

## ASSESSMENT OF SEABED FEATURES IN THE VICINITY OF KEMAMAN PORT, TERENGGANU, MALAYSIA

MUHAMMAD RIZAL RAZALI<sup>1,2</sup>, MASHA MENHAT<sup>3</sup>, IKHMAL SIDDIQ<sup>1</sup>, AZIZI ALI<sup>1</sup>, MARDIHA MOKHTAR<sup>4</sup>, SAIFUL BAHRI HAMZAH<sup>2</sup>, SITI SALIHAH MOHD SENDEK<sup>2</sup>, HAZAMRI HARITH<sup>5</sup>, MUHAMMAD ZAHIR RAMLI<sup>6</sup> AND EFFI HELMY ARIFFIN<sup>1\*</sup>

<sup>1</sup>*Institute of Oceanography and Environment, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia*

<sup>2</sup>*National Water Research Institute of Malaysia, Ministry of Energy Transition and Water Transformation, 43300, Seri Kembangan, Selangor, Malaysia*

<sup>3</sup>*Faculty of Maritime Studies, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia*

<sup>4</sup>*Department of Civil Engineering, CeDS, Universiti Tun Hussein Onn Malaysia, Pagoh Educational Hub, 84600 Pagoh, Johor, Malaysia*

<sup>5</sup>*CNH Advantech Sdn. Bhd., 47000 Sungai Buloh, Selangor, Malaysia*

<sup>6</sup>*Institute of Oceanography & Maritime Studies, Kulliyah of Science, International Islamic University Malaysia, 25200 Kuantan, Pahang, Malaysia*

\*Corresponding author: [effihelmy@umt.edu.my](mailto:effihelmy@umt.edu.my)

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### ABSTRACT

Sedimentation poses a significant challenge to navigational safety within port areas, including at Kemaman Port, Terengganu, Malaysia. This study characterised seabed morphology and identifies key features, including sediment distribution, submerged objects, and potential hazards that may impact port operations and navigational safety. Side-scan sonar (Klein 3000 dual-frequency system operating at 100 and 500 kHz) and Compressed High-intensity Radar Pulse (CHIRP) sub-bottom profiler (EdgeTech Strata Box) were employed to produce detailed seabed maps of the seabed across four survey zones (CN, P, R, CS) encompassing 23 sampling stations with 50 m survey-line spacing with 50 m line spacing. Sediment analyses revealed that the port basin is dominated by silt-clay mixtures (mean  $D_{50} = 0.045$  mm, 68% mud content), whereas the river mouth was characterised by coarse sand and gravel deposits (mean  $D_{50} = 1.2$  mm, 12% mud content). Three distinct acoustic facies were identified and showed strong correspondence with sediment grain-size distributions, achieving 87% classification agreement. A total of 37 potential navigational hazards were identified, including five major scour pits adjacent to the breakwater (15 m–45 m in diameter, 2 m–8 m in depth), 18 submerged objects, and four active bedform fields. High-energy bedforms, with ripple wavelengths ranging from 0.8 m to 1.5 m were observed in the navigation channels, indicating active sediment transport processes. CHIRP sub-bottom profiler data revealed three stratigraphic units with surficial sediment accumulation reaching 1.8 m in the port basin, corresponding to a sedimentation rate of approximately 7 cm per year since port construction. The findings provide quantitative baseline data to provide quantitative baseline information to support port management, assist with marine safety initiatives, and inform future dredging strategies and coastal monitoring programmes in the region.

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### Introduction

Ports are vital components of global maritime logistics, serving as critical hubs for trade, transportation, and economic development

(Ariffin *et al.*, 2023). Their operational efficiency and long-term sustainability directly influence shipping performance and the competitiveness

of national economies (Olapoju, 2023). However, many ports face persistent challenges related to sedimentation and coastal erosion, which can significantly alter seabed morphology and compromise navigational safety.

Sedimentation, defined as the accumulation of suspended particles that settle on the seabed, poses a direct threat to maritime navigation. In port basins and navigation channels, excessive sediment buildup reduces the under-keel clearance, restricts manoeuvrability, and increases the risk of groundings or collisions, particularly for deep-draft vessels (Ariffin *et al.*, 2018; Ariffin *et al.*, 2019; Guarnieri *et al.*, 2021, Dong *et al.*, 2023). Shoaling in critical fairways often necessitates frequent dredging, increases operational costs, and, if not consistently monitored, can jeopardize maritime safety (Thomas *et al.*, 2025). Furthermore, turbulence generated by vessel movement and propeller wash can intensify the erosion and deposition processes, resulting in unpredictable changes to the seabed that further complicate navigation (Guarnieri *et al.*, 2021).

Seabed depth is a fundamental determinant of navigational safety. Insufficient depth can impede vessel movement and increase the likelihood of accidents. Maintaining adequate depth is therefore essential for safe and efficient port operations (Baig *et al.*, 2024; Dagkiran & Bolat, 2025). The port basin, in a particularly, is a dynamic environment where water circulation and sedimentation processes interact, influencing both safety and operational performance (Saengsupavanich, 2019; Sanitwong-Na-Ayutthaya *et al.*, 2022; Dong *et al.*, 2023). Regular monitoring of seabed conditions is critical to detect sediment deposition, preserve navigable depth, and ensure uninterrupted maritime transport.

Advanced hydroacoustic technologies, especially side-scan sonar and Compressed High-intensity Radar Pulse (CHIRP) sub-bottom profilers, have become indispensable tools for seabed assessment. These systems provide high-resolution imagery of underwater features, enabling precise mapping of sediment

distribution and identification of submerged hazards. Numerous studies have demonstrated the effectiveness of side-scan sonar for characterising seabed morphology in coastal and port environments (Rattray *et al.*, 2009; Tanzil *et al.*, 2009; Anderson *et al.*, 2015). Side-scan sonar operates by emitting acoustic pulses perpendicular to the survey track and recording the intensity of backscattered energy, which varies according to seabed roughness, composition, and acoustic impedance (Jackson & Richardson, 2007). High-backscatter areas typically correspond to coarse sediments, exposed rock or anthropogenic debris, while low-backscatter areas indicate fine-grained sediments such as silt and clay (Hamilton *et al.*, 1999; Ariffin *et al.*, 2023).

CHIRP (Compressed High-intensity Radar Pulse) sub-bottom profilers complement side-scan sonar by providing information on subsurface stratigraphy. CHIRP systems use swept-frequency pulses to achieve high vertical resolution (typically 0.1 m) and can penetrate several metres into unconsolidated sediments (Schock, 2004). This capability enables identification of buried channels, erosional unconformities, and sediment layer boundaries, which are essential for reconstructing depositional histories and predicting future morphological changes (Caress *et al.*, 2016).

Kemaman Port, located on the east coast of Peninsular Malaysia in the state of Terengganu, serves as a major hub for petroleum, petrochemical, and general cargo operations. The port is situated at the mouth of the Kemaman River, which discharges into the South China Sea. This setting exposes the port to complex sediment dynamics influenced by riverine input, tidal currents, wave action, and seasonal monsoon influences (Ariffin *et al.*, 2018; Maanan *et al.*, 2018; Ismail *et al.*, 2020). Previous studies in the region have documented significant coastal erosion and sediment transport along the Terengganu coast (Husain *et al.*, 2016; Ariffin *et al.*, 2018; Akhir *et al.*, 2020; Ismail *et al.*, 2020). However, comprehensive seabed characterisation within the port area remains limited.

Accordingly, the objectives of this study were to: (1) characterise the spatial distribution of sediment grain size and composition across the port area; (2) establish quantitative relationships between acoustic facies and sediment properties; (3) identify and catalogue potential navigation hazards including scour pits, submerged objects, and active bedform fields; (4) interpret subsurface stratigraphy and depositional history using CHIRP sub-bottom profiler data; and (5) provide evidence-based recommendations for port management and dredging operations. By addressing a critical knowledge gap, this study provides baseline data essential for sustainable port management in a dynamic tropical coastal environment.

### Materials and Methods

Kemaman Port ( $4^{\circ}14' \text{ N}$ ,  $103^{\circ}26' \text{ E}$ ) is located on the east coast of Peninsular Malaysia in the state of Terengganu, approximately 170 km south of Kuala Terengganu and 30 km north of the Terengganu-Pahang state border (Figure 1). The port is situated at the mouth of the Kemaman River, which drains a catchment area

of approximately 1,530 km<sup>2</sup> before discharging into the South China Sea (Department of Irrigation and Drainage [DID], 2010). Officially opened in 1998, the port has undergone several phases of expansion to accommodate increasing cargo throughput, particularly petroleum products, Liquefied Natural Gas (LNG), and general cargo (Ariffin *et al.*, 2023; Kemaman Port Authority, 2024).

The map displays an overview of all hydroacoustic survey coverage at Kemaman Port with coordinates ranging from  $103^{\circ}25'30'' \text{ E}$  to  $103^{\circ}31'00'' \text{ E}$  (longitude) and  $4^{\circ}12'30'' \text{ N}$  to  $4^{\circ}16'0'' \text{ N}$  (latitude). The base map comprises satellite imagery depicting terrestrial and marine environments, while the overlaid orange strips represent side-scan sonar survey lines. Specific areas are labelled: “Sonar Image inside Kemaman Port” (pointing to complex network of orange strips within the port’s breakwater and harbor), “Sonar Image Line 1 outside Kemaman Port”, “Sonar Image Line 2 outside Kemaman Port”, and “Sonar Image Line 3 outside Kemaman Port” (three parallel strips running along the coast). A compass rose is located in the top right corner. Scale bar indicates distances

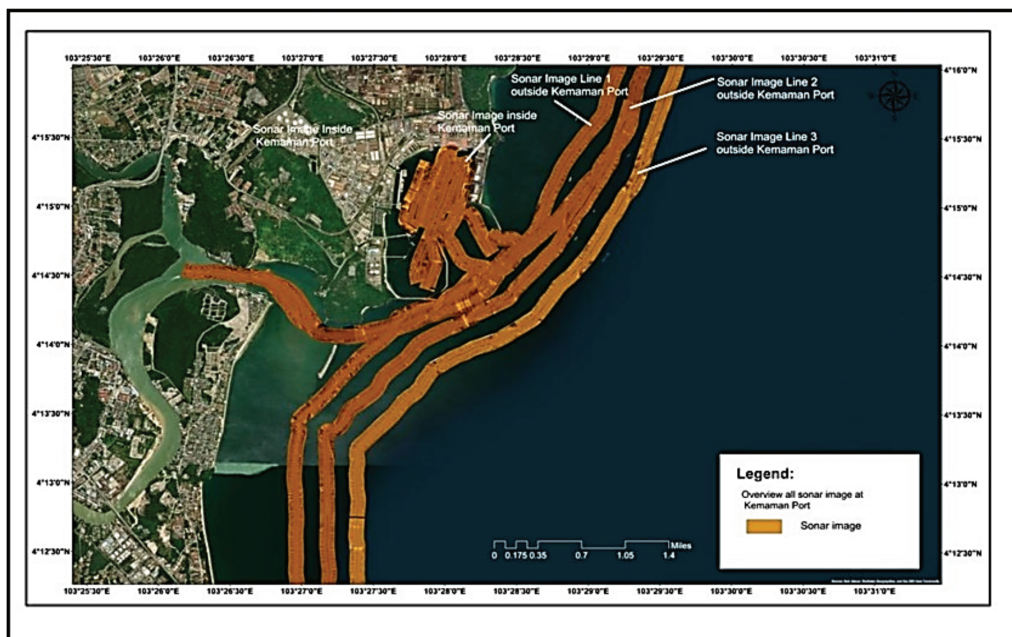


Figure 1: Location map of Kemaman Port and survey area

in miles (0, 0.175, 0.35, 0.7, 1.05, 1.4 miles), while the coordinate system was WGS84, UTM Zone 48N.

The study area covers approximately 3 km<sup>2</sup> of seabed extending from the port basin to adjacent coastal waters. To facilitate spatial analysis systematically divided into four zones according to morphological attributes and operational considerations, as illustrated in Figure 2. Zone CN (Coastal North) lies north of the port entrance and breakwater, encompassing the northern navigation channel and nearshore areas, and is characterised by moderate wave exposure and active sediment transport. Zone P (Port Basin) represents the sheltered environment within the port's breakwater system, including berthing facilities, anchorage areas, and the turning basin, where reduced wave energy prevails but vessel-induced turbulence and propeller wash are significant. Zone R (River Mouth) is situated adjacent to the Kemaman River outfall, marked by strong tidal currents, variable salinity conditions, and direct riverine sediment input, particularly pronounced during the monsoon seasons. Finally, Zone CS (Coastal South) extends south of the port

entrance, incorporating the southern navigation channel and approach fairway, and exhibits conditions of moderate to high wave energy with active sediment transport similar to Zone CN. This zonal delineation provides a structured framework for evaluating hydrodynamic conditions, sediment transport mechanisms, and seabed morphological variability across the study area.

The map shows the study area, which covers approximately 7.3 km × 6.3 km, with four distinct zones clearly delineated: CN (Channel-North, shown in the northern section), P (Port Basin, shown in the central protected area), R (River Mouth, shown at the river discharge point), and CS (Channel-South, shown in the southern section). Twenty-three sampling stations are marked as circles distributed across all zones (CN-01 through CN-06, P-01 through P-08, R-01 through R-04, and CS-01 through CS-05). Side-scan sonar survey lines are shown as light blue parallel lines with 50m spacing covering the entire survey area. The map includes geographic features such as Kuala Teluk Kalong and Pantai Teluk Mak Nik. Bathymetric contours are shown at 5 m intervals. The port

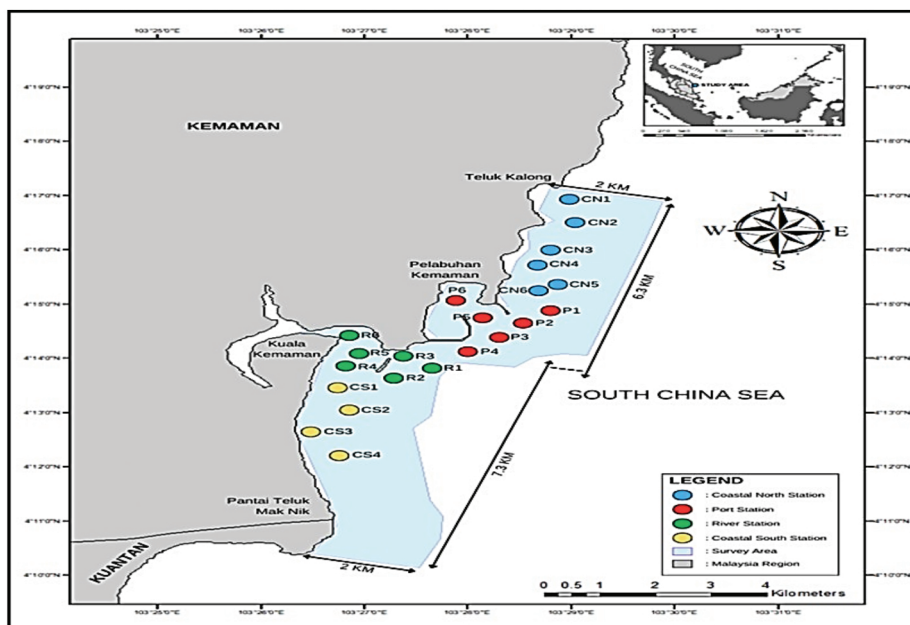


Figure 2: Survey design and zonation scheme

breakwater and infrastructure are clearly visible and the coordinate reference system is WGS84, UTM Zone 48N.

The study area is characterised by a tropical monsoon climate with distinct wet (November–March) and dry (May–September) seasons. The northeast monsoon generates elevated wave energy and elevated sediment discharge from the Kemaman River, which enters the South China Sea approximately 1.2 km north of the port entrance. The tidal regime is mixed semi-diurnal with a mean tidal range of 1.8 m (spring tidal ranges reaching up to 2.4 m). Nearshore bathymetry exhibits a gentle seaward gradient, with water depths ranging from 6 m in the river mouth area to 13 m in the navigation channels (Ariffin *et al.*, 2023).

### ***Survey Design and Sampling Strategy***

The geophysical survey was conducted in March 2024 during spring tide conditions to maximise water depth and ensure safe vessel operations. A systematic survey design was implemented with parallel survey lines oriented perpendicular to the coastline (approximately 045°–225° azimuth) to optimise coverage of alongshore and cross-shore gradients. Line spacing was set at 50 m to ensure complete side-scan sonar coverage with overlap between adjacent swaths, enabling seamless mosaic generation and minimising data gaps. Twenty-three sampling stations were strategically distributed across the four zones to capture spatial variability in seabed characteristics. Station locations were selected to represent different hydrodynamic environments (high-energy channels, sheltered basin, river-influenced areas) and operational zones (active berths, anchorage, approach channels). Station coordinates are provided in Table 1.

### ***Sediment Sampling and Analysis***

Sediment samples were collected at each of the 23 stations using a Van Veen grab sampler (0.04 m<sup>2</sup> sampling area) deployed from the survey vessel. At each station, three replicate grabs were obtained to assess spatial variability.

Samples were collected from the upper 5 cm of the seabed to represent surficial sediment characteristics relevant to acoustic backscatter interpretation. All samples were immediately sealed in labelled plastic bags and stored at 4°C until laboratory analysis.

In the laboratory, samples were wet-sieved through a 63 µm mesh to separate sand-sized ( $\geq 63$  µm) and mud-sized ( $< 63$  µm) fractions. The sand fraction was oven-dried at 60°C for 24 hours and analysed using a Retsch AS200 sieve shaker with standard phi-scale sieve stack (4.0, 2.0, 1.0, 0.5, 0.25, 0.125, 0.063 mm). The mud fraction was analysed using a Malvern Mastersizer 3000 laser diffraction particle size analyser. Grain size statistics including median grain diameter ( $D_{50}$ ), mean grain size, sorting coefficient, skewness, and kurtosis were calculated using the method of moments following Folk and Ward (1957) conventions.

Quality assurance and quality control (QA/QC) procedures were implemented to ensure the reliability of analytical results. Duplicate samples, representing 10% of the total dataset, were analysed to evaluate analytical precision, with relative standard deviations maintained below 5% for  $D_{50}$ . Certified reference materials, specifically NIST SRM 1944, were employed to verify instrument calibration and accuracy. In addition, procedural blanks were incorporated to monitor potential cross-contamination during laboratory processes. All QA/QC outcomes conformed to the established acceptance criteria, thereby confirming the reliability and suitability of the dataset for subsequent interpretation and analysis.

## **Geophysical Survey**

### ***Side-scan Sonar***

Side-scan sonar data was acquired using a Klein 3000 dual-frequency system operating at 100 kHz (low frequency; 150 m range per side) and 500 kHz (high frequency, 75 m range per side). The 500 kHz frequency was selected for detailed seabed characterisation due to its superior spatial resolution (0.05 m across-track,

Table 1: Sampling station coordinates and zone assignments

| Station ID | Zone | Latitude (°N) | Longitude (°E) | Water Depth (m) |
|------------|------|---------------|----------------|-----------------|
| CN-01      | CN   | 4.2428        | 103.4372       | 10.2            |
| CN-02      | CN   | 4.2435        | 103.4378       | 11.5            |
| CN-03      | CN   | 4.2442        | 103.4385       | 12.1            |
| CN-04      | CN   | 4.2450        | 103.4390       | 11.8            |
| CN-05      | CN   | 4.2458        | 103.4395       | 10.9            |
| CN-06      | CN   | 4.2465        | 103.4402       | 9.8             |
| P-01       | P    | 4.2361        | 103.4347       | 9.5             |
| P-02       | P    | 4.2368        | 103.4352       | 10.1            |
| P-03       | P    | 4.2375        | 103.4358       | 10.8            |
| P-04       | P    | 4.2382        | 103.4363       | 11.2            |
| P-05       | P    | 4.2390        | 103.4368       | 11.5            |
| P-06       | P    | 4.2397        | 103.4373       | 11.8            |
| P-07       | P    | 4.2405        | 103.4378       | 12.2            |
| P-08       | P    | 4.2412        | 103.4383       | 12.5            |
| R-01       | R    | 4.2485        | 103.4415       | 8.2             |
| R-02       | R    | 4.2492        | 103.4422       | 7.5             |
| R-03       | R    | 4.2500        | 103.4428       | 6.8             |
| R-04       | R    | 4.2508        | 103.4435       | 6.2             |
| CS-01      | CS   | 4.2320        | 103.4325       | 10.5            |
| CS-02      | CS   | 4.2328        | 103.4330       | 11.2            |
| CS-03      | CS   | 4.2335        | 103.4335       | 11.8            |
| CS-04      | CS   | 4.2342        | 103.4340       | 12.3            |
| CS-05      | CS   | 4.2350        | 103.4345       | 12.8            |

0.1 m along-track at 50 m range). The towfish was deployed at a constant altitude of 10 m–15 m above the seabed, maintained using real-time depth monitoring combined with manual winch adjustments. Survey vessel speed was maintained at 3 knots–4 knots to optimise data quality and ensure consistent along-track resolution.

Navigation and positioning were achieved using a Trimble SPS855 Differential Global Positioning System (DGPS) with Real-Time Kinematic (RTK) corrections, providing horizontal accuracy of  $\pm 0.02$  m. The towfish position was calculated using layback corrections based on cable length, vessel speed,

and water depth. Sonar data were recorded in eXtended Triton Format (XTF) using SonarWiz 7 acquisition software, with real-time display enabling quality control during survey operations.

Post-processing of side-scan sonar data was conducted through a structured workflow designed to optimise data quality and spatial accuracy. The procedures encompassed slant-range correction to transform raw data into ground-range coordinates, gain normalisation to compensate for geometric spreading and absorption losses, bottom tracking to isolate seabed returns and remove water-column interference, nadir gap interpolation using

adjacent swath data, and mosaic generation through weighted blending algorithms to minimize seam artefacts. The final mosaic was georeferenced to the WGS84 UTM Zone 48N coordinate system with a pixel resolution of 0.25 m, ensuring high spatial fidelity for subsequent analysis.

### ***CHIRP Sub-bottom Profiler***

Sub-bottom profiling was conducted using an EdgeTech Strata Box CHIRP sub-bottom profiling system operating in the 2 kHz–16 kHz frequency range. The system was configured to transmit swept-frequency pulses (chirps) with 20 ms pulse length, achieving vertical resolution of approximately 0.1 m in unconsolidated sediments. Penetration depth varied from 5 m in coarse-grained sediments (Zone R) to 20 m in fine-grained sediments (Zone P), reflecting differences in acoustic attenuation characteristics.

The CHIRP transducer was hull-mounted on the survey vessel, with real-time heave compensation to minimise vessel-motion artefacts. Data were acquired along the same survey lines as side-scan sonar, with ping rate adjusted to maintain 0.5 m along-track spacing. Sub-bottom profiles were recorded in JSF format using EdgeTech Discover acquisition software.

Post-processing of CHIRP data was carried out through a systematic workflow to enhance signal clarity and ensure accurate stratigraphic interpretation. The process involved bandpass filtering (3 kHz–12 kHz) to eliminate low-frequency noise and high-frequency artefacts, Automatic Gain Control (AGC) to amplify weak reflectors, and Time-varied Gain (TVG) to compensate for spherical spreading. Subsequently, Two-way Travel Time (TWTT) was converted to depth using constant sound velocities of 1,500 m s<sup>-1</sup> and 1,600 m s<sup>-1</sup> in sediment. Stratigraphic interpretation was then performed by identifying acoustic reflectors, unconformities, and variations in reflection character, providing a framework for reconstructing subsurface depositional architecture.

### ***Data Integration and Analysis***

Spatial analysis and data integration were performed using ArcGIS Pro 3.1 and QGIS 3.28. Sediment grain size data were interpolated across the survey area using ordinary kriging with exponential semivariogram models. Acoustic facies were classified based on backscatter intensity (mean grey level) and textural attributes (standard deviation, entropy, homogeneity) extracted from side-scan mosaics using a 10 m × 10 m moving window. Classification was performed using an unsupervised k-means clustering algorithm (k = 3) followed by manual refinement based on expert interpretation. This approach enabled the delineation of acoustically distinct seabed units and their subsequent comparison with sedimentological observations.

Statistical analyses were conducted using R 4.3.1. Relationships between acoustic facies and sediment properties were evaluated using Spearman's rank correlation coefficients and analysis of variance (ANOVA). Classification agreement between acoustic facies and sediment textural classes was assessed using confusion matrices and Cohen's kappa coefficient. Bedform characteristics, including wavelength, crest orientation, and asymmetry, were measured from side-scan sonar mosaics using ImageJ software, and summary statistics were subsequently generated in R.

## **Results**

### ***Sediment Grain Size Distribution***

Sediment grain size analysis revealed substantial spatial variability across the survey area, with distinct patterns corresponding to the four defined zones (Figure 3, Table 2). Zone P (Port Basin) was dominated by fine-grained sediments, with mean  $D_{50}$  of 0.045 mm (range: 0.018 mm–0.092 mm) and high mud content (mean 68%, range: 52%–84%). Sediments were classified as sandy silt to silty clay, with poor to very poor sorting (mean  $\sigma = 2.8$  phi), indicating a mixed grain-size fractions deposited under low-energy conditions. The fine-grained nature of these sediments reflects the sheltered

environment within the port basin, where wave energy is attenuated by the breakwater and settling of suspended sediments is promoted (Ariffin *et al.*, 2020).

The figure shows an interpolated surface generated using kriging with sediment sample locations shown as circles. The colour scale ranges from blue (fine sediments, <0.063 mm) through green and yellow to red (coarse sediments, >1.0 mm). The map clearly shows the spatial pattern with Zone P (Port Basin) dominated by blue colours indicating fine sediments (silt-clay), Zone R (River Mouth) showing red and orange colours indicating coarse sediments (sand and gravel), and Zones CN and CS (Navigation Channels) Intermediate grain-size distributions characterise (yellow-green colours) indicating fine to medium sand. All 23 sampling stations are marked with circles and labelled (CN-01 through CN-06, P-01

through P-08, R-01 through R-04, CS-01 through CS-05). The sediment type classifications are indicated: GN (Granule), VCS (Very Coarse Sand), CS (Coarse Sand), MS (Medium Sand), FS (Fine Sand), VFS (Very Fine Sand), MST (Medium Silt), FST (Fine Silt). The coordinate system was referred to as WGS84, UTM Zone 48N.

In contrast, Zone R (River Mouth) exhibited the coarsest sediments, with mean  $D_{50}$  of 1.2 mm (range: 0.35 mm–2.8 mm) and low mud content (mean 12%, range: 3%–28%). Sediments were classified as medium to coarse sand with gravel fractions, indicating high-energy conditions associated with river discharge and tidal currents. Sorting was moderate to well-sorted (mean  $\sigma = 1.2$  phi), suggesting selective transport and preferential removal of finer particles through hydraulic winnowing.

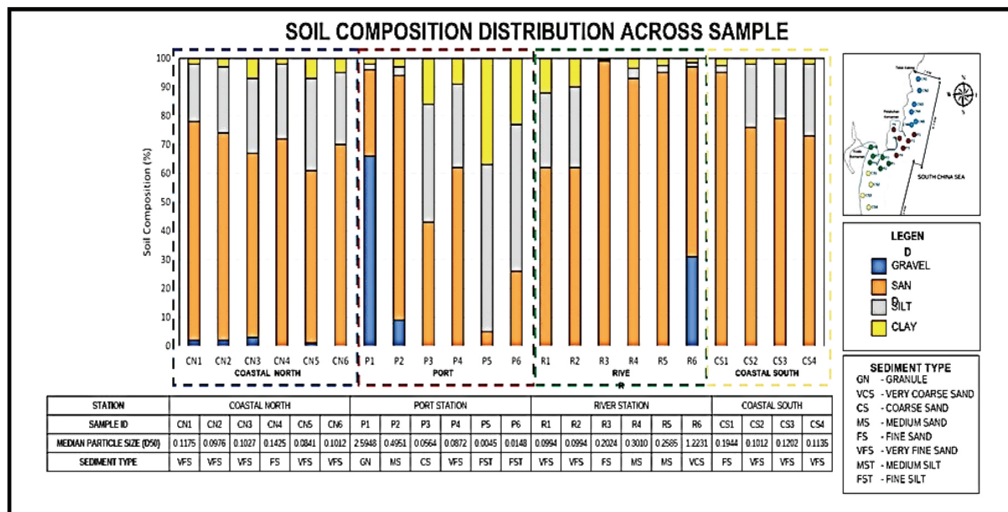


Figure 3: Spatial distribution of sediment grain size ( $D_{50}$ )

Table 2: Summary statistics of sediment grain size characteristics by zone

| Zone | n | $D_{50}$ (mm)     | Mud (%)     | Sorting ( $\phi$ ) | Dominant Texture         |
|------|---|-------------------|-------------|--------------------|--------------------------|
| CN   | 6 | $0.18 \pm 0.08$   | $35 \pm 12$ | $1.8 \pm 0.4$      | Fine to medium sand      |
| P    | 8 | $0.045 \pm 0.022$ | $68 \pm 11$ | $2.8 \pm 0.5$      | Sandy silt to silty clay |
| R    | 4 | $1.2 \pm 0.85$    | $12 \pm 9$  | $1.2 \pm 0.3$      | Medium to coarse sand    |
| CS   | 5 | $0.22 \pm 0.11$   | $42 \pm 15$ | $2.1 \pm 0.6$      | Fine to medium sand      |

Note: Values are mean  $\pm$  standard deviation

Zones CN and CS (Navigation Channels) showed intermediate characteristics, with mean  $D_{50}$  of 0.18 mm and 0.22 mm respectively. These zones contained predominantly fine to medium sand (mean mud content 35%–42%), with moderate sorting ( $\sigma = 1.8 \text{ phi} - 2.1 \text{ phi}$ ). The presence of ripple bedforms in side-scan imagery (discussed below) indicates active sediment transport in these channels.

Analysis of variance (ANOVA) revealed significant differences in  $D_{50}$  among the four zones ( $F = 45.3$ ,  $p < 0.001$ ), confirming that zonation effectively captured spatial variability in sediment characteristics. Post hoc Tukey tests indicated that Zone R differed significantly from all other zones ( $p < 0.01$ ), while Zones CN and CS were not significantly different from each other ( $p = 0.42$ ).

### *Acoustic Facies and Correlation with Sediment Properties*

Side-scan sonar mosaics revealed three distinct acoustic facies with characteristic backscatter signatures and textural patterns as shown in Figure 4. Facies 1 (High Backscatter) covered 18% of the survey area and was concentrated in Zone R and along the breakwater margins. Facies 2 (Moderate Backscatter, Rippled) covered 45% of the area, primarily in Zones CN and CS. Facies 3 (Low Backscatter) covered 37% of the area, dominating Zone P.

Figures 4(a) through 4(d) present side-scan sonar mosaics that illustrate the distribution of acoustic facies across the study area. Figure 4(a) depicts the full survey mosaic at 0.25 m pixel resolution, encompassing the entire port area and revealing distinct acoustic



Figure 4(a): Full survey area mosaic

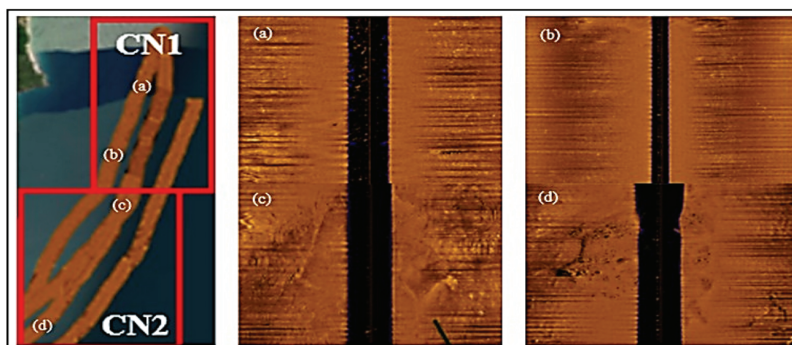


Figure 4(b): Zone CN (a, b, c & d) detailed view

signatures expressed as varying shades of dark tones corresponding to different backscatter intensities. Figure 4(b) provides a detailed view of Zone CN, highlighting Facies 2 characterised by rippled textures with moderate backscatter, as well as scour pits near the breakwater visible as dark circular features; ripple patterns appear as alternating light and dark bands oriented perpendicular to current flow. Figure 4(c) focuses on Zone P, where Facies 3 is identified as smooth, low-backscatter surfaces represented by uniform dark grey tones, alongside submerged objects that manifest as bright targets with acoustic shadows; multiple objects of varying sizes are evident. Figure 4(d) illustrates Zone R, showing Facies 1 was characterised by high mean backscatter intensity (grey level 180–240 on an 8-bit scale) and elevated textural variance

(standard deviation >30). Ground-truth sediment samples indicated coarse-grained sediments, comprising sand and gravel, with a mean  $D_{50}$  of 1.15 mm (range: 0.42 mm–2.8 mm) and mud contents generally below 15%. These facies occurred predominantly within Zone R and along the breakwater margins, where riverine inputs and wave action favour the accumulation of coarse material and the removal of finer sediment fractions.

The characteristics of acoustic facies were distinguished according to backscatter intensity, textural attributes, and ground-truth sediment composition. Facies 1 was defined by high mean backscatter intensity (grey level 180–240 on an 8-bit scale) and elevated textural variance



Figure 4(c): Zone P detailed view

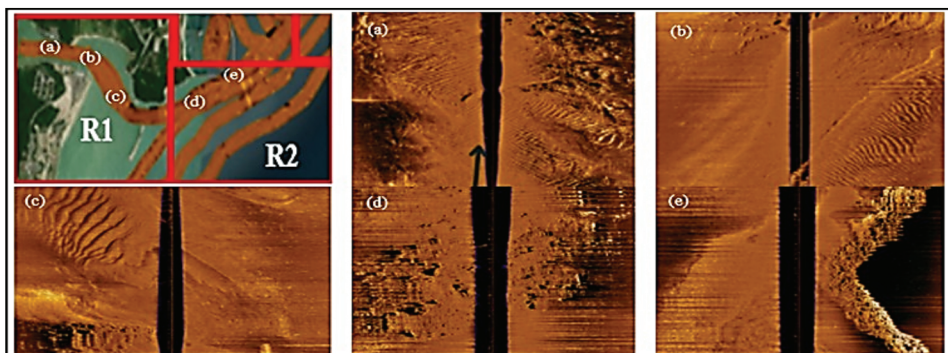


Figure 4(d): Zone R detailed view

(standard deviation  $>30$ ), corresponding to coarse-grained sediments such as sand and gravel with rough surface textures. Ground-truth samples confirmed a mean  $D_{50}$  of 1.15 mm (range: 0.42 mm–2.8 mm) and low mud content ( $<15\%$ ). These facies were most extensive in Zone R, where riverine input supplies coarse material, and along the breakwater where wave action removes finer particles. Facies 2 exhibited moderate backscatter intensity (grey level 120–180) with ripple patterns clearly visible in high-resolution imagery. Ripple wavelengths ranged from 0.8 m to 1.5 m, with crest orientations predominantly aligned  $045^{\circ}$ – $225^{\circ}$ , perpendicular to the prevailing current. Sediment samples indicated fine to medium sand (mean  $D_{50} = 0.19$  mm, range: 0.08 mm–0.35 mm) with moderate mud content (30%–45%). These facies dominated the navigation channels in Zones CN and CS, reflecting active bedform migration driven by tidal currents and vessel-induced flows. Facies 3 was characterised by low backscatter intensity

(grey level 60–120) and low textural variance (standard deviation  $<20$ ), producing a smooth, homogeneous acoustic signature. Ground-truth samples revealed fine-grained sediments (mean  $D_{50} = 0.048$  mm, range: 0.018 mm–0.095 mm) with mean mud content of  $68 \pm 11\%$  ( $>60\%$ ). These facies were concentrated in Zone P, where the sheltered port basin favours deposition and retention of fine sediments.

Quantitative correlation analyses demonstrated strong relationships between acoustic facies characteristics and sediment properties (Figure 5). Median grain size ( $D_{50}$ ) showed significant correlation with mean backscatter intensity (Spearman's  $\rho = 0.79$ ,  $p < 0.001$ ), confirming that coarser sediments produce higher backscatter (Figure 5a & 5b). Cross-tabulation of acoustic facies and Shepard sediment textural classes revealed 87% overall classification agreement (Table 3 and Figure 5d), with misclassifications occurring primarily at facies boundaries where gradual transitions exist.

Table 3: Cross-tabulation of acoustic facies and shepard sediment textural classes

| Acoustic Facies     | Sand     | Silty Sand | Sandy Silt | Silt-Clay | Total     | Agreement (%) |
|---------------------|----------|------------|------------|-----------|-----------|---------------|
| Facies 1 (High)     | 5        | 1          | 0          | 0         | 6         | 83            |
| Facies 2 (Moderate) | 2        | 7          | 2          | 0         | 11        | 64            |
| Facies 3 (Low)      | 0        | 0          | 1          | 5         | 6         | 83            |
| <b>Total</b>        | <b>7</b> | <b>8</b>   | <b>3</b>   | <b>5</b>  | <b>23</b> | <b>87</b>     |

Note: Agreement calculated as percentage of stations where acoustic facies correctly predict dominant textural class

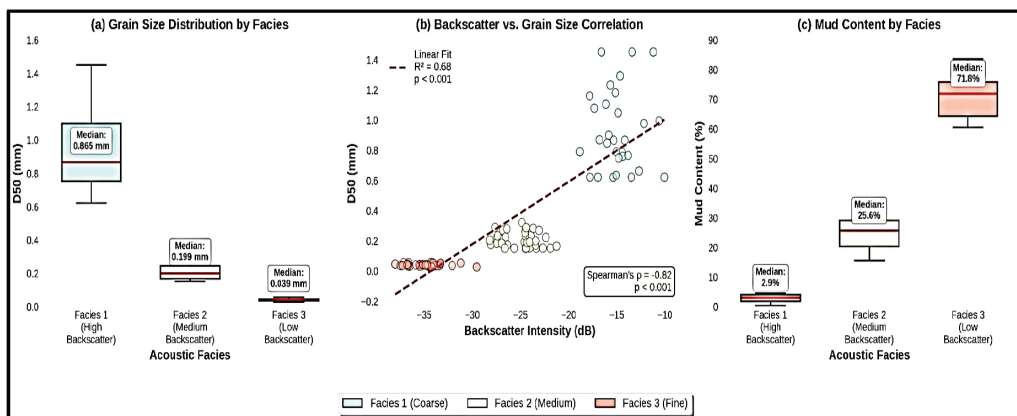


Figure 5: Correlation between acoustic facies and sediment grain size

Mud content showed inverse correlation with backscatter intensity (Spearman's  $\rho = -0.82$ ,  $p < 0.001$ ; Figure 5c), confirming that low-backscatter areas correspond to fine-grained, mud-rich sediments. Sorting coefficient showed weak correlation with facies class ( $\rho = 0.34$ ,  $p = 0.11$ ), suggesting that acoustic signatures are more sensitive to grain size than to sorting characteristics.

### Bedform Morphology and Sediment Transport Indicators

Ripple bedforms were prominently displayed in Facies 2 areas, particularly in the navigation channels (Zones CN and CS). Bedform characteristics were quantified through measurement of wavelength, crest orientation, and asymmetry from side-scan mosaics ( $n = 156$  individual ripples measured as shown in Figure 6).

Ripple wavelengths ranged from 0.8 m to 1.5 m, with mean values of 1.1 m in Zone CN and 0.9 m in Zone CS. The slightly larger wavelengths in Zone CN may reflect stronger tidal currents in the northern channel. Ripple crest orientations showed strong directional preference, with 78% of measurements falling within the  $030^{\circ}$ – $060^{\circ}$  azimuth range

(mean orientation  $045^{\circ}$ ). This orientation is perpendicular to the dominant tidal current direction ( $135^{\circ}$ – $315^{\circ}$ ), consistent with current-generated bedforms.

Ripple asymmetry analysis ( $n = 42$  profiles measured) revealed predominantly asymmetric forms with steeper lee sides facing southwest (mean asymmetry index = 1.4, where 1.0 indicates symmetric ripples). This asymmetry indicates net sediment transport toward the southwest, consistent with the dominant ebb tide current direction. The presence of active bedforms in the navigation channels confirms that these areas experience sufficient current velocities to mobilize fine to medium sand (threshold velocity  $\sim 0.3 \text{ m s}^{-1}$  for  $D_{50} = 0.2 \text{ mm}$ ).

Bedform migration rates were not directly measured in this study but can be estimated using empirical relationships. For ripples with wavelength  $\lambda = 1.1 \text{ m}$  in medium sand ( $D_{50} = 0.2 \text{ mm}$ ) under tidal currents with peak velocity  $\sim 0.5 \text{ m s}^{-1}$ , migration rates of  $0.5 \text{ m/day}$ – $2 \text{ m/day}$  are typical (Komar, 1971). This suggests that bedform configurations in the navigation channels are dynamic and may change significantly over weekly to monthly timescales.

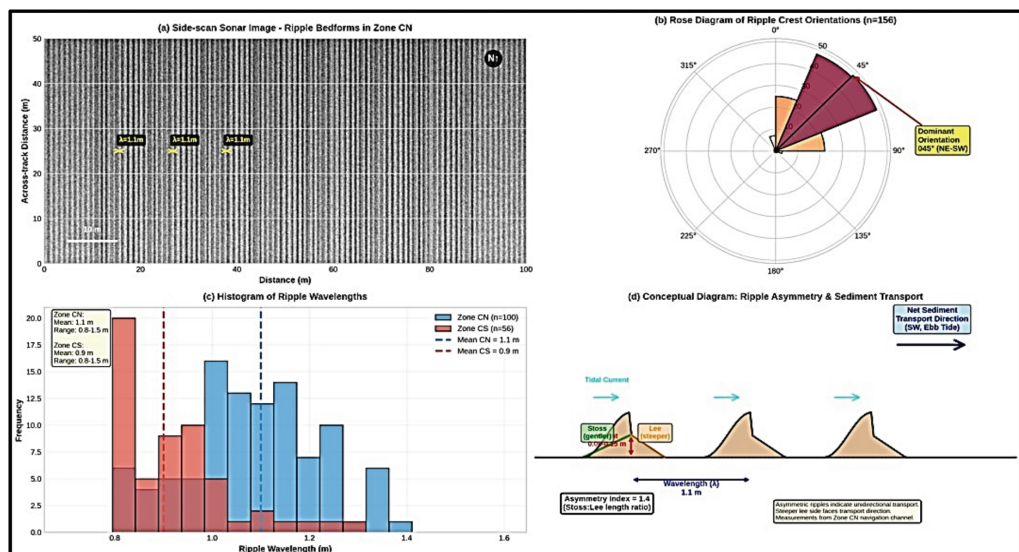


Figure 6: Bedform characteristics in navigation channels

### ***Subsurface Stratigraphy and Depositional History***

CHIRP sub-bottom profiler data revealed distinct subsurface stratigraphic architectures across the survey area as presented in Figure 7. Three primary stratigraphic units were identified on the basis of reflection character, reflector continuity, and geometric configuration (Figure 7).

This figure should contain three panels: (a) Profile across Zone P: Shows three stratigraphic units (A, B, C) with thick surficial sediment accumulation (layer A ~1.8 m thick), (b) Profile across Zone CN: Shows buried channel feature with erosional truncation of layer B, and (c) Profile across Zone R: Shows irregular acoustic basement and thin sediment cover (layer A ~0.6 m). The CHIRP sub-bottom profiler data revealed three distinct stratigraphic units that record the sedimentary evolution of the study area from pre-Holocene basement through modern port deposits as shown in Figure 7.

Layer C (Acoustic Basement) forms the basal foundation of the sedimentary sequence, characterised by irregular, high-amplitude reflectors indicative of consolidated Quaternary sediments or bedrock. The depth to this acoustic basement varies significantly across the study area, ranging from 5 m below seabed in Zone CN to more than 10 m in Zone P. This spatial variation in basement depth

suggests that the port basin (Zone P) occupies a palaeo -embayment or former estuary that has been progressively infilled during the Holocene marine transgression. The irregular topography and strong acoustic impedance contrast of layer C provide a clear boundary between unconsolidated sediments above and consolidated substrate below.

Overlying layer C is layer B (Middle Layer), which displays parallel, continuous reflectors with moderate amplitude, indicating well-stratified sediments with alternating acoustic impedance contrasts. Layer B thickness ranges from 2.5 m in the river mouth (Zone R) to 4.5 m in the port basin (Zone P). The regular, persistent stratification suggests deposition under relatively stable environmental conditions, likely representing pre-port coastal and nearshore sediments accumulated during the late Holocene. These deposits would have formed prior to human intervention in the area, recording natural coastal sedimentation processes. However, in the navigation channel zone (Zone CN), Unit B is truncated by an erosional unconformity associated with a buried palaeo-channel feature (discussed below), indicating that the sedimentary record has been locally disrupted by erosional processes.

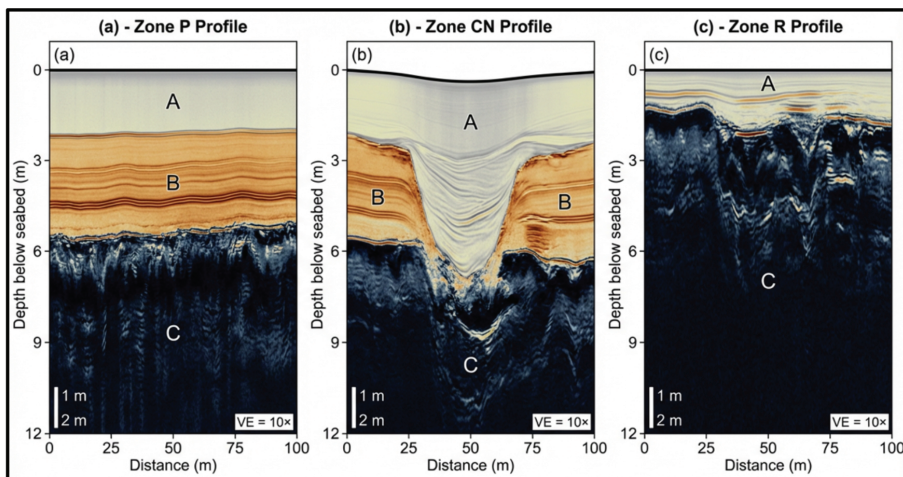


Figure 7: CHIRP sub-bottom profiler profiles showing subsurface stratigraphy

The uppermost layer A (Surficial Layer) comprises acoustically transparent to weakly stratified sediments that record recent depositional history, with thickness varying from less than 0.5 m in Zone R to 1.8 m in Zone P. This spatial variation reflects the contrasting depositional environments across the study area. In the sheltered port basin (Zone P), layer A displays a uniform acoustic character with few internal reflectors, consistent with fine-grained sediments (silt and clay) deposited under low-energy, quiescent conditions. The 1.8 m thickness accumulated over the port's 26-year operational history (since 1998) yields a mean sedimentation rate of approximately 7 cm year<sup>-1</sup> - a rate consistent with observations from other tropical ports receiving riverine sediment input (Winterwerp & Wang, 2013). This relatively high sedimentation rate underscores the ongoing challenge of sediment management in the port basin.

In the navigation channels (Zones CN and CS), layer A is thinner (0.8 m–1.2 m) and exhibits weak internal stratification, suggesting episodic deposition punctuated by erosion events. This pattern reflects the dynamic nature of maintained navigation channels, where periodic dredging activities and vessel-induced currents alternately remove and redistribute sediments. At the river mouth (Zone R), layer A becomes thin and discontinuous, reflecting active erosion and sediment bypass in this high-energy environment where strong currents prevent significant sediment accumulation.

A prominent subsurface anomaly identified in Zone CN provides evidence of past environmental conditions. This buried channel is characterised by an erosional unconformity that

cuts through layer B and is subsequently filled with layer A sediments (Figure 7b). The channel measures approximately 150 m in width and 4 m in depth (measured from the surrounding layer B surface) and exhibits an asymmetric cross-sectional geometry typical of meandering fluvial systems. This feature is interpreted as a palaeo-drainage channel that was active prior to port construction - likely during a period of lower sea level or different coastal configuration and has since been infilled with modern sediments following port development. The identification of this buried channel has practical implications for port engineering and operations: the unconsolidated channel-fill sediments may possess different geotechnical properties (e.g., lower density, higher compressibility, reduced bearing capacity) compared to the surrounding undisturbed layer B deposits, potentially affecting foundation stability for port structures and requiring special consideration during dredging operations to avoid unexpected subsurface conditions.

Systematic analysis of side-scan sonar mosaics and CHIRP profiles identified 37 potential navigation hazards across the survey area (refer to Table 4 and Figure 8). These were categorized as follows.

The map shows the survey area with all 37 identified hazards marked using different symbols and colours. Scour pits are shown as red polygons (5 features in Zone CN near the breakwater, ranging from 15 m–45 m diameter). Dredging scars are shown as orange polygons (10 features in Zone CS, elongated shapes 50 m–200 m long). Submerged objects are shown as yellow circles scaled by size (18 features: 3 in Zone CN, 11 in Zone P, 4 in Zone R; circle

Table 4: Summary of identified seabed hazards by category and zone

| Hazard Category       | Zone CN   | Zone P    | Zone R   | Zone CS   | Total     |
|-----------------------|-----------|-----------|----------|-----------|-----------|
| Scour Pits            | 5         | 0         | 0        | 0         | 5         |
| Dredging Scars        | 0         | 0         | 0        | 10        | 10        |
| Submerged Objects     | 3         | 11        | 4        | 0         | 18        |
| Active Bedform Fields | 2         | 0         | 0        | 2         | 4         |
| <b>Total</b>          | <b>10</b> | <b>11</b> | <b>4</b> | <b>12</b> | <b>37</b> |

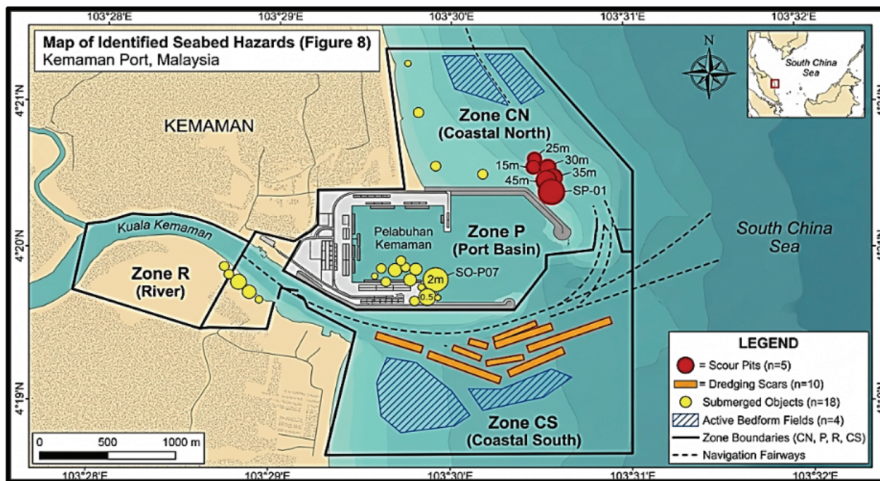


Figure 8: Map of identified seabed hazards

diameters range from 1 m–8 m representing object sizes). Active bedform fields are shown as blue hatched areas (4 features: 2 in Zone CN, 2 in Zone CS, covering areas of 5,000 m<sup>2</sup>–15,000 m<sup>2</sup>). Navigation fairways are shown as dashed black lines running through the channels. Hazards within 25 m of fairways are highlighted with red outlines (indicating high priority for monitoring). The map clearly shows the spatial distribution of hazards, with scour pits concentrated near the breakwater, submerged objects primarily in the port basin, dredging scars in the southern channel, and active bedforms in both navigation channels.

The side-scan sonar surveys identified 37 distinct seabed hazards distributed across the study area, which can be categorized into four types based on their origin, morphology, and potential impact on port operations as presented in Figure 8. These hazards range from active erosional features threatening infrastructure stability to remnant anthropogenic features that may affect navigation safety.

Five major scour pits were identified in Zone CN, concentrated near the breakwater foundation where flow acceleration and vortex generation are most intense as presented in Figure 8. These erosional features appear as circular to elliptical depressions ranging from 15 m to 45 m in diameter and 2 m to 8 m in depth

below the ambient seabed level. The largest scour pit (SP-01, located at 4.2445°N, 103.4395°E) measures 45 m × 38 m with a maximum depth of 8 m, representing a significant volume of sediment removal. High-resolution side-scan imagery reveals that the scour pit floors are armoured with coarse sediment (gravel and shell fragments), indicating winnowing of fine particles by strong currents and leaving behind lag deposits of coarser material.

The formation mechanism of these scour pits involves flow acceleration around the breakwater structure, which generates horseshoe vortices and downward-directed jets that erode the seabed. The presence and continued development of these features indicate active erosion processes that pose a threat to breakwater stability. If scouring continues to deepen, particularly around the breakwater foundation, structural integrity may be compromised through undermining of the base. Regular bathymetric monitoring of these scour pits is essential to detect progressive deepening and inform potential remediation measures, such as placement of scour protection materials (e.g., rock armour or concrete mattresses).

Eighteen discrete high-backscatter targets interpreted as submerged objects were identified across the study area, with the highest concentration in the port basin (Zone P, n = 11)

where vessel traffic and cargo handling activities are most intensive as shown in Figure 8. Object sizes range from 1 m to 8 m in maximum dimension, with most objects ( $n = 13$ ) falling within the 2 m–4 m size class. The acoustic signature of these objects is characterised by high backscatter intensity due to their hard surfaces and prominent acoustic shadows extending down current, indicating substantial vertical relief above the seabed.

Based on morphological characteristics, acoustic properties, and spatial distribution, the submerged objects identified in the side-scan sonar mosaics can be tentatively classified into four categories. Large debris ( $n = 8$ ) likely includes construction materials, lost cargo containers, or vessel components such as propellers and rudders. Small wrecks or derelict vessels ( $n = 3$ ) are interpreted as abandoned boats or sunken craft. Mooring blocks or anchors ( $n = 4$ ) may represent functional equipment or lost mooring gear. Finally, unidentified objects ( $n = 3$ ) could not be confidently classified based solely on acoustic data. This classification provides a preliminary framework for understanding anthropogenic features within the study area and highlights the need for further ground-truthing to confirm object identity and provenance.

The largest identified object (SO-P07, located at 4.2385°N, 103.4365°E) measures approximately 8 m × 4 m in plain view and produces a 12 m acoustic shadow, suggesting substantial vertical relief estimated at 2 m–3 m above the seabed. This object is of particular concern as it is located within 50 m of an active berth and may pose a snagging hazard for vessel anchors, mooring lines, or underwater equipment. Several other objects in Zone P are similarly positioned near operational berths, indicating potential interference with port operations. Removal or relocation of high-risk objects, particularly those near navigation routes or berthing areas, should be considered to enhance operational safety.

Ten linear to curvilinear features interpreted as dredging scars were identified in the southern channel (Zone CS), representing remnants of

previous maintenance dredging operations as shown in Figure 8. These features appear as elongated depressions ranging from 50 m to 200 m in length, 10 m to 20 m in width, and 0.5 m to 1.5 m in depth. The acoustic signature of dredging scars is distinct from natural seabed morphology, characterised by abrupt depth changes, sharp linear boundaries, and flat bottoms that contrast with the surrounding undisturbed seabed.

The presence of these dredging scars indicates that previous dredging operations were not conducted to achieve a smooth, uniform seabed profile, resulting in over-dredged areas that persist in the bathymetry. While these features do not pose immediate navigation hazards due to their relatively shallow depth, they may function as sediment traps that preferentially accumulate fine-grained material over time. This secondary infilling could lead to localized shoaling within the dredged depressions, potentially necessitating re-dredging to maintain design depths. Future dredging operations should aim for more uniform depth profiles to minimize the formation of such features.

Four areas of active bedforms were delineated based on the presence of well-developed ripple patterns in side-scan sonar imagery, covering areas ranging from 5,000 m<sup>2</sup> to 15,000 m<sup>2</sup> as presented in Figure 8. These bedform fields are located in the navigation channels (Zones CN and CS) where tidal currents are strongest and exceed the threshold velocity for sediment transport. The ripple morphology indicates that these areas experience active sediment movement, with bedform migration directions reflecting the dominant current orientation.

While bedforms themselves do not constitute direct navigation hazards - as they typically have low relief (wavelengths of 0.5 m–2 m, heights of 0.05 m–0.15 m), their presence serves as an important indicator of active sediment transport and potential for rapid bathymetric change. Areas with active bedforms may experience shoaling if sediment supply increases (e.g., during monsoon periods

with elevated river discharge) or if current patterns change due to port modifications such as new breakwater construction or channel reconfiguration. These dynamic areas require more frequent bathymetric surveys to detect depth changes that may affect navigation clearance (Ariffin *et al.*, 2018).

Spatial analysis of hazard distribution revealed that 14 of the 37 identified hazards (38%) are located within 25 m of designated navigation fairways, indicating potential impact on vessel operations as presented in Table 4. These high-priority hazards include three scour pits adjacent to the main channel, seven submerged objects within or near traffic lanes, and four dredging scars that intersect navigation routes. The concentration of hazards near navigation fairways underscores the need for enhanced monitoring and potential remediation efforts.

Based on the outcomes of the risk assessment, a three-tiered management framework is proposed to balance operational safety with efficient resource allocation. Immediate intervention is required for high-risk features, notably large, submerged objects located near berths and deep scour pits that pose a direct threat to breakwater stability. Medium-risk features, including smaller submerged objects and progressive scour formations, warrant regular monitoring through quarterly surveys to track their evolution and mitigate potential hazards. In contrast, low-risk features such as dredging scars and bedform fields can be managed through periodic assessment on an annual basis. This tiered approach enables port authorities to prioritise interventions according to risk severity, thereby safeguarding infrastructure integrity while optimizing the deployment of monitoring and maintenance resources.

### ***Zone-specific Synthesis***

The study area exhibits distinct spatial zonation in sediment characteristics, seabed morphology, and hazard distribution, reflecting the interplay of hydrodynamic energy, sediment supply, and

anthropogenic modifications (refer Figure 8 and Table 4). The zones can be understood as a continuum from the high-energy river mouth environment through transitional coastal areas to the low-energy sheltered port basin, with each zone presenting unique characteristics and hazard profiles.

The river mouth zone (Zone R) represents the highest-energy environment in the study area, characterised by coarse sediments (mean  $D_{50} = 1.2$  mm), high acoustic backscatter (Facies 1), and thin, discontinuous surficial sediment cover ( $< 0.5$  m). The coarse grain size and high backscatter signature reflect the winnowing effect of strong currents, which remove fine particles and leave behind a lag deposit of sand and gravel. Subsurface stratigraphy reveals a shallow or exposed acoustic basement with irregular topography (2 m–3 m relief), indicating that this zone experiences net erosion or sediment bypass rather than accumulation.

Four submerged objects were identified in Zone R, likely transported and deposited during high-discharge events when river flow velocities are sufficient to mobilize large debris. The dynamic nature of this zone suggests that object positions may shift over time in response to flow conditions. The shallow acoustic basement and irregular topography indicate that this zone has limited accommodation space for sediment accumulation, with the substrate consisting of consolidated materials that resist erosion. The sediment transport regime in Zone R is characterised by high mobility, with sediment supplied from the river being rapidly transported through the system rather than deposited locally.

Moving from the river mouth into the coastal zone, Zone CN exhibits fine to medium sand (mean  $D_{50} = 0.18$  mm), moderate acoustic backscatter (Facies 2), and well-developed active bedforms that indicate persistent sediment transport driven by tidal currents and wave action. This transitional environment experiences moderate hydrodynamic energy, sufficient to maintain sandy substrates and generate bedform migration, but lower than the river mouth zone.

The most significant hazards in Zone CN are five major scour pits concentrated near the breakwater foundation, with the largest (SP-01) reaching 8 m in depth below the ambient seabed level. These erosional features demonstrate the impact of flow acceleration around engineered structures, where the breakwater modifies local current patterns and generates horseshoe vortices that erode the seabed. The scour pits contain coarse sediment (gravel and shell fragments) on their floors, indicating winnowing of fine particles and the development of armoured surfaces.

Zone CS, located on the southern coastal margin of the study area, exhibits sediment characteristics similar to Zone CN, with fine to medium sand (mean  $D_{50} = 0.22$  mm), moderate acoustic backscatter (Facies 2), and active bedforms indicating ongoing sediment transport. However, the hazard profile of Zone CS is dominated by anthropogenic features rather than natural processes or infrastructure-related erosion.

Ten (10) linear to curvilinear dredging scars were identified in Zone CS, representing remnants of previous maintenance dredging operations. These elongated depressions (50 m–200 m long, 10m–20 m wide, 0.5 m–1.5 m deep) have sharp boundaries and flat bottoms that contrast with the natural seabed morphology. The acoustic signature of these features is distinct, characterised by abrupt depth changes and linear geometry that are inconsistent with natural seabed processes. The persistence of these dredging scars indicates that previous dredging operations achieved non-uniform seabed profiles, with over-excavation in some areas. These depressions function as sediment traps that preferentially accumulate fine-grained material over time, as evidenced by the presence of lower-backscatter sediments within the scars compared to the surrounding seabed. This secondary infilling process demonstrates that the dredging scars modify local sediment dynamics by creating topographic lows that interrupt the natural sediment transport pathways.

The port basin (Zone P) represents the lowest-energy environment in the study area, functioning as a sediment sink where fine-grained particles settle from suspension under quiescent conditions. This zone is dominated by fine sediments (mean  $D_{50} = 0.045$  mm, 68% mud content), low acoustic backscatter (Facies 3), and thick surficial sediment accumulation (1.8 m accumulated since port construction in 1998). The high sedimentation rate of approximately 7 cm a year reflects the combination of riverine sediment input, limited current energy for sediment resuspension, and trapping efficiency of the sheltered port basin configuration.

Subsurface stratigraphy in Zone P reveals three distinct units: A thick surficial mud layer (Unit A, 1.8 m), underlying pre-port coastal deposits (Unit B, ~3.5 m), and a deep acoustic basement (Unit C, >10 m below seabed). The thickness of Unit A and the uniformity of its acoustic signature indicate continuous, steady deposition under low-energy conditions over the 26-year operational history of the port. The deeper acoustic basement in Zone P compared to other zones suggests that the port basin occupies a palaeo-embayment or former estuary that has been progressively infilled during the Holocene marine transgression.

The primary hazards in Zone P are 11 submerged objects distributed across the basin, including the largest identified object in the entire study area (SO-P07: 8 m × 4 m with 2 m–3 m vertical relief). These objects include large debris, possible small wrecks, mooring blocks, and unidentified items, several of which are located within 50 m of active berths. The concentration of submerged objects in Zone P likely reflects the intensity of maritime activities in the port basin, including cargo handling, vessel traffic, and construction operations, all of which can result in loss of equipment or materials into the water. The acoustic shadows cast by these objects indicate substantial vertical relief above the seabed, with some objects partially buried in the soft mud substrate.

The four zones represent a spectrum of environmental conditions along an energy gradient (Table 4). Zone R (high-energy, coarse sediments, erosion/bypass) and Zone P (low-energy, fine sediments, rapid accumulation) occupy opposite ends of this gradient, while Zones CN and CS (moderate energy, medium sediments, active transport) represent transitional environments. This spatial pattern reflects the fundamental control of hydrodynamic energy on sediment distribution, with grain size decreasing systematically from the river mouth (1.2 mm) through the coastal zones (0.18 mm–0.22 mm) to the port basin (0.045 mm). Hazard types also vary systematically across zones: Erosional features (scour pits) dominate in Zone CN where infrastructure interacts with active sediment transport; anthropogenic features (dredging scars) dominate in Zone CS where maintenance operations have modified the seabed; discrete objects concentrate in Zone P where maritime activities are most intensive; and mobile debris occurs in Zone R where high-energy flows can transport large materials. This spatial distribution of hazards reflects the combined influence of natural processes (hydrodynamic energy, sediment transport) and anthropogenic activities (port construction, dredging, maritime operations).

The subsurface stratigraphy reveals important differences in sediment thickness and acoustic basement depth across zones. Zone R exhibits thin sediment cover (< 0.5 m) over shallow basement (5 m depth), Zone CN shows moderate sediment thickness (2 m–3 m) with a buried channel feature, Zone CS displays similar characteristics to Zone CN but with anthropogenic modifications, and Zone P contains thick sediment accumulation (> 5 m) over deep basement (> 10 m depth). These stratigraphic variations indicate that the study area has experienced a complex depositional history, with the port basin occupying a palaeo-embayment that has accumulated sediment over millennia, while the river mouth and coastal zones have experienced more dynamic erosion and deposition cycles.

The zones are interconnected through sediment transport pathways, with sediment supplied from Zone R being transported through Zones CN and CS before ultimately accumulating in Zone P. This sediment pathway is evidenced by the grain size progression, the presence of active bedforms in the coastal zones indicating sediment in transport, and the high sedimentation rate in the port basin indicating sediment deposition. The buried channel feature in Zone CN may represent a former pathway for sediment transport that is no longer active but continues to influence subsurface conditions. Understanding these spatial patterns and interconnections provides insights into the sediment dynamics of the port system and the distribution of seabed hazards.

## Discussion

The spatial patterns of sediment distribution observed in this study reflect the interplay of multiple controlling processes, including riverine input, tidal currents, wave action, and anthropogenic modifications. The coarse sediments in Zone R (river mouth) indicate that the Kemaman River delivers substantial bedload material, particularly during monsoon periods when discharge is elevated. However, the thin sediment cover and evidence of active erosion suggest that much of this material is transported alongshore or offshore rather than accumulating locally. This sediment bypass behaviour is consistent with observations from other tropical river mouths where strong tidal currents prevent deposition (Hicks & Hume, 1996; Ariffin *et al.*, 2018).

The fine-grained sediments in Zone P (port basin) represent a sediment sink where suspended material settles under low-energy conditions. The calculated sedimentation rate of 7 cm/year is higher than rates reported for many temperate ports (typically 2 cm/year–5 cm/year) (Ockenden, 2012), but is consistent with tropical systems with high riverine sediment loads. The poor sorting and high mud content in Zone P indicate that sediments are derived

from multiple sources (riverine, coastal erosion, biological production) and deposited under variable energy conditions influenced by vessel traffic and seasonal monsoon patterns.

The intermediate grain sizes and active bedforms in Zones CN and CS (navigation channels) indicate a dynamic equilibrium between sediment supply, transport capacity, and deposition. The ripple bedforms provide direct evidence of current-induced sediment transport, with asymmetry indicating net south-westward transport during ebb tides. This transport direction is consistent with regional coastal current patterns along the Terengganu coast, where the dominant alongshore current flows southward during the northeast monsoon season (Husain *et al.*, 2016; Muhammad *et al.*, 2016).

The strong correlation between acoustic facies and sediment grain size (87% classification agreement) demonstrates that side-scan sonar provides a reliable tool for mapping sediment distribution in port environments. This finding is consistent with numerous studies that have established empirical relationships between backscatter intensity and grain size (Clarke *et al.*, 1996; Cochrane & Lafferty, 2002). However, such relationships are site-specific, and local calibration with ground-truth samples is essential for accurate interpretation.

The 13% classification mismatch observed in this study occurred primarily at facies boundaries where gradual transitions exist. For example, Station P-01 (located at the edge of Zone P near the port entrance) was classified as Facies 2 (moderate backscatter) but contained fine-grained sediments ( $D_{50} = 0.065$  mm) more typical of Facies 3. This discrepancy may reflect temporal variability in sediment characteristics due to episodic deposition events, or spatial heterogeneity at scales smaller than the acoustic footprint.

The weak correlation relationship between sediment sorting and acoustic facies classification suggests that backscatter intensity is primarily controlled by grain size rather than

sorting characteristics. This finding has practical implications for acoustic classification schemes, indicating that simple backscatter thresholding may be sufficient for grain size mapping, while more sophisticated textural analysis may be required to discriminate sorting characteristics or other sediment properties.

The findings of this study have direct implications for port management and dredging operations at Kemaman Port. The high sedimentation rate in the port basin (7 cm/year) indicates that maintenance dredging may be required at intervals of approximately three to five years, subject to operational depth requirements and sedimentation monitoring results, to maintain design depth, assuming a target under-keel clearance of 2 m for typical vessel drafts.

The total volume of sediment accumulation in the port basin (area  $\sim 0.8$  km<sup>2</sup>, thickness 1.8 m) is approximately 1.4 million m<sup>3</sup> since port construction, corresponding to an annual accumulation rate of  $\sim 54,000$  m<sup>3</sup> year<sup>-1</sup>. Assuming a target under-keel clearance of 2 m, the observed sediment accumulation rates could progressively reduce navigational safety if left unmanaged.

Dredging operations should prioritise the port basin (Zone P) where sedimentation rates are highest, followed by the navigation channels (Zones CN and CS) where bedform migration may cause localized shoaling. The river mouth area (Zone R) does not presently require dredging due to natural sediment bypass but should be monitored for changes in channel configuration that may affect navigation.

The identification of 37 seabed hazards provides critical, actionable information for enhancing navigation safety within the port area. High-priority measures include the removal or marking of the largest submerged objects in Zone P, particularly SO-P07, which poses a significant snagging hazard near active berths. In Zone CN, monitoring of scour pits is essential to evaluate potential risks to breakwater stability. Meanwhile, in Zone CS,

re-surveying dredging scars is recommended to determine whether sediment accumulation has occurred, as highlighted by Ariffin *et al.* (2020). This targeted prioritization ensures that port authorities can address the most pressing hazards promptly while maintaining long-term operational safety and infrastructure resilience.

The buried channel feature identified in Zone CN has implications for foundation design and dredging operations. Channel-fill sediments typically have lower density and higher compressibility than surrounding materials, which may affect pile-driving operations or cause differential settlement of structures. Dredging in this area should be planned with awareness of the buried channel geometry to avoid unexpected changes in sediment properties.

The seabed characteristics observed at Kemaman Port reveal both commonalities with other tropical ports influenced by riverine sediment input and distinctive features shaped by local hydrodynamic and geological conditions. Sedimentation rates in the port basin, averaging 7 cm/year, are comparable to those reported for other Southeast Asian ports such as Port Klang (5 year<sup>-1</sup>–8 year<sup>-1</sup>; Latif, 2012) and Jakarta Port (6 year<sup>-1</sup>–10 year<sup>-1</sup>; Wirasatriya *et al.*, 2017), but substantially exceed those of temperate ports like Rotterdam (2 year<sup>-1</sup>–3 year<sup>-1</sup>; Wang *et al.*, 2002) and Hamburg (3 year<sup>-1</sup>–4 year<sup>-1</sup>; Kappenberg & Fanger, 2002), reflecting the higher sediment loads of tropical rivers and monsoon-driven variability (Ariffin *et al.*, 2018).

The three-facies acoustic classification scheme developed here, though simpler than schemes recognizing 5–7 facies classes (Hamilton, 2001), is well-suited to the limited sediment diversity of the study area, achieving a high classification agreement of 87%, which compares favourably with values reported elsewhere (between 70% and 85%; Harris & Collins, 1985; Buscombe *et al.*, 2016). Bedform characteristics, particularly ripple wavelengths of between 0.8 m and 1.5 m in navigation channels, align with current-generated bedforms

in medium sand under tidal velocities of 0.4 m s<sup>-1</sup>–0.6 m s<sup>-1</sup> (Soulsby, 1997), consistent with observations from other port channels under similar hydrodynamic regimes (Rubin & Hunter, 1987; Mehta, 2025). The pronounced directional preference of ripple crests (78% within 030°–060° azimuth) underscores tidal currents as the dominant control, with minimal wave influence. Finally, scour pits near the breakwater, reaching depths of up to 8 m, are comparable to scour features documented at other breakwater installations (Sumer & Fredsøe, 2001; Whitehouse, 2011), with dimensions consistent with the expected ratio of scour depth to structure width (~20 m). Their concentration on the seaward side reflects flow acceleration and vortex generation as currents are deflected around the structure (Ariffin *et al.*, 2020).

## Conclusions

This study demonstrates that the integrated application of side-scan sonar and CHIRP sub-bottom profiling provides a comprehensive assessment of tropical port environments where natural forces and anthropogenic activities interact. It identified three principal geomorphological and sedimentological settings: High-energy areas near the river mouth with active sediment transport, moderate-energy coastal zones with ongoing movement, and low-energy port basins where fine sediment settles – demonstrating that hydrodynamic energy is a primary control on sediment distribution and seabed morphology and navigational hazards.

Subsurface data revealed a long history of deposits, from older basal substrates overlain by progressively younger sedimentary units associated with recent environmental and port-development processes, while hazards such as scour pits, submerged objects, dredging scars, and shifting bedforms were linked to specific zones. The identification of these scour pits, submerged objects, dredging scars, and active bedforms further demonstrated that seabed hazards are spatially linked to specific hydrodynamic and operational zones.

Moreover, the results highlight how sediment pathways connect across zones, how buried palaeo-channels still influence modern conditions, and how port structures alter natural processes.

The strong correspondence between acoustic facies and sediment properties confirms the effectiveness of integrated hydroacoustic techniques for seabed characterisation and hazard identification

From a management perspective, the findings emphasise the importance of regular seabed monitoring to support navigation safety, optimise dredging strategies, and maintain port infrastructure.

Future research should incorporate repeated hydrographic surveys, higher-resolution subsurface investigations, and coupled hydrodynamic–sediment transport modelling to improve understanding of seabed evolution and to anticipate morphological changes associated with port expansion, changing sediment supply, and climate-driven variability.

Such efforts will contribute to the sustainable management and long-term operational resilience of Kemaman Port and comparable tropical maritime facilities.

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## Author Contributions Statement

Muhammad Rizal Razali contributed to the writing of the original draft, methodology, formal analysis, and conceptualization. Masha Menhat was responsible for the original draft, review and editing of the manuscript. Ikhmal Siddiq provided editing and figure analysis. Azizi Ali was involved in the methodology and formal analysis. Mardihah Mokhtar participated in the formal analysis, review and editing process. Saiful Bahri Hamzah participated in the review and editing process. Siti Salihah Mohd Sendek participated in the editing process and procurement. Hazamri Harith contributed to the review and editing, as well as the acquisition of funding. Muhammad Zahir Ramli was involved in the review and editing of the manuscript. Effi Helmy Ariffin contributed to the writing of the original draft, review and editing, supervision, and conceptualisation.

## Conflict of Interest Statement

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare absence of conflicting interests with the funders.

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