, revetments, and breakwaters. The existence of these structures brings along more spatial and temporal variations which might not be well represented by conventional univariate indicators like Ω , hence putting the strength of the current classification system into question.

Recent developments have indicated the prospects of using clustering analysis and multivariate methods to enhance the complexity of coastal morphodynamics resolution through combining a variety of hydrodynamic and sedimentological parameters (Scott et al., 2017). Thus, this application has been used in this research to define geoclimatically active environments and structure-dominated areas, especially in monsoon-dominated areas (Ariffin et al., 2018a, 2018b, 2019; Perera et al., 2023). Monsoonal systems are strongly seasonal, and the conditions of extreme waves are overwhelmingly influences in the monsoon seasons on sediment transport and beach morphology (Ariffin et al., 2023; Perera et al., 2023). These extreme natural environment conditions offer a highly sensitive natural laboratory for assessing the morphodynamic response of beaches, as well as the performance of coastal protection structures under near-threshold conditions or worst-case conditions (Basnayake et al., 2026).

The current study, therefore, fills a very important research gap, in that it systematically examines the morphodynamic states of beaches in structurally affected coastal systems subject to monsoon forcing. The general hypothesis is that engineered interventions cause detectable changes in morphodynamic states, caused by interference with sediment transportation pathways and hydrodynamic processes (Weerasingha & Ratnayake, 2022; Yun et al., 2023), and suggests a multivariate method will provide better diagnostic data in comparison with the classic classification models. It is also expected that various forms and designs of coastal protection systems have different control implications on local hydrodynamics and sediment budgets, leading to spatially heterogeneous morphodynamic reactions (Weerasingha & Ratnayake, 2025). Specifically, the shift between intermediate and dissipative beach conditions can be beneficial in terms of wave energy dissipation, and could lead to lower erosion intensity under high-energy storm situations, which is

confirmed by local coastal storms and waves (Ariffin et al., 2023; Perera et al., 2023). By connecting structural influence to the variability of morphodynamic states, this study will contribute to the further development of process-based knowledge and enhance the relevance of the classification frameworks in the engineered coastal setting.

2. Methodology

The study uses a combined framework to examine the morphodynamic behavior of beaches with structural effects in a monsoon-dominated setting, which concentrates on peak monsoon states as characterising high-energy driving forces. A multivariate clustering method is first used to refine a parameter based on the Dean parameter (Ω), and then the key beach morphological, hydrodynamic, and sedimentological variables are added to the first parameter. The analysis specifically explains the existence of coastal protection structures and river sediments. By so doing, a systematic assessment of morphodynamic variability and the constraints of traditional classification in structurally altered coastal systems can be made.

2.1 Site description

The study was carried out on the northeast coast of Peninsular Malaysia, which is a monsoon-related coastal area with a lot of low-lying plains, long sandy beaches, and numerous river outlets emptying into the South China Sea. There are no rocky headlands or offshore islands that can shield this coastline from aggressive wave climates, storm surges, and longshore sediment transportation processes (Ariffin et al., 2023). Consequently, the area has a high level of morphodynamic sensitivity, as the processes of coastal areas are mostly determined by the seasonal variability of hydrodynamics and sediment sources.

Six (6) representative beaches were chosen in three districts of Kelantan: K1 to K4 in Kota Bahru (Kb), K5 in Bachok (Bc), and K6 in Pasir Putih (Pp), to represent spatial variability (see **Figure 1**). The sites have site-specific structural interventions, which offer a gradient of artificial influence. **Table 1** has highlighted the important morphological, sedimentological, hydrodynamic, and tidal characteristics, riverine inputs, and types of coastal defense. The following sections provide an elaborate discussion of these parameters and their implication on the morphodynamic behavior of the beach at different hydrodynamic and structural conditions.

Table 1 Parameters included in cluster analysis for each study site.

Parameters	K1	K2	K3	K4	K5	K6
Beach morphology and sedimentology						
Slope (total) (°)	5.67	5.51	4.71	2.70	5.71	8.62
Slope (°) (segments)	6.97	8.59	8.09	1.88	2.76	2.21
D ₅₀ (upper) (mm)	0.41±0.20	0.46±0.14	0.72±0.42	0.13±0.04	0.40±0.22	0.22±0.10
D ₅₀ (lower) (mm)	0.76±0.42	0.59±0.03	0.48±0.28	0.27±0.01	0.77±0.25	0.34±0.19
Bar type	Single	Single	Single	No bar	No bar	No bar
Bar shape	Linear	Linear	Linear	No bar	No bar	No bar
Hydrodynamics and tidal						
H _s (m)	0.98	1.45	1.39	1.11	1.19	1.11
T _p (s)	4.51	5.50	5.26	4.24	4.47	4.79
MSR (m)	1.05	1.05	1.05	1.05	1.05	1.05
Additional variable						
River	Ephemeral river	Absent of river	Permanently river	Permanently river	Absent of river	Permanently river
Coastal structure	Seawall, rock revetment and perpendicular groynes	Rock revetment	Rock revetment	Offshore breakwater	Seawall and rock revetment	Seawall and rock revetment

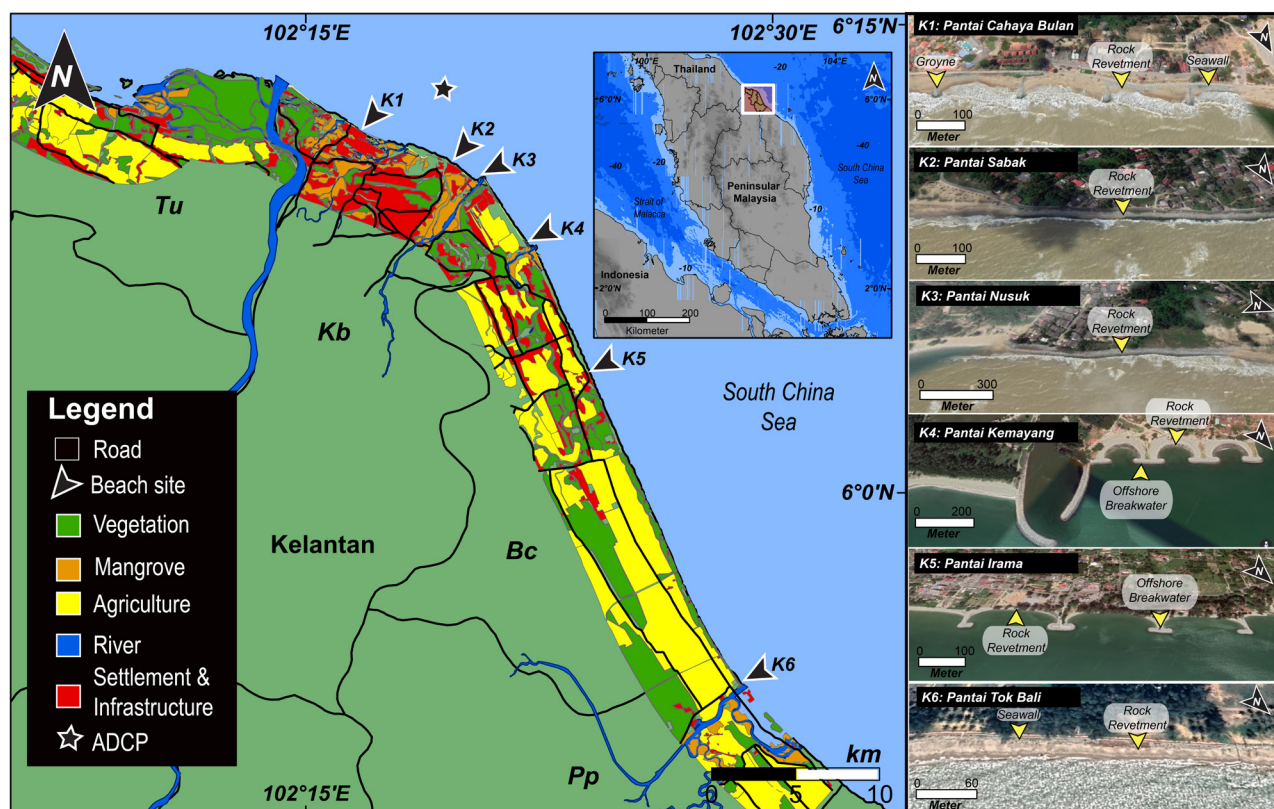


Figure 1 Map of study area in monsoonal region, highlighting six (6) selected beaches with variety of coastal defense types.

The recent research proves the fact that the northeast monsoon (November to March) generates the most active wave regime, where the offshore wave height may reach 7 - 8 m, and the nearshore conditions may be 1 - 2 m (Ariffin et al., 2018b, 2023). The southwest monsoon (May - September), on the other hand, is typified by milder southwest waves (<1 m), which facilitate accretion and recovery of shorelines (Yun et al., 2023). Wave periods are generally 2 - 8 s, with longer period waves (> 6 s) in the northeast monsoon, increasing cross-shore sediment transport, whereas shorter period waves (2 - 4 s) in the southwest monsoon contribute to local accretion (Hamsan & Ramli, 2021). There have been documented extreme events with high wave heights of 2.62 - 3.39 m at 10 - 200 year returns, which is a clear indication of the vulnerability of exposed sandy coasts in Kelantan and Terengganu (Muzathik et al., 2011; Ariffin et al., 2019). A wave condition directional distribution of the study area is shown in **Figure 2**, which represents the nearshore wave conditions during peak seasonal monsoon, with predominantly between 0.5 to 0.75 m of wave height, and 6 s to 8 s of wave period. Northern sites (K1 - K3) experiences higher wave height and shorter periods, and southern sites (K5 - K6) show lower wave height and longer periods.

2.2 Methods

The data were collected comprehensively in early December 2021, during the season of the northeast monsoon when the erosive process of storms is most active (Ariffin et al., 2018b; Yun et al., 2023), in the areas marked in **Figure 1**. This time selection sheds some light on the storm-dominated beach processes, with their erosive activity most active in December (Yun et al., 2023). Each site was characterized by morphological, sedimentological, and hydrodynamic data, as well as the local environmental setting.

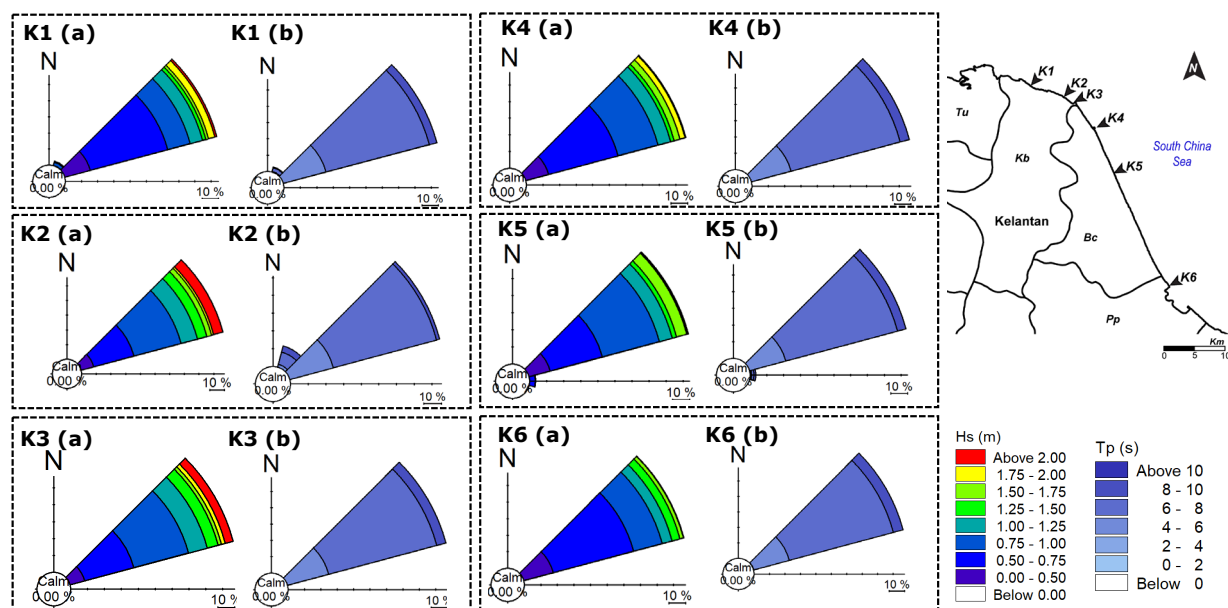


Figure 2 Offshore wave distribution at study areas during peak seasonal monsoon; (a) significant wave height, (b) peak wave period.

2.2.1 Beach morphology

Surveys of the beach profile were carried out to measure the variability of the shoreline shape, slope, and structure. Each of the sampling sites had a total of three (3) cross-shore transects placed at right angles at the shoreline, starting along the dune crest (benchmark) down to the low-tide waterline; T1 represents the northern beach profile, T2 corresponds to the central profile, and T3 denotes the southern profile at each site. Distance of each profile is about 100m interval within coastal area that had protection structures. The topography was measured by a total station (Topcon GM-50 Series), which gave elevation and position information of high resolution. Based on each profile, beach width and slope were obtained and divided into upper and lower intertidal parts. The analysis of the data was conducted with the help of Profiler 3.2 XL, created in Microsoft Excel, to create two-dimensional profile interpretations (Cohen, 2016). The profiles also enabled the visual and quantitative evaluation of the features of the sediment bars, slope variability, and nearshore morphological transitions.

2.3 Sediment characteristic

Surface sediment samples were drawn at the same transects of both the upper (backshore zone) and lower (swash zone) beach profiles, which are important in order to represent the entire range of hydrodynamic and geomorphic processes (Scott et al., 2011). Therefore, plastic scoops and bags were used to collect a total of six (6) samples per site. The samples were taken to the laboratory to dry and sieve, with six layers of sieves with mesh sizes of between less than 63 μm and 2 mm in size using standard granulometric methods (Folk, 1980). Fractions smaller than 63 μm were not analyzed. The data on the grain sizes were handled with the help of the GRADISTAT v8 program that offered such a statistical measure as the median grain diameter (D_{50}). The computation of sediment fall velocity, which is a major input of beach morphodynamic classification models, was calculated using this metric.

2.4 Wave characteristic

The northeast monsoon sectors' offshore wave conditions were propagated in the nearshore zone of the area of study under MIKE 21 Spectral Wave (SW) Flexible Mesh module packages, created by the Danish Hydraulic Institute (DHI). This model was simulated for December 2021,

whereby the model forced by wind data from European Centre for Medium Range Weather Forecasts (ECMWF) and water level as model boundary condition derived from the global DHI prediction. Coupled Model Application Platform (CMAP) from DHI was used to create the bathymetry of model using vertical chart datum. To ensure that the simulation output was valid, a field measurement of a model validation was conducted. The root-mean-square error (RMSE) of significant wave height modelled and measured was acceptable (0.07), which implies that accuracy was acceptable, as it was within the guidelines of the Department of Irrigation and Drainage, Malaysia (2001) (see **Figure 3**). Important parameters are significant wave height, H_s (the most common parameter in the study of coasts), and peak wave period, T_p (the most active period), which are taken into consideration when determining the local wave breaking height (H_b) as a further measure of assessing morphodynamic classification to be used in the assessment of beach morphodynamics (Ariffin et al., 2018b). A single value of H_s and T_p was extracted by averaging alongshore the value of breaking point fronting the each of beach site where it positions determined by of gradient as increasing water depth and wave height begins to decrease markedly (Kamphius, 2000). The depth of the wave-breaking line varies between 3 and 5 m offshore on the Kelantan coast. The wave parameters reveal that the maximum significant wave height on 30 December 2021 laterally utilized the wave value in producing the wave breaker height.

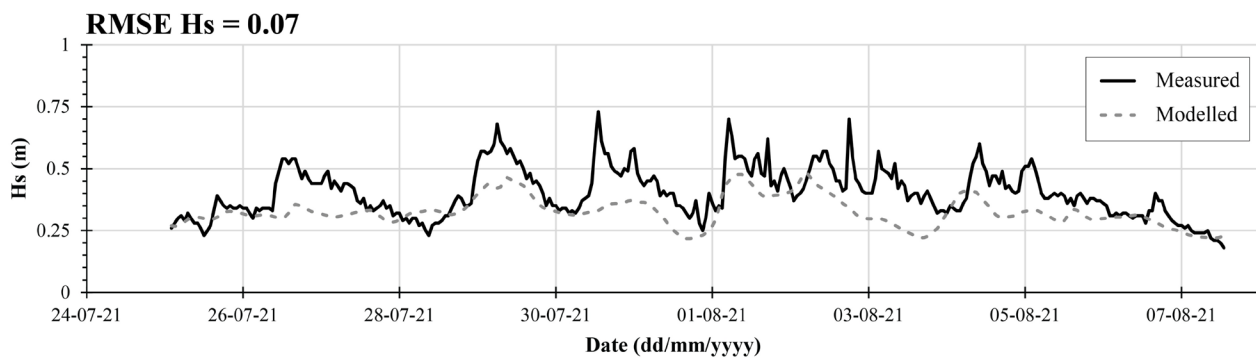


Figure 3 Comparison between measured and simulated significant wave heights used for model validation.

2.5 Beach morphodynamic classification

Beach classification was based on two widely recognized parameters: Dean parameter (Ω) and the Relative Tide Range (RTR). These indices relate wave breaking height, sediment fall velocity, and tidal influence to classify beaches into reflective, intermediate, or dissipative types. Wave breaking height, H_b (m), was computed using the formula adapted by Ariffin et al. (2018b); Komar and Gaughan (1973):

$$H_b = 0.39 g^{0.2} \cdot (T_p \cdot H_s)^{0.4} \quad (1)$$

Where, g is 9.81 ms^{-2} (gravitational acceleration), T_p (s) is the peak wave period, and H_s (m) is the significant wave height.

The sediment fall velocity, W_s (m/s), was calculated using the Soulsby (1997) equation, under the action of gravity and hydrodynamic drag force on the grain:

$$W_s = \frac{v}{d} [(10.36^2 + 1.049 \cdot D^* \cdot s^3)^{1/2} - 10.36] \quad (2)$$

Where, v is the kinematic viscosity of seawater ($1.36 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$), d is the median grain diameter (m), s is ratio of grain and water densities (2.58 as a default value), and D^* is the dimensionless grain size ($D^* = (g(s-1)/v^2)^{1/3} \cdot d$).

Dean parameter was calculated as:

$$\Omega = \frac{H_b}{W_s \cdot T_p} \quad (3)$$

According to Dean (1973), the dimensionless fall velocity can be applied to differentiate between reflective beach ($\Omega < 1$), intermediate beach ($1 < \Omega < 6$), and dissipative beach ($\Omega > 6$). Reflective beaches generally present dominantly coarse sediment, low wave energy, and a steeper foreshore. Dissipative beaches present fine sediment, high wave energy, and a low-sloping foreshore, while intermediate beaches are between the conditions of both of these types. To account for tidal influence, Relative Tide Range (RTR) was computed as:

$$RTR = \frac{MSR}{H_b} \quad (4)$$

Where, MSR is the mean spring tidal range, calculated from 30-year tidal data (1986 - 2017) at the Geting tide gauge (Department of Survey and Mapping Malaysia, JUPEM).

2.6 Identification of beach group

Interrelations among morphological, sedimentological, and hydrodynamical values were investigated to determine the presence of individual morphology groups in the beach sites. Cluster analysis was used to determine the correlation of the multivariate data set of each variable, as observed in **Table 1** (Scott et al., 2011). Cluster analysis was selected in this case due to its computation efficiency and capability of providing visual clusters of data with numerous iterations, depicting graphically the association in a distance or similarity matrix. The reason behind selecting the Gower General Similarity Coefficient is to gauge such similarity that will assign it a low value when there is high similarity, and a high value when there is high dissimilarity (Burving et al., 2017). Next, the similarity, defined between clusters, was employed in constructing the hierarchical clustering through the weighted pair group average method (UPGMA).

The hierarchical process, according to an agglomerative algorithm, was easy and simple to understand, as shown in a graphical tree (dendrogram). Based on the cluster analysis, the six beaches were delineated at an 80 % similarity level as the most suitable resolution of classes of the beaches and their current morphodynamic variability and the similarity level that are most closely associated with each other and that define the resulting group. The outcome of cluster analysis is a resolution of organized clusters yielding genuine groupings in facts that exist. Thus, the resultant classification-structured group was analyzed through a non-metric multidimensional scaling (MDS) ordination methodology, proposed by Scott et al. (2011).

This multivariate analysis tool seeks to display the samples within a data set in a reduced dimensional space (2-D) in an attempt to summarize the data. The ordination of MDS was characterized by the ranked similarities of variables. The goodness of fit measures the MDS ordination (stress value) of acceptable ordination. Stress rates of less than 0.1 are acceptable and excellent; ordination and levels of more than 0.1 are not acceptable (Clarke & Gorley, 2006). Then, to facilitate interpretation of the beach groups, all the parameters incorporated in the cluster groups were taken into account in MDS space. The beaches in this plot are plotted in MDS space, where the size and symbol of the parameter values are used.

3. Results

3.1 Beach morphology

Beach morphology is one of the fundamental parameters of the evaluation of the reflection of site-specific responses to the factors of wave exposure, sediment supply, and anthropogenic alterations. It covers some important physical features like beach profile, slopes, and sediment properties. The study aimed to analyse the beach slopes at upper and lower (intertidal) levels. The findings showed that the mean slope of the beaches is between 2.70° and 8.62° (**Figure 4** and **Table**

2). The maximum steep slope was measured at Pantai Tok Bali (K6), which is characterized by a relatively smooth gradient in the lower intertidal part. The sharp upper slope is affected by the existence of defense structures on the coast (seawalls and revetment toes) that increase the steep upper slope but lower the slope at the bottom. Conversely, Pantai Kemayang exhibits a fairly smooth downward gradient all the way along the beach profile, with the main reason being the buffering effect of the offshore breakwater.

3.2 Sediment characteristic

The sediment grain size analysis, in the form of D_{50} values, indicated a distinct bimodal pattern of grain size between the upper and lower parts of the beach. The upper and lower beach sediments were found to vary from well-sorted fine sands to medium-coarse sands. The upper beach ranged from 0.13 ± 0.04 mm (Pantai Kemayang) to 0.72 ± 0.42 mm (Pantai Nusuk), suggesting a spectrum from well sorted fine to medium sands which indicative of aeolian reworking deposition. In contrast, the lower beach sediments were typically under high wave energy at swash zone with ranged 0.27 ± 0.01 mm (Pantai Kemayang) to 0.77 ± 0.25 mm (Pantai Irama). Sediment analysis revealed that swash zone sediments were consistently coarser material compared to the backshore, reflecting the higher energy conditions of the swash environment. In contrast, the most uniform sediment layers were observed at Pantai Tok Bali and Pantai Kemayang, which were both sites dominated by fine sand deposits.

3.3 Spatial variation in wave parameter

Wave dynamics is a severe control on coastal morphodynamics, sediment transport, and shoreline stability, particularly in monsoons. **Figure 5** shows the spatial distribution of significant wave height (H_s) of statistical mean in the study area in December 2021, which is a characteristic of the hydrodynamic conditions of the northeast monsoon. The H_s values were between 0.30 m and 0.70 m, with clear spatial gradients observed at the six study sites (K1 to K6). It has been found that the most important areas were the highest energy waves ($H_s > 0.70$ m, red shades) at Pantai Sabak (K2) and Pantai Irama (K5), which face the open coast to the northeast, and are directly exposed to the prevailing monsoonal swell.

The nearshore areas of Pantai Cahaya Bulan (K1) and Pantai Nusuk (K3) were characterized by moderate wave energy fields (H_s lying between 0.58 and 0.62 m). Pantai Kemayang (K4) and Pantai Tok Bali (K6), on the contrary, had much lower H_s values, with ranges between 0.30 m and 0.48 m, especially in the nearshore region. The attenuation of the waves at these locations could be attributed to the power of the offshore breakwater structures, which affects such attenuation.

3.4 Beach morphodynamic classification

The findings from beach morphodynamic classification based on the Ω and RTR demonstrated that there was definite spatial variability of beach types (**Table 2**). The Ω values varied between 3.81 and 16.67, which had a range of intermediate to dissipative systems. In particular, the Ω values and sediment peculiarities allowed identification of specific beach types with the help of the morphodynamic classification along the Kelantan coast. In the intermediate beaches like Pantai Cahaya Bulan (K1), Pantai Sabak (K2), and Pantai Nusuk (K3), the values of Ω were 3.81, 4.59, and 3.91, respectively. These beaches had steeper profiles, moderate- to coarse-grained sediments, and well-expressed linear bars. Conversely, dissipative beaches such as Pantai Kemayang (K4), Pantai Irama (K5), and Pantai Tok Bali (K6) were observed to have a higher Ω of more than 7.0. The low-energy wave conditions, finer sediments, and less vigorous and flat beach populations of these locations were a product of the more dissipative hydrodynamic environment.

Tidal impact on morphodynamic expression is further contextualized by the RTR index, which is the tidal range divided by the wave height. RTR values of all six beaches were in the range of 0.72 to 1.07; this reflected microtidal to lower mesotidal conditions, and was typical of wave-dominated beaches. Although the range of RTR is rather limited, it can be combined with Ω in the morphodynamic plot (**Figure 6**), which shows some critical differences between the research

locations. Pantai Cahaya Bulan, Pantai Sabak and Pantai Nusuk are categorized as intermediate beaches, whereas Pantai Kemaynag, Pantai Irama, and Pantai Tok Bali are set in the category of dissipative beaches.

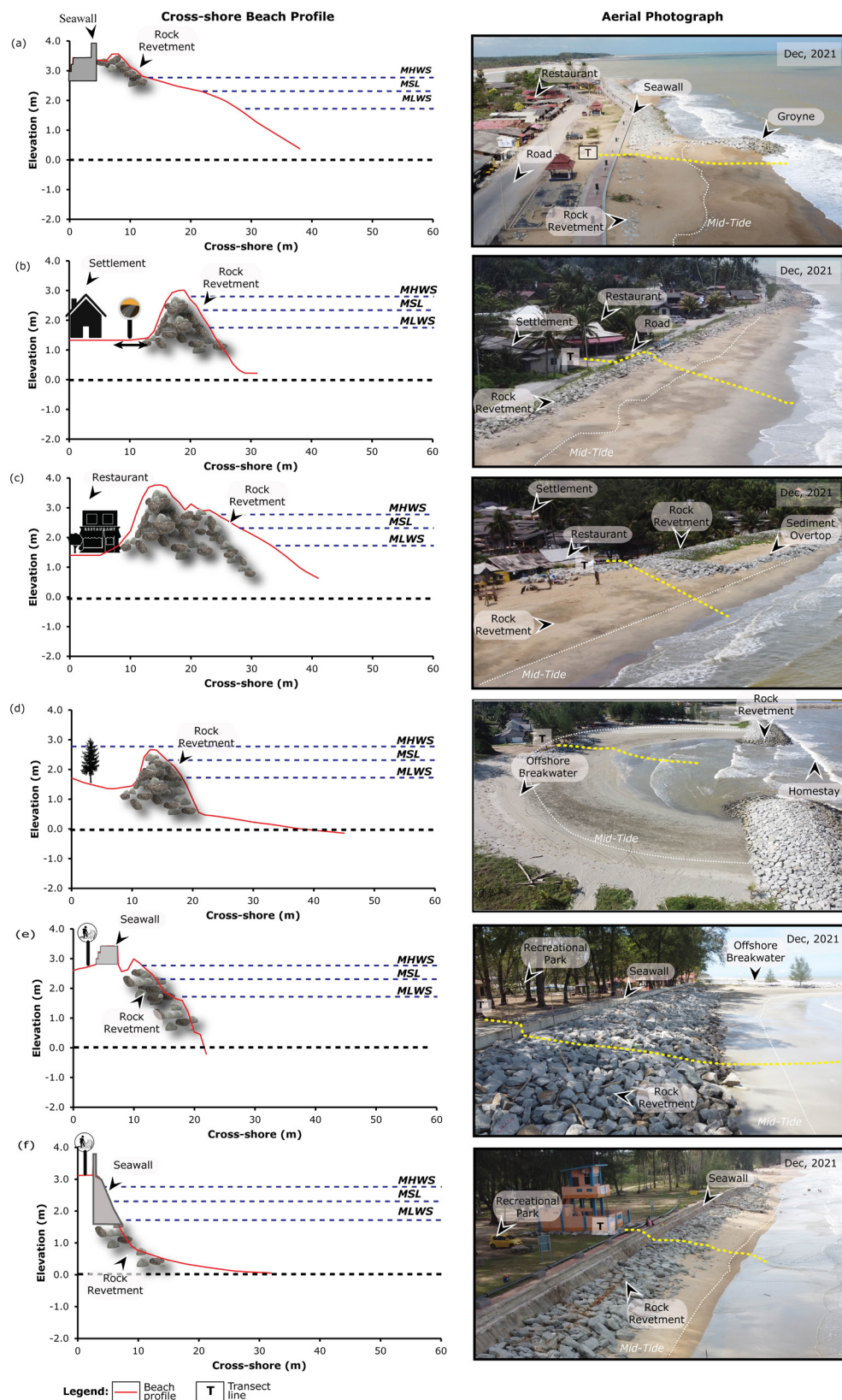


Figure 4 Cross-shore profile variability of six beaches along the Kelantan coast.

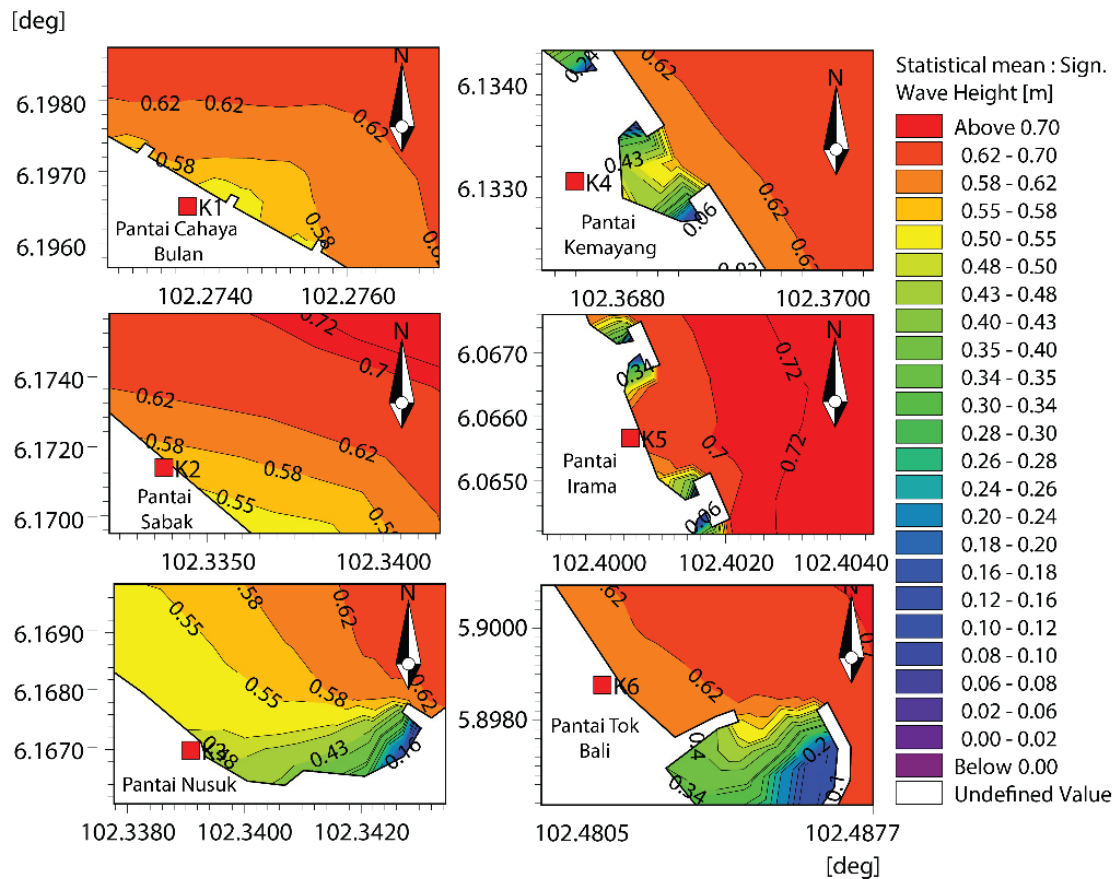


Figure 5 Spatial variation of wave power for six beaches in monsoonal region.

Table 2 Beach morphodynamic classification and parametric classification.

Research Sites	Hb (m)	Tp (s)	Ws (m/s)	Ω	RTR (m)	Type of Beach
K1 – Pantai Cahaya Bulan	1.11	4.51	0.065	3.81	1.07	Intermediate Beach
K2 – Pantai Sabak	1.64	5.50	0.065	4.59	0.72	
K3 – Pantai Nusuk	1.56	5.26	0.076	3.91	0.76	
K4 – Pantai Kemayang	1.19	4.24	0.017	16.67	0.95	Dissipative Beach
K5 – Pantai Irama	1.29	4.47	0.041	7.03	0.88	
K6 – Pantai Tok Bali	1.26	4.79	0.033	7.99	0.95	

3.5 Multivariate classification of beach morphodynamics

Table 1, which includes eleven (11) parameters, was used in the investigation of the grouping of sites on similarity criteria. The clustering analysis revealed three (3) different beach clusters using differences in morphodynamic, sedimentologic and hydrodynamic, and supplementary details of the riverine, in addition to the nature of the coastal defense structures (refer to **Figure 7**). Group 1 includes Pantai Cahaya Bulan (K1) only; this showed some peculiarities that made it particular item stand out from the others. Groups 2, Pantai Sabak (K2) and Pantai Nusuk (K3), were similar in terms of intermediate morphodynamic profiles. Group 3 included Pantai Kemayang (K4), Pantai Irama (K5), and Pantai Tok Bali (K6), which were grouped due to their similarity in terms of sediment texture and wave energy conditions.

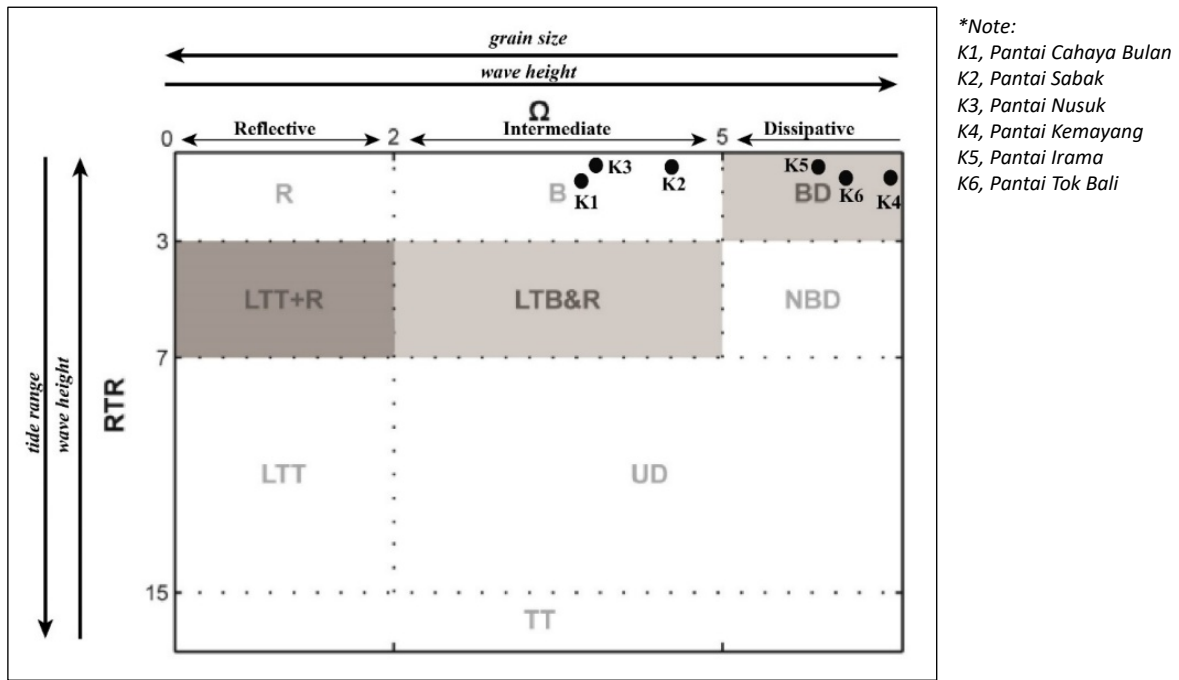


Figure 6 Ω -RTR subplot indicates values of Ω and RTR for each beach group. Marker indicates beach sites, and framework of grey dashed lines indicate delineations from Masselink and Short (1993) models.

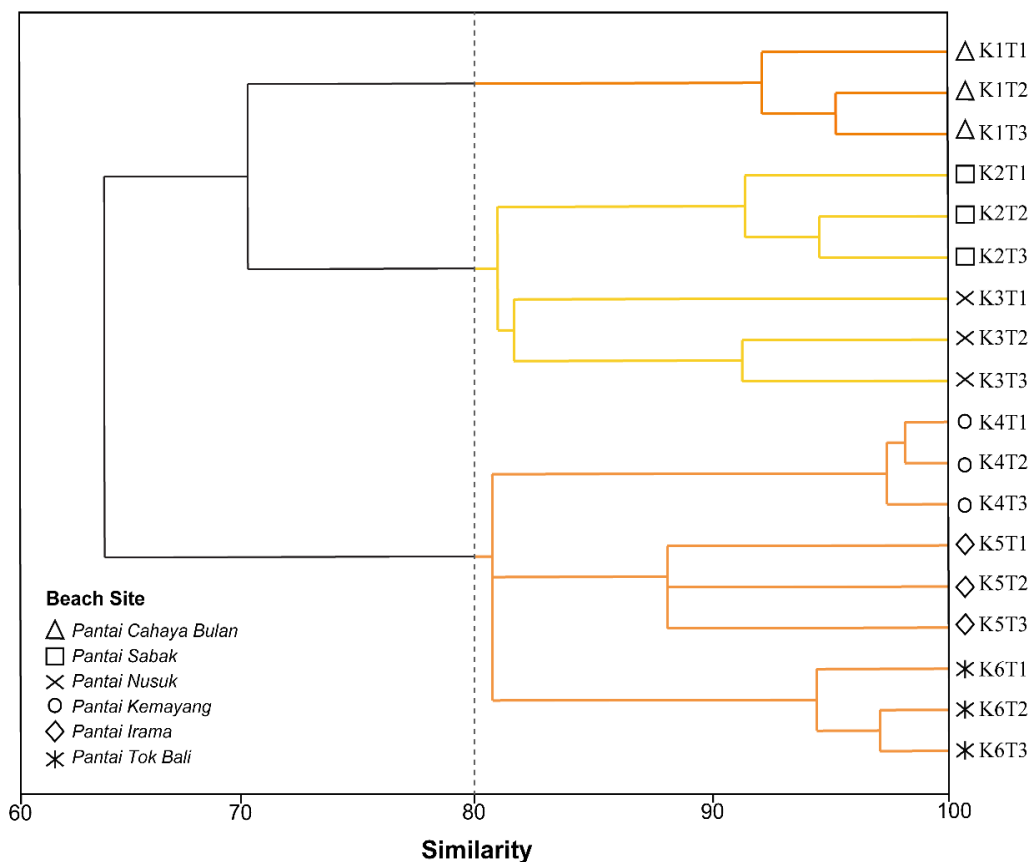


Figure 7 Dendrogram clustered using unweighted pair group average (UPGMA) method. Dashed line represents discrete beach groups attained using a cut-off level of 80 % similarity. The symbol at y-axis represents sampling sites (K# = beach sites; T# = transect lines), as specified in the legend.

In the details, Group 1 had characteristic morphodynamic features such as a moderately steep slope, coarse upper beach sediment, and intermittent bar features. Group 2 also exhibited a steep beach profile and a moderate-high level of wave energy exposure with a single, linear bar system present. Group 3 covers beach sites of the coastline that are located in the south. The features of these locations were low beach gradients, smooth sediment surfaces, and the total lack of offshore bars. The high spatial correlation in morphodynamic characteristics in individual groups indicates that there is an evident environmental gradient running along the monsoon coast, from a relatively reflective environment in the north to a more dissipative environment in the south.

Indeed, an overall perspective of the relationship between each beach site and others in terms of their collective physical and environmental attributes is shown in the non-metric multidimensional scaling (MDS) plot (**Figure 8**). The individual beaches are plotted as points on a diagram of **Figure 9**, with a distance between two points showing the degree of resemblance of their slope, grain sizes, and heights of waves, among other variables measured. Beads that are relatively nearer to each other, like Pantai Sabak (K2) and Pantai Nusuk (K3), have a lot of similarities (intermediate, moderate, wave energy, and bar systems), whereas beads that are more distant in form, such as Pantai Cahaya Bulan (K1) and Pantai Kemayang (K4), lack any similarities (steeper versus flatter). Practically, **Figure 8** converts complex data to a simple spatial graph, which makes it easy to visualize how natural wave forces and coastal structures interact to determine the behavior of each beach.

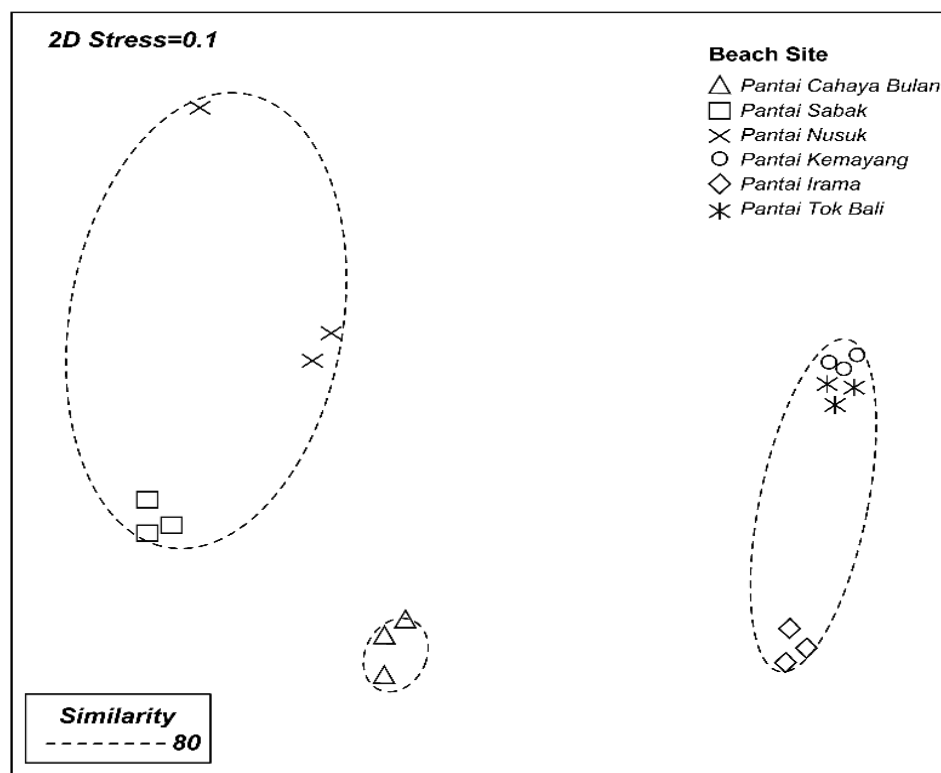


Figure 8 MDS ordination plot, representing rank order similarities in a 2-D space. Dashed line represents groupings at the 80 % similarity level.

Group 1 was linked to moderate to steep slopes, as well as coarse sediment texture that reflected reflective beach conditions. Group 2 had more homogeneous linear bar morphology at moderate wave forcing, which is typical of intermediate beach states. Group 3 showed a shift towards finer sediments, flatter profiles, and structurally changed nearshore environments, which is consistent with dissipative beach environments. These differences are in line with morphodynamic classifications adapted from the traditional approach. Novelty of riverine influence did not

significantly contribute to the formation of site groupings, as two sites (K2 and K5) were characterized by the absence of sediment input.

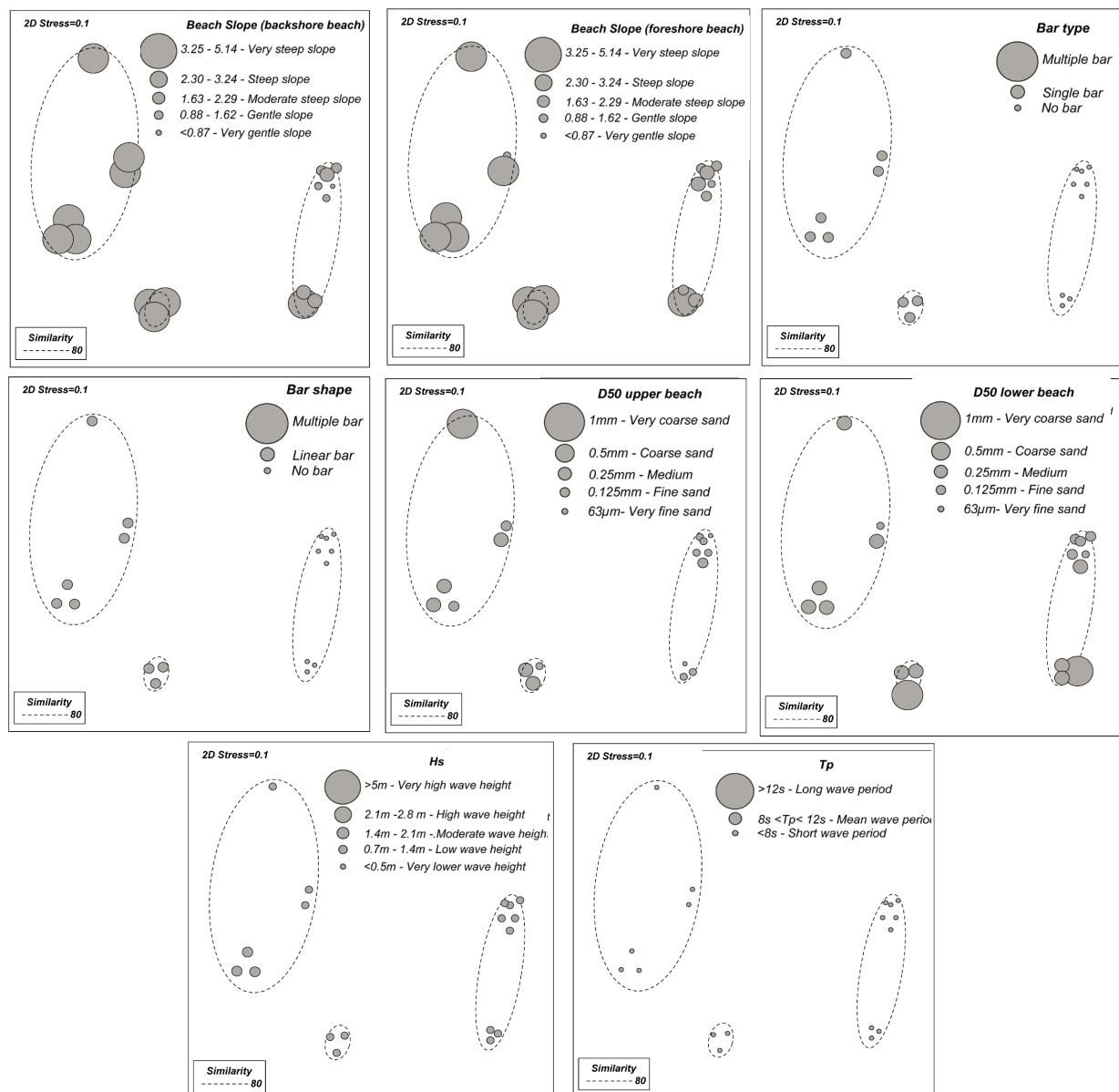


Figure 9 MDS ordination of beach sites from similarity matrix. Marker size scaling with beach slope, Hs, Tp, and upper and lower beach D50 allows graphical assessment of trends within and between groups.

The combination of individual parameters in the framework of MDS also indicated the latent environmental forces of morphodynamic groupings. An example is that steeper beaches (a steep slope of more than 5), larger waves (Hs greater than 1.4 m), and a middle-to-coarse sand texture were prevalent in Groups 1 and 2, hence classifying them as intermediate-to-reflective beach types. Conversely, Group 3 sites were linked to very fine sand (D50 < 0.3 mm), reduced beach gradients (< 30), and reduced hydrodynamic energy. Engineered coastal defenses, such as seawalls and offshore breakwaters, were also important factors that affected these beaches, and this may have led to their lower morphodynamic variability and being less mobile.

The results show a significant change in the north-south direction in the morphodynamics of the beaches along the Kelantan coastline. The natural aspects of the northern beaches (K1 to K3) (bar systems, active sediment transport, etc.) may be attributed to the fact that there are fewer anthropogenic interferences and more exposure to the northeast monsoonal wave energy. By contrast, more simplified profiles in the southern beaches (K4 to K6) have low geomorphic variability, and much of this can be explained by trapping of sediments behind coastal defense structures and reduced wave action.

4. Discussion

Today, extensive use of coastal defences occurs with an aim to control rapid coastal erosion, but the efficiency of these structures is directly related to their type, geometry, and relation to the underlying coastal morphodynamics. Numerous studies across Asia, Europe, and Australia have demonstrated that coastal defenses such as offshore breakwaters, revetments, or seawalls, in most cases, fail to ensure the long-term sustainability of shorelines; in fact, in most cases, they completely change the natural shoreline profile, the sediment transport system, and the shoreline stability (Gunasinghe et al., 2021; Castelle & Masselink, 2023; Sanitwong-Na-Ayuttahaya et al., 2023). The results of six coastal locations examined in this study reflect these globally observed responses, while also highlighting the role of local hydrodynamic forcing and human intervention in shaping site-specific outcomes.

At Pantai Tok Bali (K6), the exceptionally steep upper-beach profile is characteristic of vertical seawall-backed beaches reported in densely defended coastlines of Southeast Asia, whereby wave reflection and increased nearshore seabed turbulence promote persistent toe scour and frontal beach narrowing. Sanitwong-Na-Ayutthaya et al. (2023) summarized that shore-parallel revetments and seawalls intensify wave reflection and near-bed turbulence, frequently triggering toe scour and progressive beach narrowing. Wangkulangkul et al. (2025) presented a recent study in which the vertical structures often had slopes of approximately 75 % of those of natural shorelines and exhibited downdrift erosion. In the long run, this process oftentimes enhances high-energy feedback mechanisms, accelerating sediment export during storm conditions and leading to long-term beach thinning. The stiffer lower foreshore sediments observed at this site are consistent with recurrent overwash and sediment winnowing processes that have been widely documented in structurally constrained beaches worldwide.

A comparable, though less extreme, response is observed at Pantai Irama (K5), where an offshore breakwater with insufficient gap spacing allows partial wave penetration, maintaining a relatively energetic nearshore environment and coarser sediment regime, despite the site being located south of the geographic line. This behavior closely mirrors observations from breakwater systems along Mediterranean and East Asian coastlines. Ding and Cheng (2020) found that suboptimal structure spacing and orientation result in complex diffraction patterns and spatially heterogeneous erosion–accretion responses. Storm-scale investigations of semicircular coastal defenses further demonstrate that inadequate gap spacing enhances wave penetration and induces unpredictable sediment dynamics, even in otherwise sheltered settings (Vieira et al., 2024). These comparisons reinforce the notion that local hard structure design can dominate over expected natural morphodynamic behavior, even within regions morphodynamically classified as dissipative.

In contrast, Pantai Kemayang (K4) exhibits a gentle beach slope and finer sediment texture, consistent with beaches sheltered by offshore breakwaters that effectively attenuate incident wave energy. The reduced energy environment permits smaller-scale sediments to prevail and is more permissive of a dissipative morphodynamic state. This site tends to be more stable due to the presence of a river acting as a continuous sediment supplier to the coastal system. Ratnayake et al. (2018) supports this by showing that riverine sediment supply is a critical factor in maintaining coastal stability, and its disruption leads to severe erosion. The moderate profiles in Pantai Cahaya Bulan (K1), Pantai Sabak (K2), and Pantai Nusuk (K3) further represent intermediate morphodynamic

conditions comparable to wave-dominated sandy beaches. These sites are characterized by steep beach slopes and coarser sediments. The presence of rock revetments provides protection against high wave energy, particularly as this region experiences stronger wave action compared to the southern sector. Nevertheless, revetments can interfere with natural sediment deposition processes along the beach profile, potentially altering sediment dynamics and leaving them more exposed to erosional forces (Rahidi et al., 2021; Sanitwong-Na-Ayuthaya et al., 2023).

On consideration of the Dean parameter and the RTR framework proposed by Masselink and Short (1993), the northern sites (K1 - K3) are best described as intermediate beaches, while the southern sites (K4 - K6) tend toward dissipative states. This north-south morphodynamic gradient, characterized by higher wave energy, steeper slopes, and coarser sediments in the north transitioning to lower energy, gentler slopes, and finer sediments in the south, reflects latitudinal and exposure-driven patterns reported in multiple coastal settings globally. Nevertheless, the presence of hard structures, particularly breakwater gaps and revetments, demonstrates that human intervention can locally modify or even override natural morphodynamic tendencies, as emphasized in recent global syntheses (Ratnayaket et al., 2018; Castelle & Masselink, 2023).

Similarity analysis further distinguishes three morphodynamically coherent groups, a pattern also commonly reported in comparative studies of engineered coastlines worldwide. There are three more different groupings that similarity analysis distinguishes. Group 1 (Pantai Cahaya Bulan) is influenced by a row of groyne fields and episodic fluvial sediment inputs, producing a distinct and dynamic morphodynamic signature akin to river-influenced beaches in Southeast Asia. This arrangement leads to the periodic supply of sediments and also relatively lower local wave energy than the nearby northern locations (Bozzeda et al., 2023). Group 2 (Pantai Nusuk and Pantai Sabak) share rather general morphological and sedimentological features, such as a moderate to steep slope of the beach, coarser sediment texture, and moderate to high wave exposure, with differences primarily related to sediment sourcing, a distinction comparable to river-fed versus drift-dominated beaches elsewhere. Group 3 (Pantai Kemayang, Pantai Irama, and Pantai Tok Bali) is typified by lower slopes, finer sediments, and extensive use of offshore breakwaters, broadly consistent with engineered dissipative beaches, although structural mismatches at specific sites generate localized erosive responses.

The outcomes show that there is a distinct spatial gradient down the coast from north to south; northern beaches (Groups 1 and 2) are steeper, contain coarser sediments, and experience higher wave energy, which aligns with the intermediate morphodynamic categories. In contrast, the southern beaches (Group 3: K4, K5, K6) have gentler slopes and finer sediments, which more consistent with the dissipative classification. This zonation directly impacts coastal management: to the north, conservation-based interventions should focus on sediment supply and defense effect management; to the south, restoration and structurally gentler interventions (i.e., low-crested breakwater or beach nourishment) can be closer to the natural dissipative regime. Overall, the findings highlight a clear spatial morphodynamic zonation that aligns with widely observed global coastal processes, while simultaneously illustrating how inappropriate defense design can undermine expected beach states. An example is Pantai Irama (K5), where the sediment is coarser, implying that defense geometry (gap in offshore breakwater, rock revetment) permits stronger-energy penetration, which is indicative of the fact that, in the so-called “dissipative” regions, the mismatch in structure design can achieve reflective or erosive results.

Beyond these physical considerations, as discussed above, it is essential to recognize and quantify the role of human pressures on coastlines as well. While the initial assessment addressed anthropogenic influence qualitatively, incorporating a Human Intervention Index (HII) offers a standardized metric for evaluating the degree of coastal modification on coastal areas (Xu et al., 2024). The proposed approach complements integrating morphodynamic zonation with quantitative indices of human intervention and will enhance reproducibility, facilitate cross-region comparisons, and provide policymakers with prioritized intervention accordingly.

5. Conclusions

The study is a detailed evaluation of the morphodynamic response of beaches in a structurally reinforced, monsoon-dominated coastal system through a synthesis of traditional classification with a multivariate theoretical approach. The findings show that the reflective-intermediate-dissipative paradigm can still be used, but as structural controls and variability of the supply of sediments are explicitly included, its predictive power is much greater. There was a detectable spatial gradient, as northern beaches were found to have intermediate properties in higher wave energy, and southern beaches more dissipative ones. This natural zonation is also often altered by coastal protection works, and here the variation in type and form (e.g., seawalls, revetments, and offshore breakwaters) causes a site-specific alteration in the predicted morphodynamic behavior.

The results support the main hypothesis, according to which engineered coastal interventions trigger quantifiable changes in the morphodynamic conditions, caused by the changes in the hydrodynamic processes and the sediment transportation pathways. Reflective-intermediate designs have been observed to increase scour and sediment export, but energy-dissipating designs increase the retention of sediment and dissipative environments. The multivariate method proved to be better than the traditional ones in terms of diagnostic capability, as the complex coastal responses could be differentiated more clearly. On the whole, the research meets its goal through developing the process-based knowledge of engineered coastal systems. Enhanced prediction frameworks should be developed through future work that includes long-term monitoring, high-resolution numerical modelling, and other parameters, including sediment budgets and extreme event effects.

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Competing Interest

The authors declare no conflict of interest in the production and submission of this work.

Declaration of Generative AI and AI-assisted technologies

The authors used ChatGPT (OpenAI) and Grammarly for assistance in conceptualization and grammar refinement of the manuscript. With or without AI applications, the authors are fully accountable for every process of the work and manuscript writing. All final edits, interpretations, and conclusions are the sole responsibility of the authors. The authors academically and ethically confirmed that the stated AI statements are true, and the authors are ultimately responsible and accountable for the contents of the published work, including the correctness of the references in the reference list.

CRedit author statement

Aminah Ismailluddin: Conceptualization; Data Curation; Methodology; Software; Validation; Formal Analysis; Investigation; Writing-Original Draft; Writing – Review & Editing; Visualization. **Faerah Nasir:** Writing – Review & Editing; Visualisation; Resources; Formal analysis. **Lee Shin Yun:** Resources; Data Curation; Methodology; Formal Analysis; Writing-Review & Editing. **Siti Nur Hanani Zainuddin:** Methodology. **Muhammad Rizal Razali:** Software; Writing – Review & Editing. **Muhammad Zahir Ramli:** Methodology; Writing – review & editing. **Mohd Azhafiz Abdullah:** Writing – Review & Editing. **Effi Helmy Ariffin:** Methodology; Writing – Review & Editing; Conceptualisation; Project administration; Supervision.

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