

Ecological implications of Coastal Defence Structures (CDS) in Kuala Nerus, Terengganu

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ABSTRACT

Coastal defense structures (CDS) play a significant role in erosion control and reducing the risk of flooding, thereby protecting human residences and properties. In Kuala Nerus, Terengganu, the construction of the CDS is expanding as erosion continues, especially during the northeast monsoon season. However, after the CDS completion, information on the ecological impacts of the structures remains limited. Hence, this study determined the sediment characteristics, total organic matter (TOM), and heavy metal contents, as well as physical and oceanographic water parameters in the CDS area of Kuala Nerus, Terengganu. Sampling was conducted from March to December 2021, involving five stations: four representing different CDS types – St. 1) groin (G), St. 2) semi-enclosed jetty-type breakwater (S), St. 3) breakwater with tombolo (B), St. 4) breakwater without tombolo (T), and St. 5) a control station. Sediments were collected from both exposed and sheltered areas using a Ponar grab. Results revealed that all stations predominantly consist of very fine sand (St. 3: 23.891% - Control: 75.799%), medium sand (Control: 9.258% - St. 2: 30.160%), and coarse sand (Control: 2.348% - St. 1: 28.593%). The sheltered stations documented higher TOM ($2.21 \pm 1.52\%$). Heavy metal concentrations of lithium (Li), chromium (Cr), iron (Fe), copper (Cu), zinc (Zn), cadmium (Cd), lead (Pb), arsenic (As), and mercury (Hg) are within the allowed value for the upper continental crust (UCC). Sheltered stations documented lower current speeds and wave heights. Overall, the present study demonstrated that the CDS have significantly altered the sediment characteristics, chemistry, and nearshore hydrodynamic conditions in the Kuala Nerus coastal area, underscoring the need for continued ecological monitoring in the modified coastal environment.

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1. INTRODUCTION

In the tropical region of the east coast of Peninsular Malaysia, the coastlines are directly exposed to the South China Sea's (SCS) strong winds and dynamic coastal processes (Mohd-Salim *et al.* 2018). The negative impacts of the annual Northeast Monsoon Season (NEM) exposure have been well mitigated by various types of coastal defense structures (CDS), which act as the first line of defense against strong winds, waves, and storm surges (Antunes 2020). Within this broader regional context, Kuala Nerus, Terengganu, which is located on the shallow Sunda shelf of the SCS (Kok *et al.* 2019), represents one of the most affected coastal districts.

This district, which experiences rapid development and economic growth driven by industrialization, serves as an eco-tourism gateway, hosts sports and recreational events, and undergoes infrastructure development (Data Asas Negeri Terengganu 2020), intensifying pressure on the coastal zone.

This densely populated district, with an approximate population of 153,700, has seen the implementation of several CDS projects aimed at mitigating erosion and protecting key infrastructure. The CDS in Kuala Nerus was initiated by the large groin in Teluk Ketapang Beach, which was constructed for the runway extension of Sultan Mahmud Airport (Ariffin *et al.* 2020). Following this, the state authority constructed a semi-enclosed jetty-type breakwater in Tok Jembal to support the local fishing community (Ariffin *et al.* 2018). Additional parallel breakwaters, some with tombolos, were constructed as a defence against wave action and currents, hence reducing the erosion rate in the affected areas.

The installation of the CDS has a significant positive impact on erosion control and flood risk reduction, thus saving human residences and properties (Rashidi *et al.* 2021). These structures offer a spectacular 180° panoramic view, enticing people to engage in leisure activities such as sightseeing, fishing, and stargazing. The land-sea breezes give people a

peaceful mind and significantly lower stress levels (Alomar-Garau and Grimalt-Gelabert 2022). Moreover, these structures are increasingly recognized as artificial reefs that support abundant and diverse marine communities in coastal areas.

However, these CDS structures greatly affected the environmental characteristics of the area. The shoreline configuration is frequently altered by the modified littoral transport system caused by the CDS (Hashish *et al.* 2012). The CDS structures interrupt the natural longshore sediment transport by blocking and redirecting sediment movement along the coast, leading to sediment accretion on the updrift side and erosion on the downdrift side. Additionally, seawater chemistry has been altered by coastal structures, leading to increased concentrations of suspended solids, dissolved oxygen, and biological oxygen demand (BOD) (Hashish *et al.* 2012). Additionally, coastal structures influence the current's speed, direction, circulation patterns, and wave regimes (Shih *et al.* 2022). These effects are interrelated and can only be mitigated through properly designing the structures and reconsidering everything beforehand.

Besides aiming to mitigate shoreline erosion and flood risk, designing CDS prioritises minimum impact on shore stability and water quality preservation (Moosavi 2017). The water quality, which can deteriorate due to poor flushing systems and stagnant water, poses risks to the area's biological productivity and aesthetic appeal (Bashir *et al.* 2020). The effective flushing system improves water quality by reducing pollutant concentrations in sheltered coastal basins (Tech 1988). The relatively high current velocity, combined with proper water circulation, promotes onshore water flow, ensuring maximum productivity in the area (Hsueh and Zhong 2004).

In CDS areas, hydrodynamics - encompassing currents, tides, and waves- have been considered the primary factor affecting the spatial distribution of different sediment types and organic matter (Xu *et al.* 2021). Studies by Martin *et al.* (2005) on King's Parade defence scheme in the North Wirral (England) and Zanuttigh *et al.* (2005) in Lido di Dante (Italy) and Elmer beaches (United Kingdom) reported a higher percentage of total organic matter and silt and clay contents in the sediment at the landward side of these structures. The sediments exhibited finer, muddier, and anoxic characteristics attributed to the tide and wave hydrodynamic conditions. Notably, as the distance from the structure increases, the disparities in organic matter, silt, and clay content gradually diminish. The low-crested structures did not significantly affect the sediment characteristics on the beaches, either near the structures or at increasing distances (Zanuttigh *et al.* 2005).

Limited information is available on the environmental characteristics of the CDS areas in Kuala Nerus, Terengganu,

as only a few studies have specifically addressed sediment dynamics in this region (e.g., Ariffin *et al.* 2020; Zulfakar *et al.* 2020; Ibrahim *et al.* 2023, 2025). After the completion and establishment of the structures, the ecological aspect and environmental response, including changes in sediment composition, heavy metal accumulation, and hydrodynamic alterations, remain unknown, as the focus remains solely on reducing the impact of erosion and flooding. The lack of scientific understanding represents a critical knowledge gap, as long-term modifications to sediment and water quality parameters may affect the stability and resilience of the coastal ecosystem. Moreover, the construction of the CDS in Kuala Nerus is still ongoing and expanding, as erosion continues to occur, especially during the annual NEM season (Malay Mail 2025; Bernama 2025). Thus, this study addresses this problem by investigating how CDS influence the sediment characteristics, Total Organic Matter (TOM), heavy metal contents, and nearshore hydrodynamic conditions in Kuala Nerus, Terengganu, Malaysia.

2. MATERIALS AND METHODS

2.1 Study area and sampling design

Sampling was conducted from March to December 2021 - across five stations comprising nine sub-stations, representing different types of CDS commonly found along the Kuala Nerus coastline, and a natural, unmodified control station in Batu Rakit (Figure 1 and 2; Table 1). The control station was selected as the area remains naturally stable and is not influenced by any CDS or significant erosion activities. The four CDS stations were: (St. 1) Groin (G-1.1, G-1.2), (St. 2) Semi-enclosed jetty-type breakwater (Inside and Outside lagoon), (St. 3) Breakwater without tombolo (B-3.1, B-3.2), and (St. 4) Breakwater with tombolo (T-4.1, T-4.2). The station codes are as follows: Groin (G), semi-enclosed jetty-type breakwater (S), breakwater without tombolo (B), and breakwater with tombolo (T). Each CDS station comprised both exposed and sheltered sub-stations, representing areas directly influenced by oceanic wave and current actions and those protected from it (Table 1). Sampling activities were scheduled according to high tides, calm sea conditions, and favourable weather (avoiding rough seas), ensuring safe sampling and data consistency.

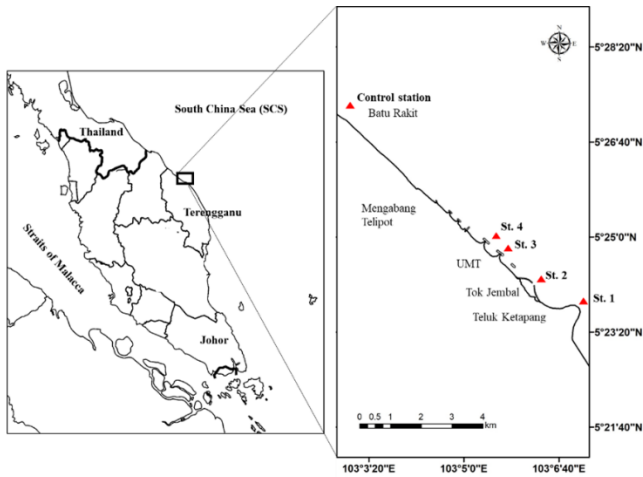


Figure 1: Map of sampling sites along the Kuala Nerus coastal area. The map of Peninsular Malaysia shows the location of Kuala Nerus, Terengganu (left), and four main stations near the coastal defence structures (CDS) along the Kuala Nerus coastal area + control station in Batu Rakit (right). St. 1- Groin, St. 2- Semi-enclosed jetty type breakwater, St. 3- Breakwater without tombolo, St. 4- Breakwater with tombolo, Control station - Batu Rakit.

Table 1: Geographical location and category of nine substations from five main stations of different coastal defence structures (CDS).

Stations	Locations	Substations	Latitude (N)	Longitude (E)	Category
Groin (G)	Teluk Ketapang	G-1.1	5°23'47.5"	103°07'04.3"	Exposed
		G-1.2	5°23'58.0"	103°06'26.6"	Sheltered
Semi-enclosed jetty-type breakwater (S)	Tok Jembal	S-Outside lagoon	5°24'08.2"	103°06'06.6"	Exposed
		S-Inside lagoon	5°24'12.6"	103°06'15.5"	Sheltered
Parallel breakwater without tombolo (B)	Tok Jembal	B-3.1	5°24'32.4"	103°05'54.2"	Exposed
		B-3.2	5°24'32.0"	103°05'45.7"	Exposed
Parallel breakwater with tombolo (T)	UMT	T-4.1	5°24'45.9"	103°05'40.3"	Exposed
		T-4.2	5°24'42.9"	103°05'33.4"	Sheltered
Control station	Batu Rakit	Control	5°27'09.0"	103°02'58.4"	Control

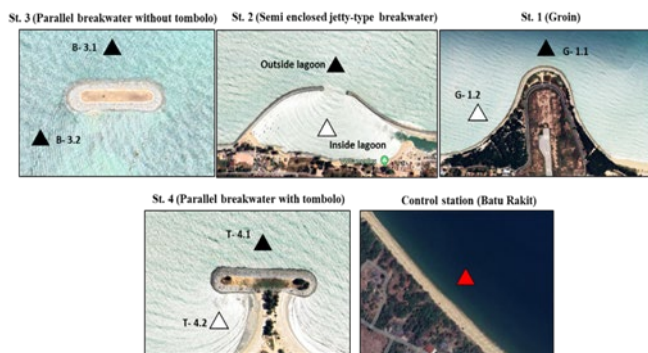


Figure 2: Control station and sampling stations along the coastal defence structure (CDS) areas of Kuala Nerus, Terengganu. St. 1. G- Groin, St. 2. S- Semi-enclosed jetty-type breakwater, St. 3. B- Breakwater without tombolo, St. 4. T- Breakwater with tombolo, and Control station- Batu Rakit. Black triangle: Exposed stations. White triangle: Sheltered stations. Red triangle: Control station.

2.3. Laboratory procedures

In grain size analysis, sediment samples (~100g) were oven-dried (70° C, 72 hours) and subjected to a dry sieving technique using an Octagon digital shaker with mesh sizes 4, 2, 1, 0.5, 0.25, 0.15, and 0.63 mm (Bachok *et al.* 2009). The results were calculated using the statistical moment method to determine the mean grain size, sorting, and skewness (Folk and Ward 1957). The sediments were classified into gravel, sand (coarse, medium, fine, and very fine), silt, and clay based on their particle size ranges (Wentworth 1922) (Table 2).

Table 2: Descriptive terminology for grain size analysis - modified from Udden (1914) and Wentworth (1922).

Grain Diameter (mm)	Mean grain size (phi)	Descriptive terminology
4-2	-12-(-1)	Gravel
2-1	-1-0	Very coarse sand
1-0.5	0-1	Coarse sand
0.5-0.25	1-2	Medium sand
0.25-0.125	2-3	Fine sand
0.125-0.0625	3-4	Very fine sand
0.0625-0.031	4-5	Very coarse silt
0.031-0.0156	5-6	Coarse silt
0.0156-0.0078	6-7	Medium silt
0.0078-0.0039	7-8	Fine silt
0.0039-0.0020	8-9	Very fine silt
<0.0020	>9	Clay

TOM content in the sediment was determined using the loss-on-ignition (LOI) method (Bensharada *et al.* 2022). Heavy metals concentration in sediment - lithium (Li), chromium (Cr), iron (Fe), copper (Cu), zinc (Zn), cadmium (Cd), lead (Pb), arsenic (As), and mercury (Hg) were analysed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS, Perkin Elmer ELAN 6100) after digestion (Ong *et al.* 2016).

2.4. Contamination assessment methods

The level of heavy metal contamination in the study sites was determined using quantitative contamination indices, including the Index of Geo-accumulation (Igeo) (Müller 1969), Pollution Load Index (PLI) (Hakanson 1980), and enrichment factor (EF) (Barbieri 2016). The EF and Igeo represent the single-element indices as they focus on determining single heavy metal levels. In contrast, the PLI represents the multi-element pollution indices. Those assessments were calculated using Upper Continental Crust (UCC) values of elements as background. The UCC for each metal are as follows: Li= 22 ppm; Cr= 35 ppm; Fe= 308.9%; Cu= 14.3 ppm; Zn= 52 ppm; Cd= 0.1 ppm; Pb= 16 ppm; As= 2 ppm; Hg= 0.06 ppm.

2.5. Statistical analysis

Environmental parameters (sediment characteristics, TOM, heavy metal concentrations, and physical parameters) were analyzed for comparative analysis across stations. As

the data did not follow a normal distribution ($p < 0.05$, Shapiro-Wilk and Kolmogorov-Smirnov tests; $p < 0.05$, Levene's test), non-parametric tests were applied using the Statistical Package for the Social Sciences (IBM SPSS Statistics version 26). The Kruskal–Wallis test was used to compare the environmental parameters among the five sampling stations. The Mann–Whitney U test was used to compare the same environmental parameters between the two exposure categories (sheltered and exposed sites).

The relationship between the environmental parameters of sediment characteristics, TOM heavy metal contents, and the physical parameters (current speed, wave height, depth (bathymetry), temperature, salinity, and pH) across stations was analysed using Principal Component Analysis (PCA), computed from Paleontological Statistics Software (PAST version 2.14). Variables with loading values greater than 0.30 were considered to contribute significantly to each principal component.

3. RESULTS

3.1 Sediment characteristics

All sampling stations predominantly consist of very fine sand (St. 3: 23.89% - Control: 75.80%), medium sand (Control: 9.26% - St. 2: 30.16%), and coarse sand (Control: 2.35% - St. 1: 28.59%) with a consistent pattern across the stations (Figure 3A). The sediment variation is high in all stations related to CDS (st. 1–4). In comparison, the control station is less varied and exhibits a higher proportion of very fine sand (75.80%). There are statistically significant differences in the amount of coarse and very fine sands between different sampling stations ($p < 0.05$). Specifically, the differences between the control station and St. 1, 2, and 3 are noted.

At the sheltered stations (inside the lagoon and T-4.2), the surface sediments are mainly composed of very fine sand. Station T-4.2 contains 75.84% very fine sand (3.231 Φ), while the station inside the lagoon has 50.38% (3.390 Φ) (Figure 3B; Table 3). These sands are poorly sorted (T-4.2 = 1.05 Φ ; inside lagoon = 1.13 Φ), meaning the grains vary widely in size, and both are very coarse skewed (T-4.2 = -2.47 Φ ; inside lagoon = -1.64 Φ).

In contrast, the exposed stations show a mix of sediment types, including coarse, medium, and very fine sands. Coarse sand dominates at stations G-1.1 (0.498 Φ ; 32.93%) and B-3.1 (0.678 Φ ; 43.28%), while medium sand is common outside the lagoon (1.385 Φ ; 46.19%) and at T-4.1 (0.827 Φ ; 20.51%). Very fine sand dominates station B-3.2 (3.785 Φ ; 46.61%). The sediments range from poorly sorted (B-3.2 = 1.05 Φ to T-4.1 = 1.10 Φ) to moderately sorted (outside lagoon = 0.71 Φ ; B-3.1 = 0.94 Φ). The skewness

varies, showing symmetrical (G-1.1 = 0.00 Φ to outside lagoon = 0.05 Φ), fine-skewed (B-3.1 = 0.12 Φ), and very coarse-skewed (B-3.2 = -1.59 Φ ; T-4.1 = -0.41 Φ) distributions. The control station also contains very fine sand (3.234 Φ ; 75.8%), which is moderately sorted (0.97 Φ) and very coarse-skewed (-2.52 Φ). There are statistically significant differences in the percentages of coarse, medium, and very fine sand between sheltered and exposed stations ($p < 0.05$). However, no significant difference is observed in the amount of fine sand between the sheltered and exposed sites ($p > 0.05$).

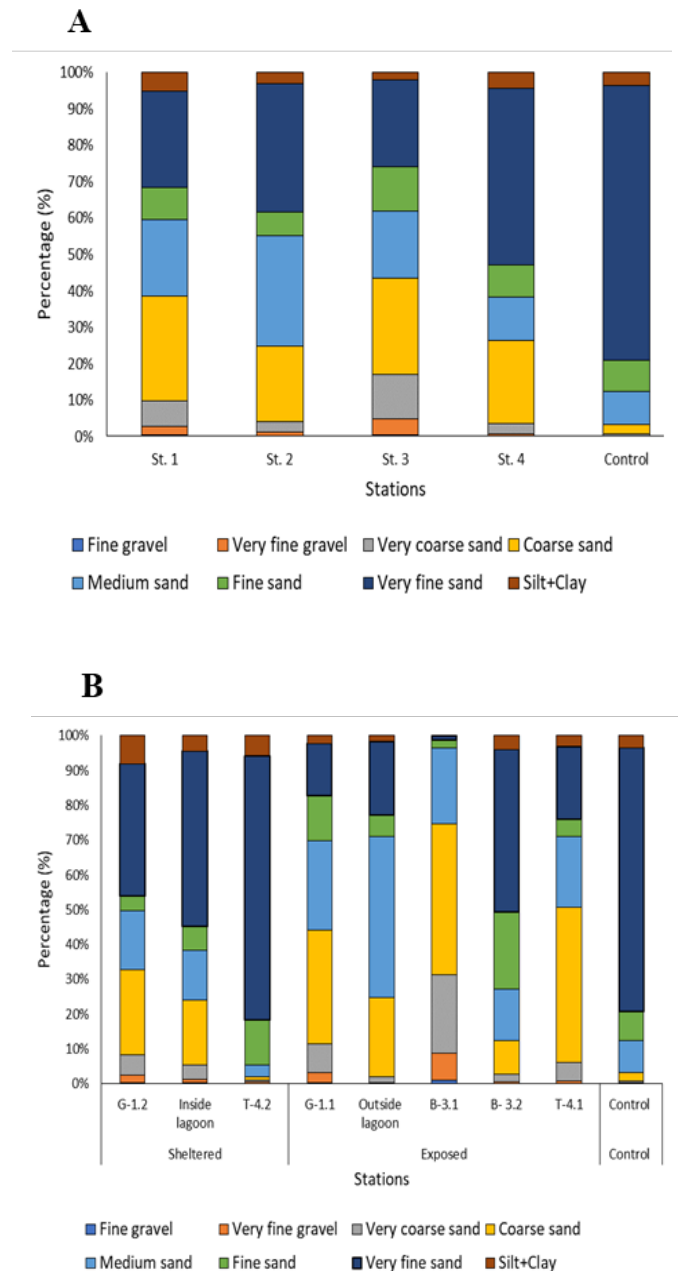


Figure 3: Sediment characteristics at coastal defence structure (CDS) areas in Kuala Nerus, Terengganu, Malaysia. A. Across the main stations, B. Across sheltered, exposed and control stations. St. 1: Groin (G); St. 2: Semi-enclosed jetty type breakwater (S); St. 3: Parallel breakwater without tombolo (B); St. 4: Parallel breakwater with tombolo (T).

Table 3: Sediment characteristics (mean, sorting, skewness, and textural classification) at nine substations (sheltered, exposed and control stations) in the Coastal Defense Structure (CDS) area in Kuala Nerus, Terengganu. G- Groin; S- Semi-enclosed jetty type breakwater; B- Breakwater without tombolo; T- Breakwater with tombolo.

	Sub-stations	Mean (Φ)	Description	Sorting (Φ)	Description	Skewness (\emptyset)	Description	Texture
Sheltered	G- 1.2	1.920	Medium sand	1.17	Poorly sorted	-0.11	Coarse skewed	Sand
	Inside lagoon	3.390	Very fine sand	1.13	Poorly sorted	-1.64	Very coarse skewed	Sand
	T- 4.2	3.231	Very fine sand	1.05	Poorly sorted	-2.47	Very coarse skewed	Sand
	G- 1.1	0.498	Coarse sand	1.09	Poorly sorted	0.00	Symmetrical	Sand
	Outside lagoon	1.385	Medium sand	0.71	Moderately sorted	0.05	Symmetrical	Sand
Exposed	B- 3.1	0.678	Coarse sand	0.94	Moderately sorted	0.12	Fine skewed	Sand
	B- 3.2	3.785	Very fine sand	1.05	Poorly sorted	-1.59	Very coarse skewed	Sand
	T- 4.1	0.827	Medium sand	1.10	Poorly sorted	-0.41	Very coarse skewed	Sand
Control	Control	3.234	Very fine sand	0.97	Moderately sorted	-2.52	Very coarse skewed	Sand

3.2 Total Organic Matter (TOM) content

Station 4 recorded the highest TOM content (2.30%), followed by the control station (2.08%), and St. 1 (1.81%) (Figure 4A). The lowest percentage of TOM is represented by St. 3 (1.38%). No significant difference exists in TOM content across stations ($p > 0.05$). In detail, TOM content ranges from 0.98% (station B- 3.1) to 3.32% (station T- 4.2) throughout all stations (Figure 4B). The sheltered stations recorded higher TOM (average 2.21%) than the control station (average 2.08%) and the exposed stations (average 1.52%). The control station recorded almost equal TOM values as the sheltered stations (2.08%). In sheltered stations, the values range from 1.62% (G-1.2) to 3.32% (T-4.2), indicating that TOM in the northern part of the Kuala Nerus CDS area is twice that of the southern part. In exposed stations, TOM ranges from 0.98% (B-3.1) to 2.00% (G-1.1), which is nearly equal to the control station (2.08%). No significant difference exists in the TOM content between sheltered and exposed stations ($p > 0.05$).

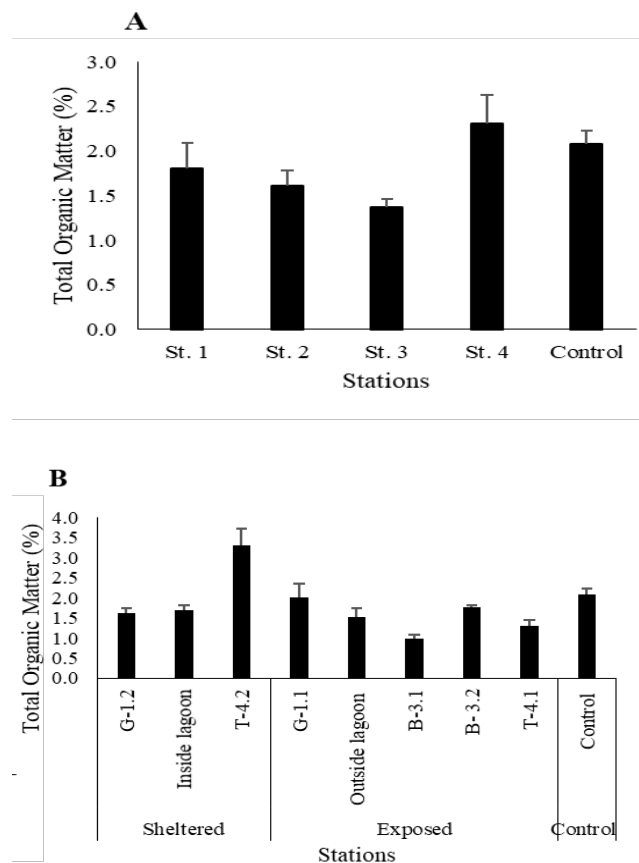


Figure 4: Percentage of total organic matter (TOM) content (%) at coastal defense structure (CDS) areas in Kuala Nerus, Terengganu, Malaysia. A. Across the main stations, B. Across sheltered, exposed and control stations. St. 1: Groin (G); St. 2: Semi-enclosed jetty type breakwater (S); St. 3: Parallel breakwater without tombolo (B); St. 4: Parallel breakwater with tombolo (T).

3.3 Heavy metal concentration

The heavy metal concentrations of Li, Cr, Fe, Cu, Zn, Cd, Pb, As, and Hg in the Kuala Nerus CDS areas are within the allowed value for the upper continental crust (UCC) (Figure 5). Most heavy metals in CDS stations are lower than the control station, except the Li in St. 4 (5.26 ppm vs 4.51 ppm), Cr in St. 3 (10.71 ppm vs 9.85 ppm), Zn in St. 4 (6.31 vs 5.89 ppm), Cd in St. 3 (0.04 vs 0.02 ppm), Pb in St. 4 (1.54 vs 1.36 ppm), and As in St. 4 (1.16 vs 0.88 ppm). No significant difference exists between all heavy metal types across main stations ($p > 0.05$).

The sheltered stations have higher concentrations of Fe and Pb compared to the exposed and control stations (Figure 6). Notably, the sheltered station at T-4.2 has the highest concentrations for several metals. The exposed stations exhibit wider ranges for Cr and Zn, with some stations having the highest concentrations for these metals. Station B-3.2, which is exposed, shows the highest concentrations of Cr, Zn, and Cu. The control station falls within the ranges of sheltered and exposed stations, but is often exceeded by specific high-value stations in both categories, particularly for Fe and Cr. No significant difference exists in all heavy metal types between sheltered and exposed stations ($p > 0.05$).

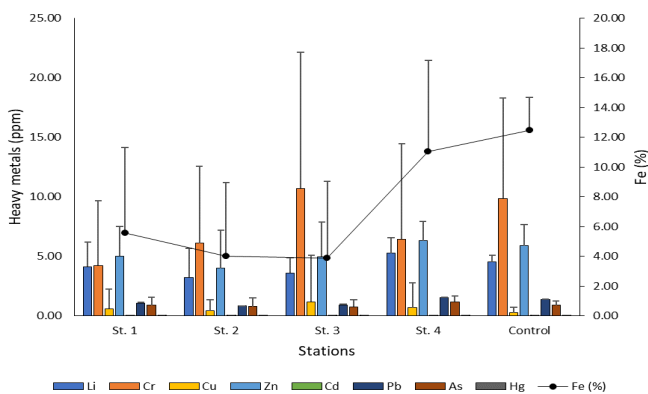


Figure 5: Heavy metal concentrations at coastal defense structure (CDS) areas in Kuala Nerus, Terengganu, Malaysia. St. 1: Groin; St. 2: Semi-enclosed jetty type breakwater; St. 3: Breakwater without tombolo; St. 4: Breakwater with tombolo and a control station. UCC: Li= 22; Cr= 35; Fe (%) = 308.9; Cu= 14.3; Zn= 52; Cd= 0.1; Pb= 16; As= 2; Hg= 0.06

3.4 Geo-accumulation index (Igeo)

Across the sheltered, exposed, and control stations, all analyzed heavy metals have an Igeo of less than zero (negative value) (Table 4). The sediment at the CDS area in Kuala Nerus is considered uncontaminated. Sheltered stations of B- 3.3 and T- 4.3 recorded the highest Igeo values for almost all heavy metals, except for Zn, which was the highest in the exposed station of G- 1.1. The lowest Igeo values for nearly all heavy metals were recorded at the exposed station (B-3.2) and the sheltered station (B-3.1).

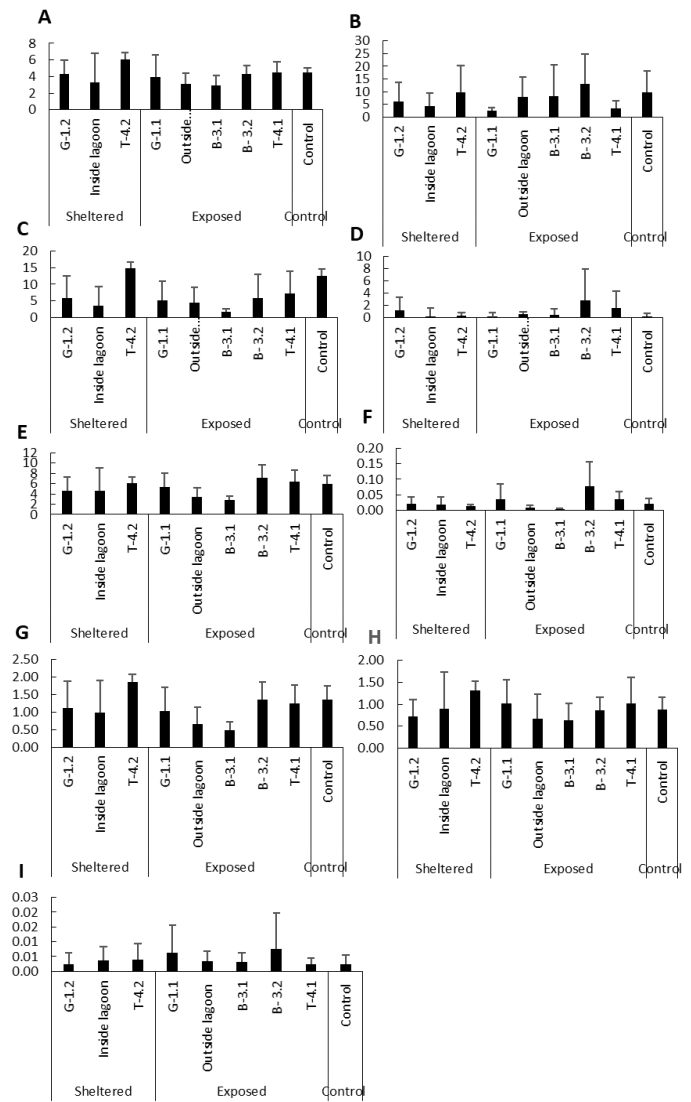


Figure 6: Concentration of heavy metals (ppm & %) across substations in Coastal Defence Structure (CDS) area and a control station in Kuala Nerus, Terengganu. A. Lithium (Li), B. Chromium (Cr), C. Fe (Iron), D. Copper (Cu). E. Zinc (Zn), F. Cadmium (Cd), G. Lead (Pb), H. Arsenic (As), I. Mercury (Hg).

3.5 Pollution Load Index (PLI)

Throughout the sheltered, exposed, and control stations, the PLI recorded values of less than one for all heavy metal types (Table 5), indicating all chosen metals were free of pollution. The highest PLI values are primarily recorded in sheltered stations, specifically B-3.2 and T-4.2. The lowest PLI values were mainly documented in the exposed station of B-3.1.

3.6 Enrichment Factor (EF)

Enrichment factor analysis revealed that most heavy metals exhibit no enrichment across the sampled sites, suggesting that their concentrations are comparable to natural background levels (Table 6). The lowest EF values were primarily recorded by the exposed station B-3.1, which included only Zn, Cd, and Pb, while the rest were patchily

distributed. The highest EF values for most metals were recorded at the sheltered station of B-3.2, involving Cu, Zn, Cd, and Hg.

3.7 Current speed

The sheltered stations revealed a lower current speed (m/s) with a magnitude between 0.007 m/s (T- 4.2) to 0.0318 m/s (station G- 1.2) as compared to the exposed stations of magnitude 0.0304 m/s (B- 3.2) to 0.0812 m/s

(station G- 1.1) and a control station (0.0521) (Figure 7). The current speed in sheltered stations starts higher at G- 1.2 (large groin) and gradually decreases towards the northern station of T- 4.2. Meanwhile, a similar decreasing pattern was detected throughout the exposed sites, starting from G-1.1 and extending towards the northern station, B-3.2. The trend, however, then changed towards T-4.1, which documented a higher current speed. There are significant differences in current speed between sheltered and exposed stations ($p < 0.05$).

Table 4: Geo-accumulation index (Igeo) of all selected heavy metals in Coastal Defense Structure (CDS) area in Kuala Nerus, based on sheltered, exposed and control sites. G- Groin; S- Semi-enclosed jetty type breakwater; B- Breakwater without tombolo; T- Breakwater with tombolo.

	Sheltered			Exposed					Control	Igeo Class	Pollution level
	G-1.2	Inside lagoon	T-4.2	G-1.1	Outside lagoon	B-3.1	B- 3.2	T-4.1	Control		
Li	-3.11	-3.41	-2.99	-3.16	-3.41	-3.58	-2.98	-2.99	-2.89	0	Uncontaminated
Cr	-3.40	-3.90	-3.80	-4.60	-3.90	-2.95	-2.24	-3.80	-2.70	0	Uncontaminated
Fe	-6.57	-6.98	-6.18	-6.68	-6.98	-6.62	-6.18	-6.18	-5.20	0	Uncontaminated
Cu	-5.00	-6.18	-4.25	-7.01	-6.18	-4.58	-3.32	-4.25	-6.20	0	Uncontaminated
Zn	-4.24	-4.25	-3.71	-3.96	-4.25	-4.80	-3.55	-3.71	-3.70	0	Uncontaminated
Cd	-3.12	-3.28	-2.35	-2.39	-3.28	-4.98	-1.26	-2.35	-2.94	0	Uncontaminated
Pb	-4.65	-4.82	-4.35	-4.72	-4.82	-5.79	-4.24	-4.35	-4.17	0	Uncontaminated
As	-2.30	-1.91	-1.74	-1.76	-1.91	-2.46	-1.73	-1.74	-1.85	0	Uncontaminated
Hg	-5.50	-4.87	-5.25	-4.10	-4.87	-4.98	-3.89	-5.25	-5.49	0	Uncontaminated

Table 5: Pollution Load Index (PLI) values of all selected heavy metals, across all sheltered, exposed and control stations in Kuala Nerus Coastal Defense Structure (CDS) areas. G- Groin; S- Semi-enclosed jetty type breakwater; B- Breakwater without tombolo; T- Breakwater with tombolo.

	Sheltered			Exposed					Control	PLI Class	Pollution level
	G-1.2	Inside lagoon	T-4.2	G-1.1	Outside lagoon	B-3.1	B- 3.2	T-4.1	Control		
Li	0.823	0.805	0.867	0.820	0.797	0.794	0.832	0.831	0.837	0	Unpolluted
Cr	0.805	0.775	0.853	0.734	0.853	0.833	0.880	0.781	0.849	0	Unpolluted
Fe	0.630	0.611	0.707	0.625	0.616	0.628	0.650	0.650	0.701	0	Unpolluted
Cu	0.712	0.650	0.642	0.609	0.671	0.735	0.810	0.754	0.649	0	Unpolluted
Zn	0.754	0.754	0.795	0.771	0.733	0.723	0.796	0.786	0.787	0	Unpolluted
Cd	0.823	0.812	0.834	0.870	0.733	0.713	0.950	0.873	0.834	0	Unpolluted
Pb	0.731	0.722	0.791	0.728	0.693	0.670	0.755	0.748	0.759	0	Unpolluted
As	0.876	0.903	0.955	0.914	0.870	0.866	0.916	0.915	0.907	0	Unpolluted
Hg	0.685	0.719	0.721	0.763	0.717	0.713	0.775	0.698	0.685	0	Unpolluted

Table 6: Enrichment factor (EF) values of all selected heavy metals, across all sheltered, exposed and control stations in Kuala Nerus Coastal Defence Structure (CDS) areas. G- Groin; S- Semi-enclosed jetty type breakwater; B- Breakwater without tombolo; T- Breakwater with tombolo.

	Sheltered			Exposed					Control	Categories
	G-1.2	Inside lagoon	T-4.2	G-1.1	Outside lagoon	B-3.1	B- 3.2	T-4.1	Control	
Li	1.0000	1.0000	1.0000	1.000	1.0000	1.0000	1.0000	1.0000	1.0000	No enrichment
Cr	0.8185	0.7099	0.8658	0.3683	1.8513	1.5531	1.6712	0.5695	1.1364	No enrichment
Fe	0.0907	0.0841	0.1585	0.0871	0.0985	0.1215	0.1097	0.1095	0.2019	No enrichment
Cu	0.2709	-0.1463	-0.0668	-0.0693	-0.2139	0.5003	0.7883	0.4165	0.1009	No enrichment
Zn	0.4564	0.5566	0.4607	0.5756	0.4703	0.4303	0.6740	0.6074	0.5705	No enrichment
Cd	0.9925	1.0890	0.7077	1.7035	0.4730	0.3794	3.3069	1.5616	0.9625	No enrichment
Pb	0.3444	0.3753	0.4383	0.3409	0.2855	0.2166	0.4175	0.3885	0.4123	No enrichment
As	1.7485	2.8292	2.3798	2.6533	2.2006	2.1884	2.3803	2.3797	2.0571	No enrichment to minimal enrichment
Hg	0.1913	0.3626	0.1904	0.5226	0.3858	0.3808	0.5317	0.2083	0.1643	No enrichment

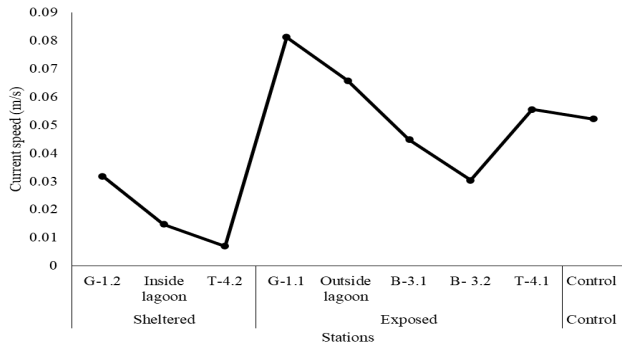


Figure 7: Current speed (m/s) in the Kuala Nerus coastal area throughout sheltered, exposed and control stations. G- Groin; S- Semi-enclosed jetty type breakwater; B- Breakwater without tombolo; T- Breakwater with tombolo.

3.8 Significant Wave Height, Hs

Significant Wave Height (H_s) refers to the one-third height of the highest waves in a sea state and is also denoted as $H_{1/3}$. The lowest H_s was consistently recorded in a sheltered station of the inside lagoon (0.533 m) (Figure 8). In contrast, the highest H_s was consistently documented in the exposed station of G-1.1 (1.14 m), followed by the outside lagoon (1.13 m) and B-3.1 (1.078 m). The control station overall recorded a higher H_s (1.278 m) compared to the sheltered and exposed stations. There are significant differences in H_s between sheltered and exposed stations ($p < 0.05$).

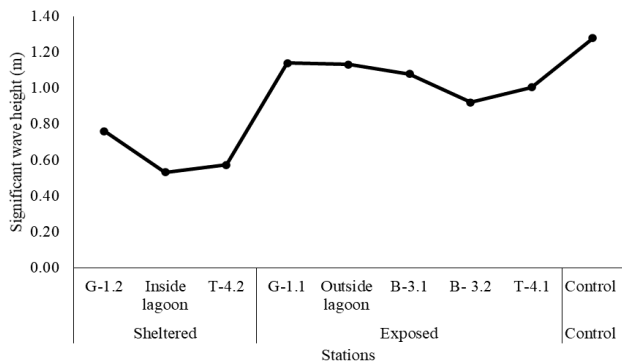


Figure 8: Significant wave height (m) in the Kuala Nerus coastal area throughout sheltered, exposed and control stations. G- Groin; S- Semi-enclosed jetty type breakwater; B- Breakwater without tombolo; T- Breakwater with tombolo.

3.9 Bathymetry

The bathymetry of the Kuala Nerus coastal area, specifically in the vicinity of CDS, varied from 2.5 ± 0.5 m (station B-3.2) to 8 ± 0.5 m (station G-1.2) in depth, with the control station of 10 ± 1 m (Figure 9). The deepest station of the coastal structure area was represented by station G-1.1 (8.0 m in depth), followed by station G-1.2 and the outside lagoon (5.0 m in depth). Station B-3.2 represented the shallowest station. In the same coastal structure system, a combination of shallow sheltered and deeper exposed sites is

frequently and commonly spotted, as documented in the St. 2 of semi-enclosed jetty type breakwater, where the inside lagoon recorded a shallower depth of approximately 3 to 4 m, than the outside lagoon of 5 meters. In general, the control station (10 m in depth) documented a deeper depth compared to sheltered stations (3.5–5.8 m) and exposed stations (2.5–8 m), with all-inclusive patterns being highly irregular and complex. There are significant differences in bathymetry between sheltered and exposed stations ($p < 0.05$).

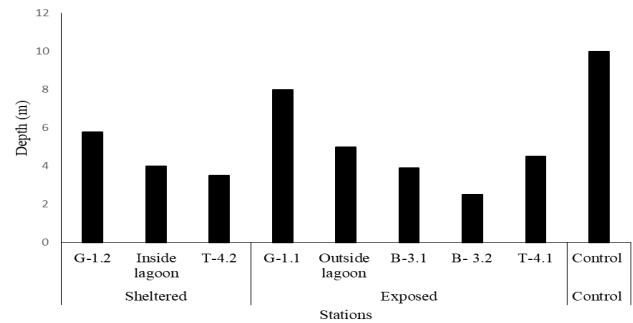


Figure 9: Bathymetry in sheltered, exposed and control stations of the Kuala Nerus coastal area in relation to the Coastal Defence Structure (CDS) system. G- Groin; S- Semi-enclosed jetty type breakwater; B- Breakwater without tombolo; T- Breakwater with tombolo.

3.10 Physico-chemical properties

The average sea surface temperature showed a fairly consistent reading with a minimal range detected, from 29.30°C (St. 1) to 29.62°C (control station) (Figure 10A). The salinity clearly showed a fluctuation pattern throughout the stations, with the highest salinity recorded in the control station (31.97 ppt) and the lowest in St. 2 (31.57 ppt). However, the salinity range was still very brief among all the study sites. pH values exhibit a similar pattern to temperature, with readings increasing from St. 1 (8.33) to the control station (8.42), within a very short range.

Overall, among the five study sites, the control station exhibited higher water physical parameters (temperature, salinity, and pH) compared to the other CDS stations. However, no station has consistently shown lower water physical parameters, except St. 1, which recorded the lowest readings for temperature and pH. No significant difference exists in all water physical parameters at the five main stations ($p > 0.05$).

The average water parameters at sheltered, exposed, and control stations showed a fairly consistent reading with a minimal overall range (Figure 10B). The sheltered stations recorded higher readings of temperature, salinity, and pH compared to the exposed and control stations. Similar to the five major stations, no significant differences were detected in all water physical parameters at the substations of both sheltered and exposed sites ($p > 0.05$).

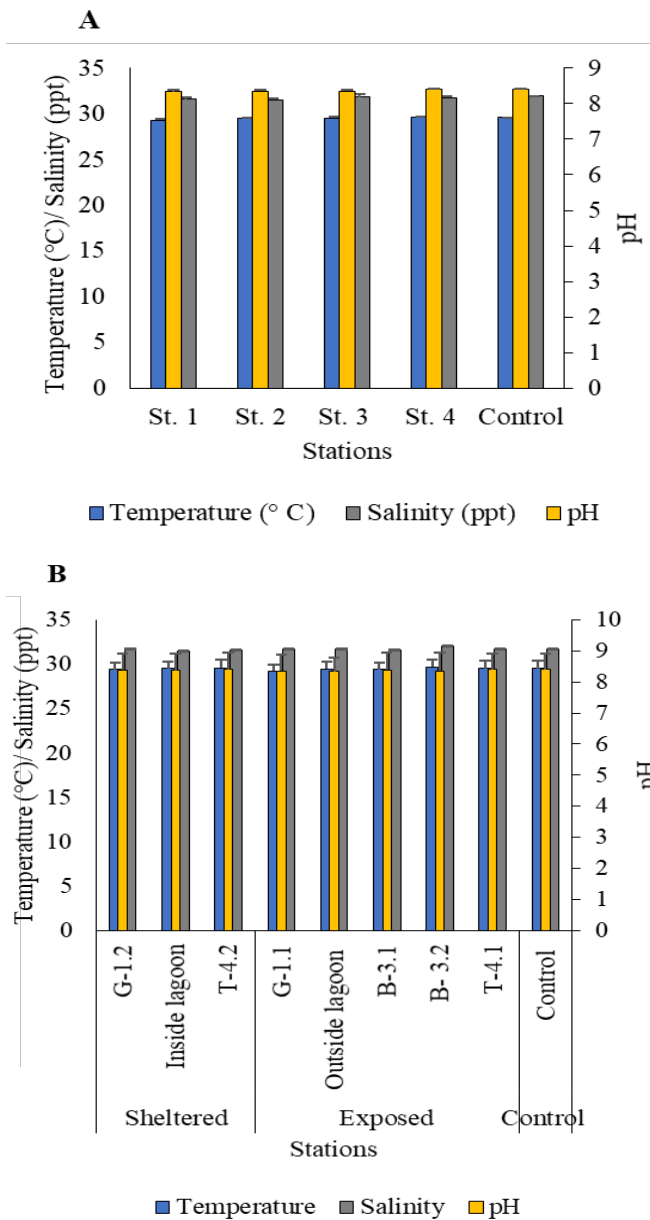


Figure 10: Water physical parameters at coastal defense structure (CDS) areas in Kuala Nerus, Terengganu, Malaysia. A. Across the main stations, B. Across sheltered, exposed and control stations. St. 1: Groin (G); St. 2: Semi-enclosed jetty type breakwater (S); St. 3: Parallel breakwater without tombolo (B); St. 4: Parallel breakwater with tombolo (T).

3.11 Multivariate analysis

The environmental parameters consist of sediment characteristics (fine gravel, very fine gravel, very coarse sand, coarse sand, medium sand, fine sand, very fine sand, and silt and clay), sediment chemistry (TOM and heavy metals of Li, Cr, Pb, Cu, Zn, Fe, Cd, and As) and water physical parameters (current speed, wave height, depth, temperature, salinity and pH) were related among each other across CDS stations. The first and second PCA components accounted for 59.73% of the total variance (Table 7). PC1 accounted for 34.43% and was significantly contributed to by fine gravel (0.314), very fine

gravel (0.306), and very coarse sand (0.328). In PC2, which accounts for 25.30% of the total variance, TOM (0.324), Li (0.357), Fe (0.354), Pb (0.366), As (0.344), and pH (0.304) contribute significantly (Table 8).

Table 7: Eigenvalues (more than 1) and percentage of variance of principal component axes.

PC	Eigenvalue	% variance
1	8.17483	34.427
2	6.0077	25.301
3	2.83465	11.938
4	2.3764	10.008

Table 8: Factor loadings of principal components (PCs) in Kuala Nerus Coastal Defence Structure (CDS)

Variable	PC 1	PC 2	PC 3	PC 4
TOM	0.088	0.324	-0.041	0.281
Fine gravel	0.314	-0.137	0.114	-0.084
Very fine gravel	0.306	-0.142	0.161	-0.012
Very coarse sand	0.328	-0.106	0.096	0.019
Coarse sand	0.258	-0.038	-0.152	0.323
Medium sand	0.047	-0.238	-0.291	0.299
Fine sand	-0.151	0.010	0.025	-0.377
Very fine sand	-0.241	0.164	0.155	-0.250
Silt and Clay	-0.224	0.103	0.279	0.003
Li	0.125	0.357	0.012	0.139
Cr	0.251	-0.005	-0.182	0.151
Fe	0.068	0.354	0.017	0.212
Cu	0.279	-0.079	0.074	-0.284
Zn	0.202	0.251	0.267	-0.125
Cd	0.248	-0.014	0.341	-0.209
Pb	0.148	0.366	0.064	0.022
As	0.054	0.344	0.045	0.083
Current speed	-0.109	-0.203	0.326	0.302
Wave height	-0.067	-0.127	0.353	0.268
Depth	-0.178	0.067	0.382	0.233
Temperature	0.254	0.128	-0.184	-0.240
Salinity	0.294	-0.057	0.262	0.044
pH	-0.074	0.304	-0.166	-0.053

In the PCA triplot, the heavy metals such as As, Fe, Pb, Li, and Zn have a positive close association with TOM (Figure 11). Meanwhile, Cd, Cr, and Cu are positively and closely related to temperature and salinity, characterised by very coarse sand, fine gravel, coarse sand, and very fine gravel. The hydrodynamic factor of current speed has a positive correlation with wave height and a negative correlation with TOM and heavy metals. The very fine sand and fine sand are closely and positively related to silt and clay, as well as depth.

The exposed stations, such as those outside the lagoon (B-3.1) and G-1.1, are related to current speed and wave height. The sheltered stations of inside lagoon, G-1.2, and the control station are related to pH, very fine sand, silt, and clay, depth, and fine sand. The sheltered station of T-4.2 is related to TOM, temperature, and several heavy metal types, including As, Fe, Pb, Li, and Zn. The exposed station of B-3.2 is related to very coarse sand, fine gravel, coarse sand, very fine gravel, and salinity.

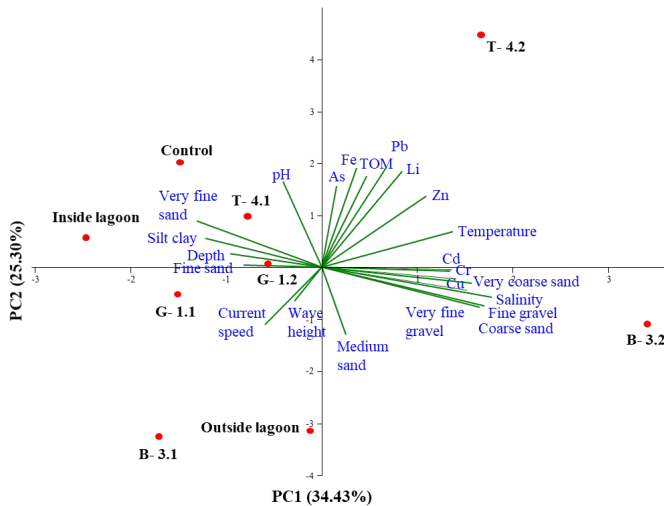


Figure 11: Principal Component Analysis (PCA) ordination showing environmental parameters clustering based on an Euclidean Distance matrix in coastal defense structure (CDS) areas of Kuala Nerus, Terengganu. G- Groin; S- Semi-enclosed jetty type breakwater; B- Breakwater without tombolo; T- Breakwater with tombolo.

4. DISCUSSION

The present study demonstrated that the CDS of the groin, semi-enclosed jetty-type breakwater, and parallel breakwaters have altered and influenced the dynamics of bottom sediment and nearshore hydrodynamic circulation in the Kuala Nerus coastal area. This alteration is evident on the UMT shore (near St. 4), which was once predominantly characterized by coarse sand, as highlighted by Ariffin et al. (2018). The disruption to the natural sediment composition in the study areas has occurred due to the installation of the CDS, contributing to the shift in the sedimentary environment.

The northern part of Terengganu, encompassing the Kuala Nerus and Kuala Terengganu districts, historically experiences low-wave energy (Ariffin et al. 2018). This low-energy environment enabled the stable accumulation of coarse sand along the UMT shore. However, the installation of the CDS, commencing from the groin of Sultan Mahmud Airport's runway, has disrupted the low-energy environment, leading to the installation of several other CDS, especially the parallel breakwaters. The alteration of the nearshore hydrodynamic circulation by the CDS affects the natural

sediment transport process, hence causing changes in the grain size distribution and overall sediment characteristics of the area (Zulfakar et al. 2020).

4.1 Sediment characteristics

Based on the results of higher domination of coarser and medium sands in exposed stations, the possible reason might be due to the combined effects of stronger wave propagation, fast water current flow, low water level, weather events and turbulence in the areas, which have inhibited the deposition of fine particles and allowed for the settlement of coarser and medium size particles (Bertasi et al. 2007). The heaviest particles will settle first along the coast, while the finest ones are carried the farthest, contributing to the muddy bottoms (López 2017). In exposed stations with stronger water currents, coastal structures are suggested to reflect wave energy seawards, creating turbulence and water flow.

Water flow is crucial in transporting sediment as it picks up and moves the light, fine particles to another stable hydrodynamic area, while leaving the heavy, coarse grains settled in the strong current area. This finding is parallel with that of Davis (1982) and Barros et al. (2004), which indicates that wave-retention coarser materials have resulted in frequent records of shell debris and coarse sediments near rocky reef areas. Subsequently, Carugati et al. (2018) also reported similar findings in which sand represented the dominant fraction in the wave-exposed area of the seaward side (approximately 90% sand and 10% pelite, which refers to fine-grained sediment composed mainly of silt and clay particles).

On the contrary, Davis (1982) and Barros et al. (2004) reported that muddy sediments characterize the sediments in sheltered areas behind low-crested structures, with patches of dead shells and very coarse calcareous granules. Meanwhile, in the present study, the surface sediments at the sheltered stations are dominated by very fine sand, with poorly sorted and very coarse, skewed sands, possibly due to the calm hydrodynamics, which allowed for the settlement of fine particles in the area. This result agreed with Masucci et al. (2020), who highlighted the finer sediment at the landward side of the wall (Breakwater-Back – fine sand, moderately sorted, very coarse skewed), possibly due to the lower water energy levels.

4.2 Sediment chemistry

The higher TOM content in sheltered sites, compared to the exposed and control stations of Kuala Nerus, is presumed to be contributed by the hydrodynamic conditions (current velocity) and uniform characteristics of the sediments

(very fine sand), as agreed upon by Xu et al. (2021). The very fine sand is easily transported by waves and currents into suspension and sustained by turbulent fluctuations. Furthermore, the organic matter exhibits a pronounced affinity for fine-grained sediment, effectively adsorbing onto mineral surfaces. In addition, the greater and wider surface area of very fine particles successfully adsorbed a greater amount of organic matter.

In relation to the lower heavy metal concentrations in the surface sediment of the CDS area in Kuala Nerus, the allowable concentration is presumed to pose no impact on the function of the coastal ecosystem (Anzecc 2000). Notably, the currents and waves in CDS areas have contributed to the movement of different pollutants, as agreed upon by Tao and Han (2002). This condition occurs due to the transformation of the wave field due to the ambient current. Heavy metals are generally transported by prevailing currents through various sources, including sewage and industrial effluents, brine discharge, agricultural activities, and coastal development. However, the enrichment factor results revealed that most elemental sources were natural, with no enrichment sources detected. Hence, it most likely represented the background values of the area. The coastal ecosystem of Kuala Nerus is thus suggested to have a good flushing system, supported by the observed heavy metal concentrations, which are within the permissible limits, as well as by the Igeo values (<0) indicating no contamination, PLI values (<1) indicating no pollution, and EF values (<1) indicating no enrichment. Therefore, the area can be classified as unpolluted, with the sediments considered uncontaminated.

In addition, as sandy-type substrates mainly dominate the CDS area, heavy metals are suggested not to absorb well onto the sand fraction of a smaller surface area, as agreed upon by Yuan et al. (2012). The clay, fine, and very fine silt particles, with a wider surface area-to-volume ratio, provide more extensive and active sites for the absorption of heavy metals. These minute particles have a better ability to form large aggregates of metals, bound together by electrochemical force and organic matter, than the sandy particles (Yunus et al. 2020). This supports the lower concentrations of heavy metals in the CDS areas of Kuala Nerus.

4.3 Water physical parameters

In the Kuala Nerus coastal area, the depth along the coastal structures is highly varied and considered complex, with sheltered and exposed sites differing by up to 2 and 8 meters in depth, respectively. This intricate bathymetry may significantly affect the dynamic process of water flow, exchange, and various particle transport pathways, as

highlighted by Daryabor et al. (2016). In addition, the complex seafloor may also be influenced by wave-current interactions, affecting wave refraction and diffraction (Liau et al. 2011), particularly in exposed sites with deeper depths, attributed to scouring activity around the foundation structure (Fausset 2017).

In the sheltered sites of shallower depth, the dissipation of wave energy and relatively calm water on the lee side of the CDS have encouraged sediment accretion (Masucci et al. 2020). However, the different designs of the CDS may result in varying accretion levels. For example, in St. 4, the tombolo (sand accretion) is considered natural due to the excessive salient built-up, which reduces longshore drift shoreward of the breakwater, as supported by Specht et al. (2021). The accumulated sediment near the parallel breakwaters may cause the area to flatten, resulting in a decrease in depth compared to the open sea at the control site. In summary, the presence of various CDS along the Kuala Nerus coastal area has created a deeper depth of exposed sites and a shallower depth of sheltered spots, potentially governed by the hydrodynamic activity of the area.

The control station, located approximately six kilometers from the last CDS station, at a depth of 10 meters, serves as a notable example of the typical effects of wave and current actions in the coastal region. In fact, the surrounding area also showed a consistent depth profile of approximately 10 to 11 m. The findings have proven that the CDS has successfully reduced the magnitude of the current speed and wave action. Thus, reducing the impact of scouring and erosion while concurrently fostering accretion in the areas and producing shallower depth in the surrounding areas. However, the effectiveness of the CDS in reducing scouring and enhancing accretion varies between different CDS designs, as local hydrodynamic conditions, sediment composition, and structural configurations influence it.

5. CONCLUSION

The present study evidenced that CDS directly impacts the ecological features of the Kuala Nerus coastal area, particularly those related to sediment-water interactions. The CDS significantly affected the bottom sediment characteristics, including texture, grain size distribution, and chemistry, as well as the nearshore hydrodynamic circulation. The sediment distribution and composition in the Kuala Nerus CDS areas are varied, ranging from coarse to very fine sands, compared to the control station, which is mainly composed of very fine sand. The variance in sediment type is intricately linked to wave propagation, current water flow, water level, weather events, and turbulence. The CDS thus contributes to a more dynamic and heterogeneous sediment environment, in

contrast to the relatively homogenous sediment composition at the control site.

Regarding TOM, the CDS in Kuala Nerus has no significant impact, as the control station recorded a higher TOM content. The higher TOM is attributed to natural greater depth and lower hydrodynamic energy, which reduces current speed and sediment transport, thereby promoting the settling and accumulation of fine sediments and TOM. In contrast, the CDS areas are more exposed to wave action and stronger currents, resulting in enhanced sediment resuspension and less TOM deposition.

The heavy metal concentration in the control station falls within the range of those in CDS stations. The permissible level of heavy metals indicates a good current flushing system in the Kuala Nerus coastal area, even with the presence of CDS. The Kuala Nerus CDS areas create both stronger and weaker current speed areas. While the control station has a moderate current speed, the CDS, on the other hand, successfully reduces the current strength. However, the exposed stations in CDS areas remain documented at a higher current speed.

The significant wave height in CDS areas is lower than at the control station, indicating that CDS effectively reduces wave action. Furthermore, the irregular and complex bathymetry of the CDS areas is attributed to continuous erosion and accretion activities driven by the hydrodynamic effects of tides, waves, and current actions. In contrast, the control site with no hydrodynamic impacts from CDS documented a deeper area, which is typical for coastal areas. Despite these differences, the physical water parameters in this tiny locality of the study site, including those at the control station, are not significantly different, indicating that the CDS does not contribute to the poor flushing system.

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STATEMENTS AND DECLARATIONS

The authors declare that they have no conflict of interest.

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