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Sand dune restoration as sustainable natural architectural design for coastal protection along seasonal storm-prone beach

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ABSTRACT

Monsoonal storms cause coastal erosion of worldwide sandy beaches, including coasts in Malaysia. Although hard engineering structures are effective in mitigating erosion, those constructions can create several environmental issues such as down-drift erosion. The Effective Sand Fence (also known as E-Fence) is considered one of the sustainable alternative structures to protect beach erosion. Therefore, the objective of the current study is to identify the effectiveness of E-Fence for dune restoration. In this study, we measured beach profile survey, grain size distribution, and wind speed. In addition, XBeach simulation was used to determine sediment accumulation under the E-Fence protection. Results of the beach profile survey (i.e., slope and dune volume) indicate dune restoration in protected areas of the E-Fence. Grain size distribution and wind speed suggest the decreasing of wind velocities from the swash zone to the backshore. Accordingly, the E-Fence acts as a barrier, and the reduction of energy leads to accumulate sediments by passing through gaps in the structure. The E-Fence is thus capable of sustaining against wave attack and can maintain stable coastal ecosystems. Consequently, this coastal protection structure assists in developing cheaper coastal erosion mitigation strategies in Malaysia and elsewhere.

1. Introduction

Coastal dunes play an important part in coastal protection along sandy beaches across the world. It provides storm surge protection for low-lying hinterlands. Coastal dunes play an important part in coastal protection along sandy beaches across the world. It provides storm surge protection for low-lying hinterlands. However, the majority of sandy beaches are prone to erosion due to energetic waves, wind, and currents [1–4]. Sand-trapping fences are a popular natural technique to overcome coastal erosion. These trapping fences are very affordable, due to easy construction and faster completion time. In addition, sand-trapping fences promote dune toe growth along sandy shorelines [5]. Sand-trapping fences thus resemble natural buffer systems with minimal synthetic and man-made impacts [6]. These fences can also cost-effectively restore dunes compared to hard engineering structures [7]. Accordingly, sand fences have been widely used as environment-friendly man-made barriers to regulate the movement and rate of aeolian erosion and sand deposition [8]. Furthermore, sand fences have been used in Europe since the 15th century, especially in deserts, beaches, and near man-made buildings [9]. Wind-blown sand emission can drop with the fence erection [10]. Accordingly, sand deposition can occur when wind speed slows down, where shear velocity no longer exceeds the threshold [11]. Consequently, sand fences can be considered as an efficient strategy for assisting dunes recovery and

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growth.

Deploying sand fences is recommended on coastal areas that are (i) exposed under storm conditions [11] and/or (ii) sediment subjected to frequent high wind velocity and have open bare spaces for deposition of blowing sands [12]. The effectiveness of sand fences can be simply determined by accumulated sand volume in dune areas. However, there are still a few examples in the literature to determine the efficiency and sustainability of sand trapping by fences in coastal areas. The objectives of this research are thus to determine the effectiveness of sand trapping by fences in restoring coastal dunes, and to investigate coastal dynamic processes after erecting sand fences. Therefore, the current study investigates the effectiveness of sand trapping as an alternative strategy for coastal erosion and sustainability.

2. Study area

Study area is located in Ma' Daerah, Terengganu, Malaysia (Fig. 1), known for its sandy and natural beach [13,14]. This area (marked in red marker) is identified as Turtle Sanctuary where turtles use the land as nesting sites [15]. Textural characteristics and morphology (e.g., beach width) also affect the nesting process of sea turtles [16], and thus the study area can be identified as a biological hotspot. The location is surrounded by green vegetation and is categorized as a lowland forest and stream. The study area is also exposed to high-energy monsoon waves, and it can reach up to 5.3 m [17–19]. In addition, the average wind speed is between 4.0 and 8.0 ms^{-1} along this coast [20].

3. Methodology

There different methods were used in this study to determine the effectiveness of sand trapping, along the E-Fence (also known as Effective Sand Fence). The E-Fence is solely made up of wooden blocks, *Kayu Seraya* with 3 m long and 8 cm wide, and it has been installed zigzag parallel to the shoreline at Ma' Daerah, Terengganu. This design prevents powerful waves in multiple directions from eroding the dune through overwash and aeolian transport towards the landward side [7]. The fence height was approximately 1 m above the ground surface, and the porosity was around 50 %. Our study area has 13 transects which sand-trapping fences, with 10 transects having sand-trapping fences and 3 transects without E-Fence protection (Fig. 2). The distance between each transect is roughly 7 m. The maximum angle width of the fences is about 90°, and they are installed to face the wave pattern. For this study, we analyze and observe the effectiveness of the fences in only 4 transects, as these areas exhibit the most active accretion and erosion (sediment transport processes). Fig. 2 shows different transects with E-Fence protection (T4 and T10) and without E-Fence protection (T7 and T13).

Monthly beach profile surveys were conducted during the early northeast monsoon season (from October to December) along (4) selected transects. These surveys were performed during low tide using a theodolite, levels, and a Total Station (Topcon GPT-3100 N). The survey started at the dunes, where vegetation began, and extended to the low tide mark, with the average beach width ranging from 30 to 55 m. Benchmark elevations for each location were adjusted to the DTGSM datum, and the positions of transects and bearings were accurately redone in each monthly measurement. These procedures were employed to record elevation and other measurements for beach profile analysis (beach volume and slope) at each survey point using the Profiler 3.2XL programme.

Two different approaches were used to understand morphological changes through aeolian sediment transportation and numerical modelling. Sediment samples ($n = 12$) were collected from (2) transects,

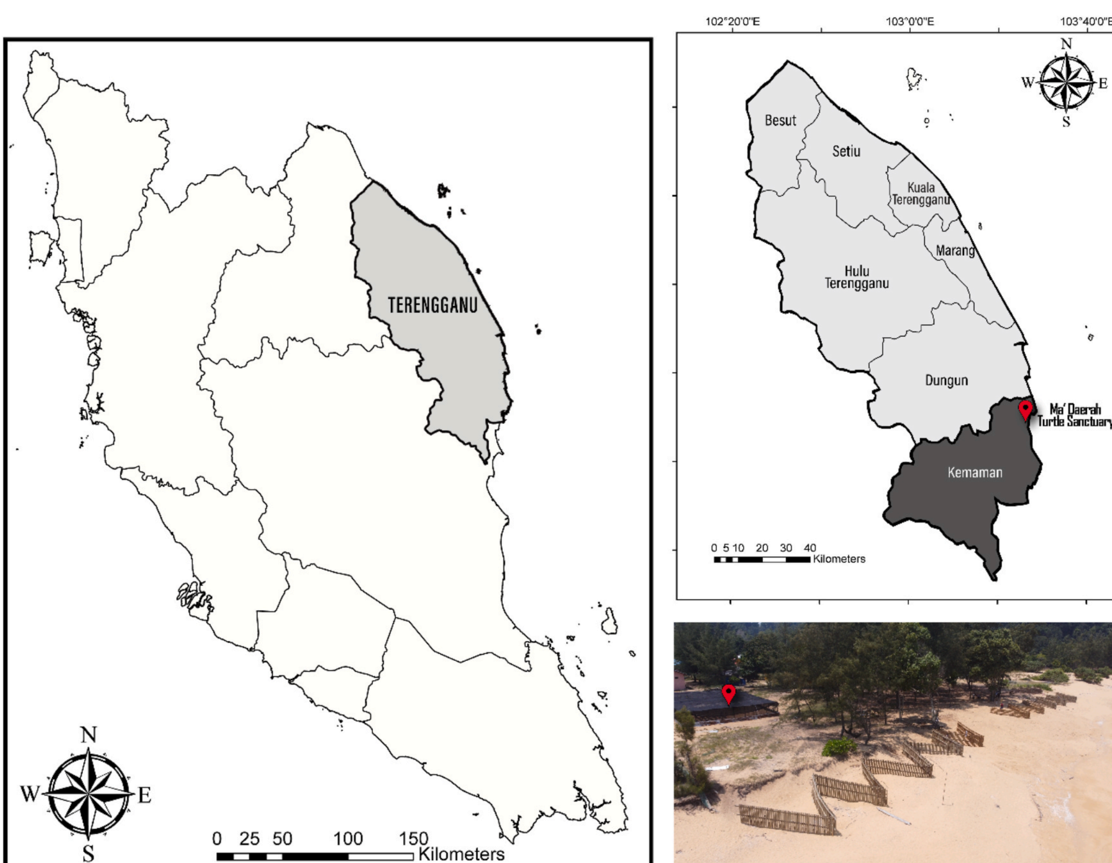

Fig. 1. Regional map showing the study area (Pantai Ma'Daerah). The picture shows the sand fences that had been erected along the beach.

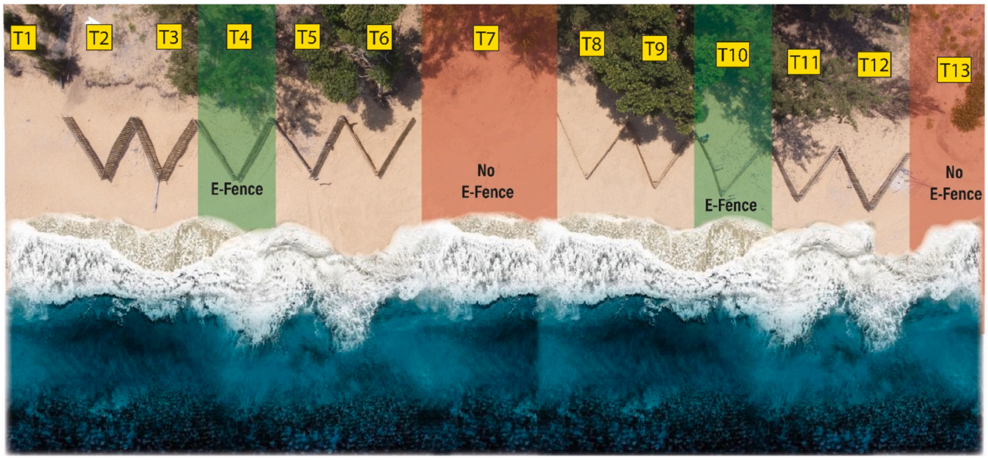

Fig. 2. Study site showing areas with E-Fence protection (T4 and T10) and without E-Fence protection (T7 and T13).

Transect 10 (protected by E-Fence) and Transect 7 (unprotected beach). Only (2) transects were used to compare grain size within and without E-Fence. This collection took place in December, covering the area from the vegetation down to the low tide mark every 5 m. Grain sizes were determined by using 7 sets of dry-sieves method with mesh ranging from 2000 to below 63 μm and were analyzed by using GRADISTAT 4.0 software.

Next, real-time wind speed and direction were studied to assess the movement of wind and sediments. A weather station was set up in (3) different zones, including backshore, foreshore, and swash zones during November and December. These stations were placed at a height of 0.5 m from the ground surface, which is the same level as the E-Fence, to record wind speed and direction simultaneously for 15 min. The optimal accumulation of sediment in the study area is significantly influenced by the wind speed and direction. Understanding these wind patterns is vital for comprehending sediment dynamics and their impact on the study area. Observations on both sediment sizes and wind parameters were used to determine the coastal dynamic process after the installation of sand fences.

XBeach numerical simulation was used to predict how sand would accumulate under the E-Fence. Essential data, including area depth, grid setup, wave and water parameters, sand size, and the non-erodible E-Fence were gathered. A variable grid size had a cross-shore dx range of 1–100 m and an alongshore dy of 0.01 m. Bathymetry and topography were obtained from in-situ measurement while secondary wave and water parameters came from Mike 21 for sediment movement simulation. The distribution of sediment grain size was incorporated from sieving. The E-Fence remained non-erodible to stay visible during the simulation. Most of the other parameters followed the recommendations from XBeach and related research conducted in similar conditions [21]. Accordingly, the E-Fence structure effectively diminishes wave energy impact, concurrently trapping sediment to prevent its dispersion into the ocean and subsequent erosion. Therefore, the simulation of the XBeach model serves as an additional computational framework to substantiate and forecast upcoming findings on a large scale. Empirical evidence from beach profiles, sediment distribution, and wind speed is solid, with the simulation model providing supplementary support to the outcomes of this investigation. Consequently, it is allowed to determine changes in the coastal dynamic process within the installation of sand fences.

4. Results and discussion

4.1. Beach profile

Selected beach profile variations are shown in Figs. 3 and 4. In general, the accretion rate remained relatively low during October and November. However, a significant increase in accretion occurred in December (Fig. 3). There is about 0.5–2 % increment of sediment inside the E-Fence within (3) months which highly shows great potential for this implementation to keep trapping more of the sand dunes in the future. We also compared beach erosion and accretion with E-Fence protection (T4 and T10) and without E-Fence protection (T7 and T13). It suggests that the E-Fence installation was successful in restoring dune formation in the study area. Therefore, natural sand fences are proven to be vital in sustaining and expanding the volume and protecting the upper backshore and dune. Throughout the sampling phases, the E-Fences were intended to aid in the growth of dunes located inside and behind the fences. In addition, it generates a significant crest that acts as backup protection for the newly formed crest. Accordingly, the beach profiles can indicate the trapping efficiency of the study area.

4.2. Beach volume and beach slope

The study area is divided into two hypothetical sections, backshore (10 m–18 m) and foreshore (19 m–27 m) beaches for the slope calculations (Table 1) and volume (Figs. 3 and 4). In Table 1, 'M' stands for Moderate slope, while 'F' represents Flat slope. The effectiveness of sand fences is determined by measuring the sand volume in dune areas. Figs. 3 and 4 depict the dune volume over three consecutive months prior to E-Fence installation. Therefore, a comparison was made between the E-Fence-protected area and an area without protection. Results reveal a gradual increase in dune restoration in the E-Fence area, whereas the unprotected area experiences sand erosion.

4.2.1. Backshore (10 m–18 m)

From October to November, the volume of sand increased by + 0.2 m^3 to + 0.4 m^3 in protected near areas of E-Fence, whereas unprotected areas, especially T13, experienced erosion at a minimal rate of – 0.14 m^3. The slope measurements indicate varying degrees of slope, ranging from 4° to 8° (flat to moderate) on the E-Fence and 5°–7° (moderate) for the unprotected area (Table 1). From November to December, all transects show sand accretion, with the maximum accretion rate exceeding +6.0 m^3, primarily observed in the E-Fence protection area (T4). During this time, the slope measurements also reveal varying degrees of slope on the E-Fence area and without protection, ranging from 2° to 10° (flat to moderate) and 5°–9° (moderate), respectively (Table 1). Within (3) months of sampling, the volume of sand within E-Fence protection increased, ranging from +7.0 m^3 to + 12.0 m^3. The area within E-Fence protection was expected to have a continuous increase in sediment trapping.

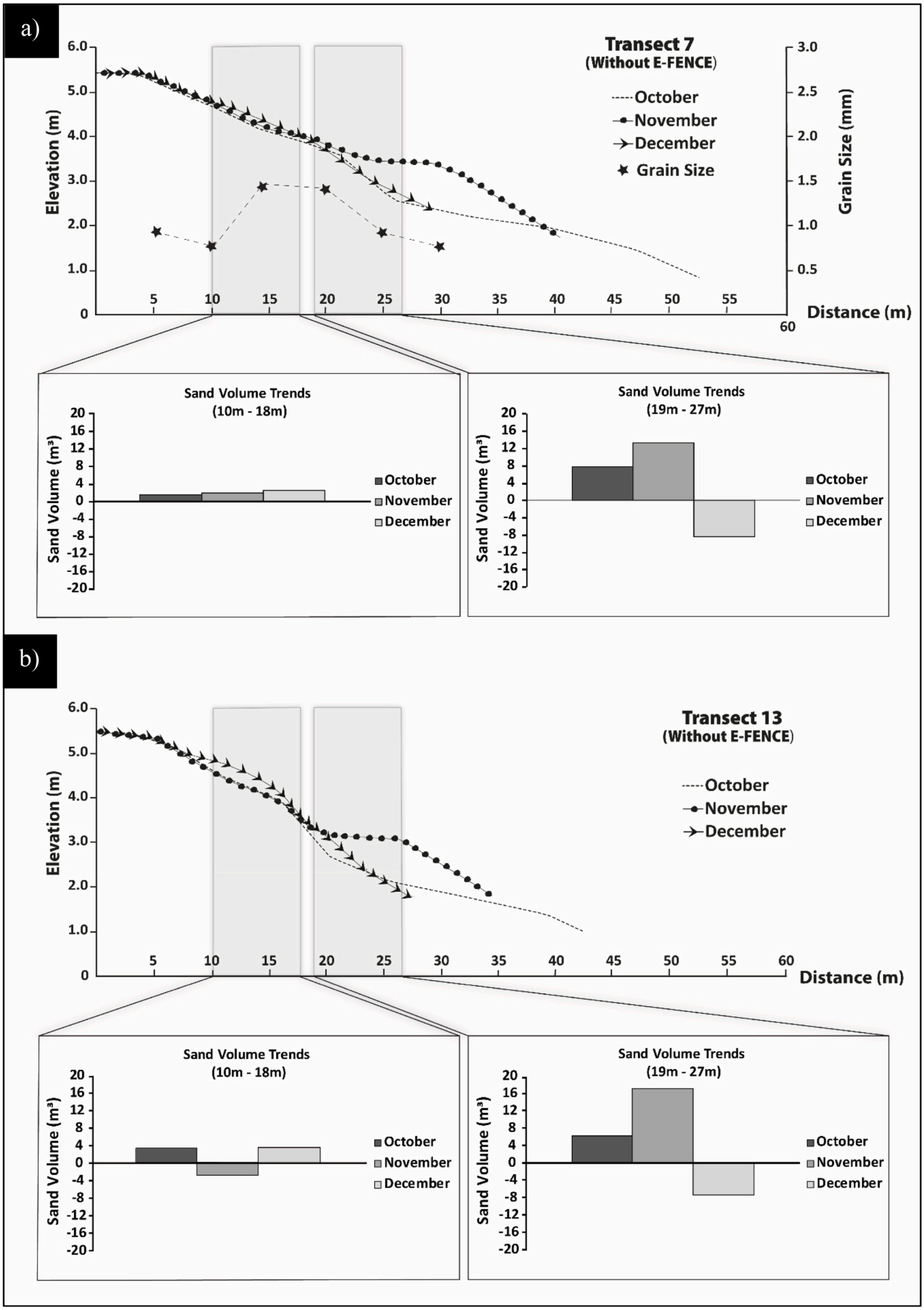

Fig. 3. Beach profile, sand volume trends, and grain size for the backshore (10 m–18 m) and the foreshore (19 m–27 m) beaches, without E-Fence protection. a) Transects 7, and b) Transect 13.

4.2.2. Foreshore (19 m–27 m)

From October to November, all transects show sand accretion, and the maximum rate reached up to + 7.0 m^3 in the E-Fence protected area (T10). The slope measurements indicate that both the E-Fence (protected) and unprotected areas had similar degrees of slope below 4° (flat beaches). In addition, the flattest slope is observed along the T13 transect. However, all transects showed erosion (i.e., sediment being reduced or removed) from November to December. The maximum

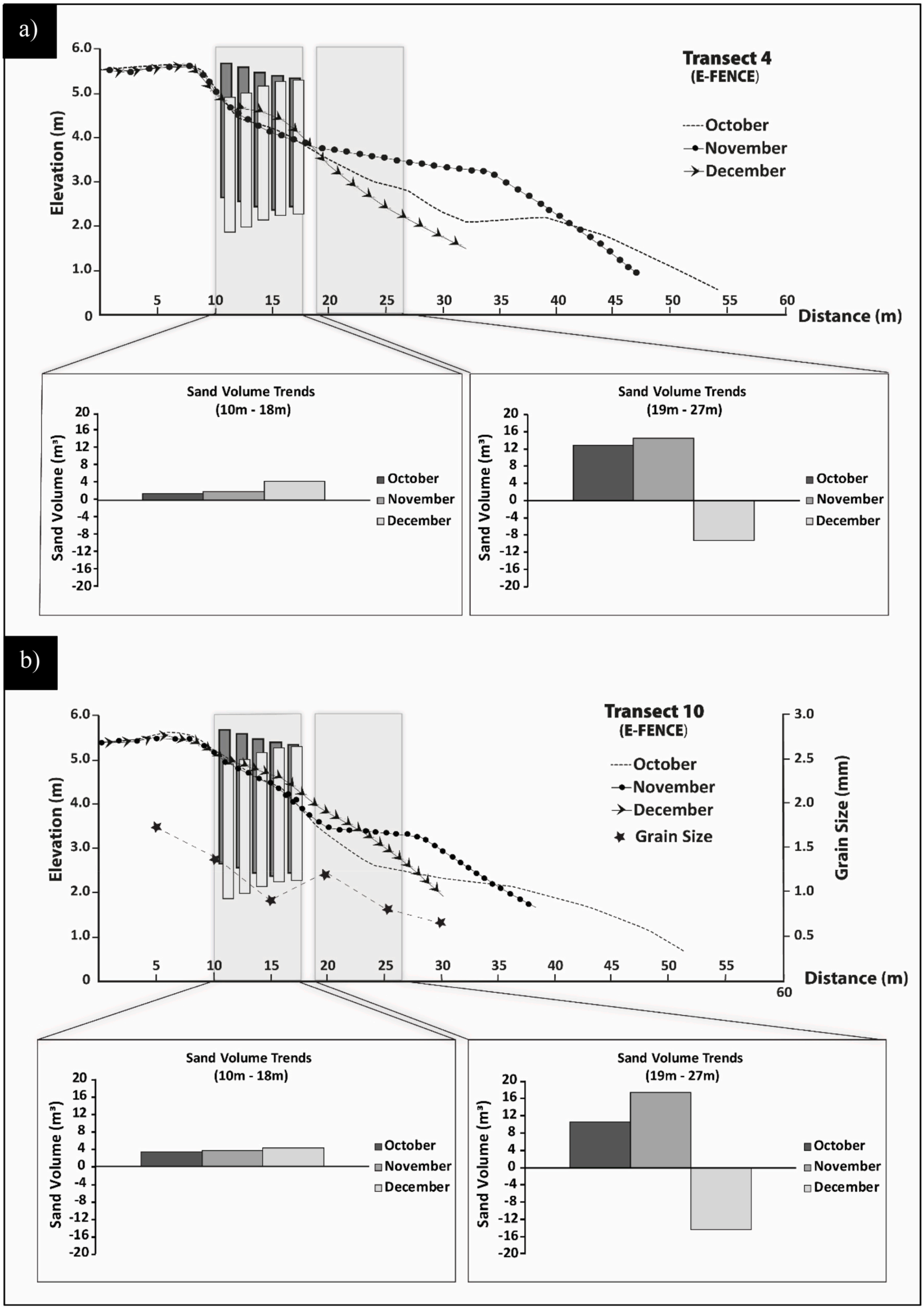

Fig. 4. Beach profile, sand volume trends, and grain size for the backshore (10 m–18 m) and the foreshore (19 m–27 m) beaches, along the E-Fence protection. a) Transects 4, and b) Transect 10.

erosion rates exceed – 5.0 m^3 along transects T4, T7, and T13. During this period, the slope measurements indicate that both the E-Fence (protected) and unprotected areas had similar moderate slopes ranging from 8° to 11° (Table 1).

4.3. Sediment distribution

Figs. 3 and 4 also illustrate D50 values of grain size analysis against distance, for E-Fence (protected: T10 transect) and unprotected (T7

Table 1
Slope measurement along different survey lines.

Months	Transect 4 (°)		Transect 10 (°)		Transect 7 (°)		Transect 13 (°)	
	10–18 m	19–27 m	10–18 m	19–27 m	10–18 m	19–27 m	10–18 m	19–27 m
October	5.3 (M)	6.4 (M)	9.0 (M)	6.5 (M)	5.8 (M)	8.8 (M)	7.7 (M)	7.5 (M)
November	4.8 (M)	2.9 (F)	8.4 (M)	3.0 (F)	5.6 (M)	3.2 (M)	6.9 (M)	2.1 (F)
December	2.0 (F)	9.8 (M)	5.7 (M)	10.3 (M)	6.0 (M)	8.5 (M)	9.2 (M)	11.0 (M)

transect) areas. Grain size distribution patterns are relatively comparable with each transect. However, the area inside the fences predominantly consists of smaller grain sizes compared to the unprotected area. For example, grain size distribution at a distance of 15 m is less than 1.0 mm and the average is less than 1.5 mm between distances from 10 to 18 m. Meanwhile, the unprotected area predominantly consists of coarse grain sands compared to the protected area, particularly greater than 1.3 mm between distances from 10 to 18 m. The implementation of fences influences the particle size distribution of sandy beach sediments, both in front of and behind the fences. Therefore, the E-Fence sorts and filters the wind-blown sand that passes through it.

4.4. Wind parameters

Fig. 5 shows the variation of wind speed across the E-Fence, during November and December. It shows that wind speed is significantly reduced across the fences in both months (Fig. 5). In addition, wind speed values are notably different in front of the fence (swash zone) and behind the fence (backshore). Accordingly, the fences slow down winds and deposit windblown sand. Furthermore, the wind speed is apparently high in November compared to December (Fig. 5). On average, the wind speed from offshore towards the sand-trapping E-Fence tends to impede from 1.3 m/s to 1.1 m/s in November and from 1.5 m/s to 1.0 m/s in December.

4.5. Simulation

Figs. 6 and 7 show conducted morphological simulations using in-situ bathymetry and topography data at Ma' Daerah, Terengganu. It illustrates the simulated bed profiles along unprotected (Transect 7) and protected (Transect 10) beaches, and it reveals a modest change in the bed level after the one-week simulation. Figs. 6 and 7 also show beach profile graphs for fence-protected and unprotected beaches. In addition, simulations indicate that erosion can be pronounced in the non-fenced area (Transect 7) compared to the protected area (Transect 10), with the presence of a fence. No significant differences can be observed for backshore erosion, but erosion was notably substantial in the swash zone. Therefore, this study highlights the significance of protective measures, such as fences, in mitigating beach erosion.

4.6. Synthesis

The overall morphology of the dune system shows significant differences between fenced and non-fenced dune sites. Sand fences deployed on the dynamic backshore have become a significant human adaptation, influencing the morphology and vegetation on the sandy beach. Sand trapping fences allow the seaward migration of the dune crest and effectively prevent wind-blown sands from moving further inland.

The presence of sand fences can alter the shape of the shoreline and affect grain size composition and slope. Similarly, previous studies have reported a correlation between mean grain size and beach-face slope [22]. Fine grain areas are associated with reduction wave energy producing lower slope angles, whereas erosion leads to higher slopes [23–26]. In this study, areas protected by the E-Fence tend to have flatter slopes between 10 and 18 m (inside the E-Fence) and fine-grain sediments. However, unprotected areas tend to have steeper slopes and coarser sediments. Wave attack tends to remove fine sand, resulting in a negative skew or coarse-grained sediments [14,27,28]. In addition, most of the coarse-grained and steep slopes are not in stable equilibrium

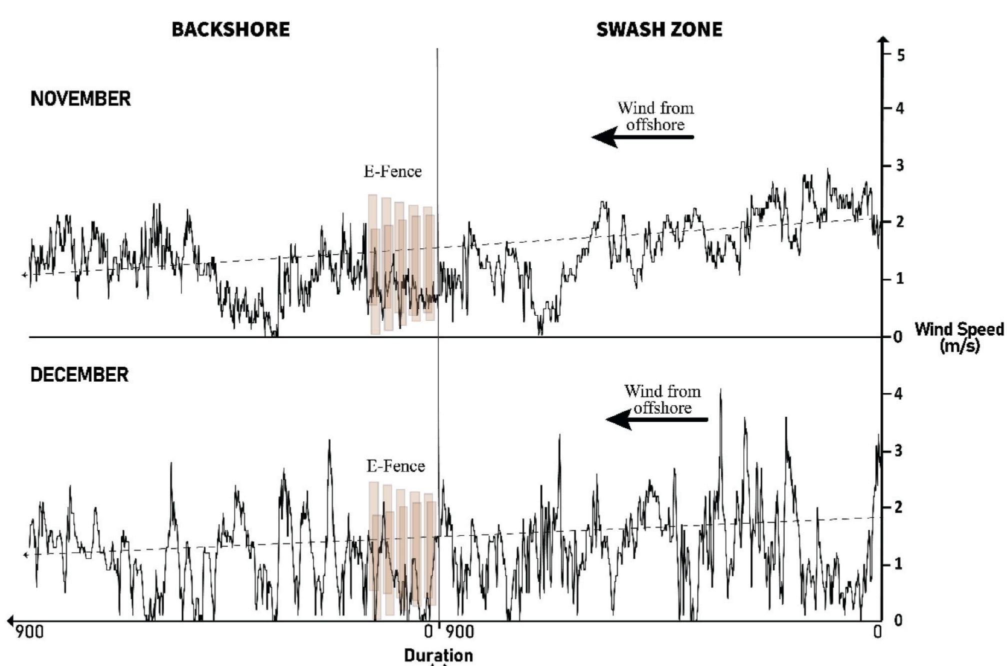

Fig. 5. Real-time wind speed in November and December 2022.

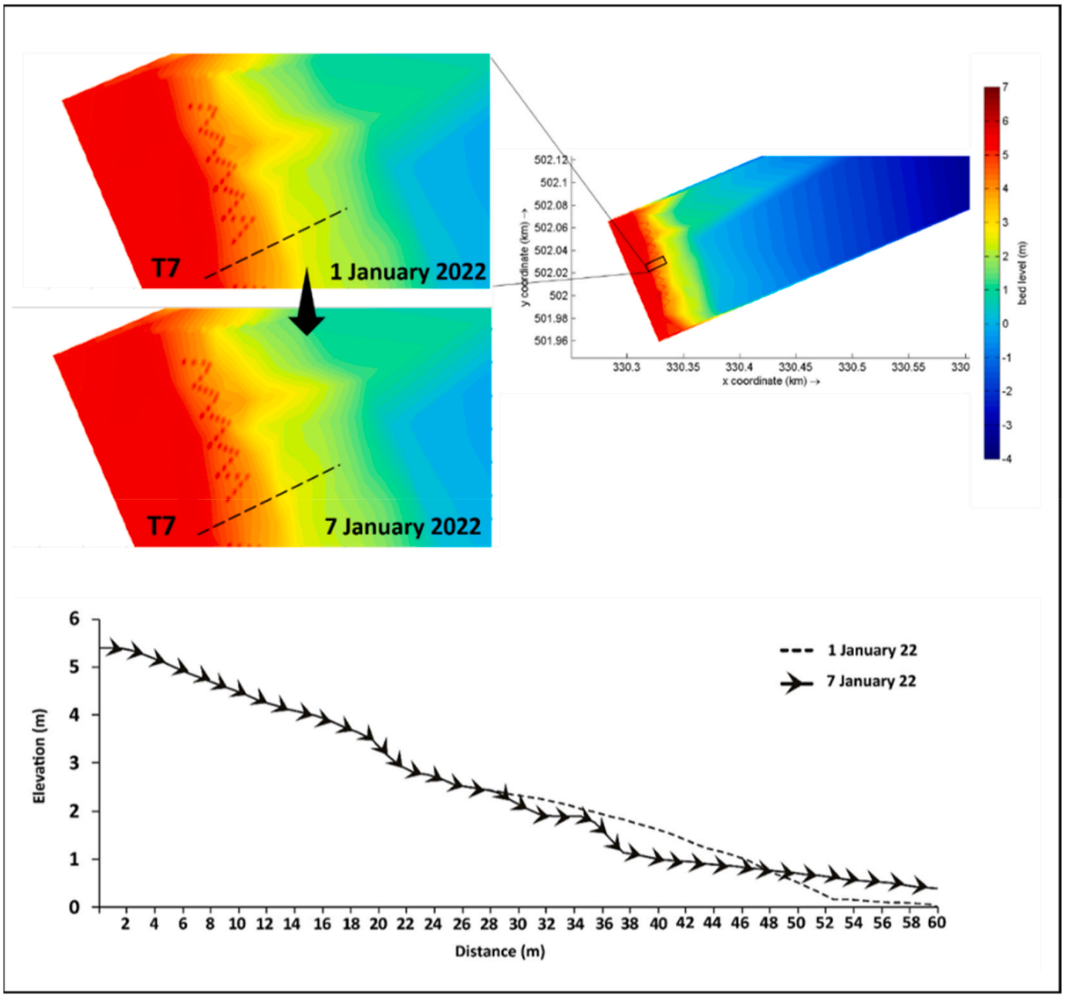

Fig. 6. Simulated coastal dynamics and extracted cross-shore profile variations, along the without E-Fence protection (Transect 7).

concerning wave conditions.

Fine sediments found inside the E-Fence are mainly due to prominent wind activities. Similarly, previous case studies also investigated the effectiveness of sand fences for sand prevention [29,30]. Those studies found that grain composition and size of sand particles varied in front and behind the fence. As wind speed decreases during onshore winds, the rate of sediment transport increases, and grain sizes get finer farther inland. Numerical simulations using XBeach show good agreement with observations, and dune morphology can be predicted after a quick initial adjustment [22].

The E-Fence, an affordable and eco-friendly structure, positively impacts dune restoration and it ensures minimal harm to coastal habitats. The E-Fence induces accretion, creating diverse microhabitats as vegetation grows around it [31]. This not only restores the natural habitat but also shapes the coastal landscape to safeguard against hazards. Accordingly, making E-Fence is a valuable tool for sustainable shoreline resilience. The E-Fences are strategically located where the highest waves hit, especially during the monsoon season, to mitigate potential erosion. Acting as an extra layer of defense, this sand trapping becomes a vital shield, attenuating wave energy and safeguarding coastal dunes [7]. The E-Fences prevent powerful storm waves from drifting away the dune through overwash and aeolian transport toward the landward side of the dune. This, in turn, halts the sediment to resist wave attack and drifting into the hinterland. However, the majority of protective structure constructions, particularly those on the downdrift side, deal with erosion issues and this is also associated with the E-Fence [32,33]. It is essential to recognize that complete erosion prevention remains unattainable, but the control of erosion rates is feasible. The E-Fence emerges as a promising solution in mitigating erosion rates. The protected areas experienced a notably reduced erosion impact, showcasing the effectiveness of the E-Fence in achieving its intended purpose.

5. Conclusions

This study identified the effectiveness of sand-trapping in restoring coastal dunes and investigated the coastal morphological process after implementing the E-Fence at Ma' Daerah, Terengganu. The E-Fence emerges as a promising solution, as evidenced by beach profile surveys showcasing dune restoration in protected areas. The grain size distribution and wind speed analyses reveal reduced wind velocities and sediment accumulation further inland under the E-Fence protection, emphasizing its role as a barrier. Although moderate to flat slopes do not indicate significant changes in terms of beach erosion and accretion, the majority of the dunes have certainly been rebuilt and preserved behind fences. However, some erosion occurs in specific transects in both protected and unprotected areas. In this study, the beach subject to waves and tides showed good agreement with the model simulation. Leveraging XBeach simulation, the study illuminates the capacity of the E-Fence to sustain against wave impact, contributing to stable coastal ecosystems. The E-Fence contributes to more economical coastal erosion mitigation by providing a sustainable solution that reduces the need for costly interventions, while effectively preserving and restoring coastal dunes. This research not only demonstrates the effectiveness of E-Fence but also hints at the potential as a cost-effective strategy, not only in

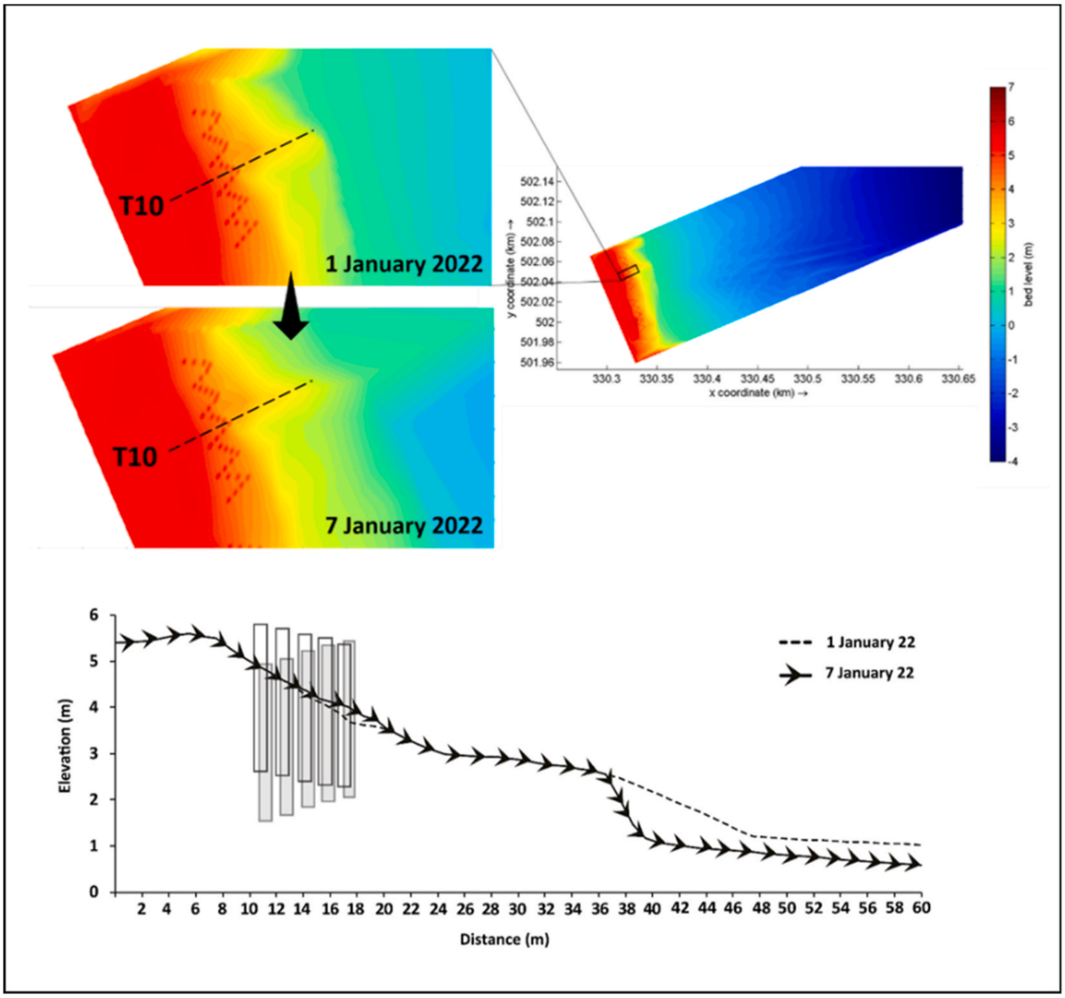

Fig. 7. Simulated coastal dynamics and extracted cross-shore profile variations, along the E-Fence protection (Transect 10).

Malaysia but also for global coastal erosion mitigation. The limitation lies heavily in the implementation of hard structures, which can exacerbate future erosion issues, emphasizing the need for a shift toward sustainable protection methods. The future outlook involves refining and implementing such sustainable measures for holistic coastal protection.

Declaration and verifications

Not applicable.

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CRediT authorship contribution statement

Siti Nur Hanani Zainuddin: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft. **Effi Helmy Ariffin:** Methodology, Writing – review & editing, Conceptualization, Supervision, Writing – original draft. **Puteri Nurfarah Adawiyah Taslin:** Resources, Validation, Writing – review & editing. **Wan Shiao Dong:** Resources, Validation, Writing – review & editing. **Muhammad Zahir Ramli:** Supervision, Writing – review & editing. **Khairul Nizam Abdul Maulud:** Writing – review & editing. **Nor Aslinda Awang:** Supervision, Writing – review & editing. **Muhammad Izuan Nadzri:** Writing – review & editing. **Muhammad Shazril Idris Ibrahim:** Writing – review & editing. **Amila Sandaruwan Ratnayake:** Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Effi Helmy Ariffin reports financial support was provided by Malaysia Ministry of Higher Education. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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