Research Article

Erosion processes driven by monsoon events after a beach nourishment and breakwater construction at Uswetakeiyawa beach, Sri Lanka

Nalin Prasanna Ratnayake[1] · Amila Sandaruwan Ratnayake[1,2] · Rukshan M. Azoor[1] · Shanaka Maduranga Weththasinghe[1] · Indunil De J. Seneviratne[1] · Nilupul Senarathne[3] · Ranjith Premasiri[1] · Nimila Dushyantha[1]

Abstract

The first beach nourishment project in Sri Lanka was carried out in 2012 over a 1.8-km stretch in the Uswetakeiyawa area by the Coast Conservation Department. About 300,000 m^3 of offshore sand in the Indian Ocean was pumped using a dredging vessel for the nourishment. Three breakwaters were constructed nearly 1 year after the beach nourishment. This research was carried out to analyze the performance of the above soft and hard engineering coastal protection strategies. Beach profiles and grain size data were collected over a 1-year period. This monitoring program covered entire seasonal cycles with a comparison to the pre-nourishment beach profiles. Satellite images were also analyzed spanning much larger time periods from 2010 to 2015. Beach profile data indicated both sand accretion and erosion in the nourished area. However, the variations of sand deposition showed enhancement of the sand volume. Satellite images indicated the irregular changes of the beach profiles after the construction of breakwaters. The field observations and calculated relationships of the breakwaters demonstrated either subdued salient or gap erosion at the specific locations of the nourished beach. In this study, no permanent or periodic tombolo formations were observed at Uswetakeiyawa beach. The lack of sediment supply from longshore currents and the high-energy cross-shore monsoon currents can enhance coastal erosion related to the presence of the breakwater.

Keywords Coastal erosion · Coastal protection · Beach nourishment · Breakwaters · Indian Ocean · Sri Lanka

1 Introduction

Sri Lanka, being an island country in the Indian Ocean, relies heavily upon its coast for economic, domestic, recreational and tourism activities [5, 26, 46]. Coastal erosion is one of the major challenges in this regard [18, 38], and the Coast Conservation Department of Sri Lanka was established to undertake coastal protection and management schemes. The Coast Conservation Department initially gave priority to constructing hard engineering structures for preventing coastal erosion in the west to southwest coasts of Sri Lanka over the past few decades, but this would generally enhance down-drift erosion and reduce the economic value of the coasts [18, 24, 46]. However, in this scenario, beach nourishment can be considered a suitable coastal management strategy for stakeholders and communities [4, 6, 23]. Beach nourishment can be simply identified as a soft engineering solution for shoreline stabilization in areas that are affected by a reduction of sand owing to either natural or man-made reasons [8, 21, 22]. In contrast, breakwaters are recognized as hard engineering

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✉ Amila Sandaruwan Ratnayake, as_ratnayake@uwu.ac.lk | [1]Department of Earth Resources Engineering, Faculty of Engineering, University of Moratuwa, Moratuwa, Sri Lanka. [2]Faculty of Science and Technology, Uva Wellassa University, Passara Road, Badulla 90000, Sri Lanka. [3]Lanka Hydraulic Institute Ltd., No. 177, John Rodrigo Mawatha, Katubedda, Moratuwa, Sri Lanka.

SN Applied Sciences (2019) 1:52 | https://doi.org/10.1007/s42452-018-0050-7

Received: 2 July 2018 / Accepted: 9 November 2018 / Published online: 20 November 2018

structures to protect an anchorage and nourished beaches from both weather and longshore drift [29, 41, 47].

The performance of beach nourishment is largely site specific because coastal geomorphology can be controlled by several factors such as meteorologic (seasonality), oceanographic, geologic and anthropogenic processes in the particular region [2–4, 23, 51]. Performance analyses of beach nourishment and breakwater constructions have been performed in many parts of the world (e.g., [9, 16, 17, 23]), but few studies have been carried out on the Indian Ocean. In this study, the authors examine dynamic changes in coastal geomorphology along the first nourished beach project in Sri Lanka. Therefore, the performance analysis of the beach nourishment program and associated breakwater structures offers detailed information on the longevity of the project.

2 Methodology

2.1 Study area

Sri Lanka consists of an approximately 1600-km-long coastline characterized by different geomorphologic features such as bays, lagoons, headlands and spits sandbars [12, 26, 35]. The coastline of Sri Lanka is also associated with diverse coastal habitats such as mangroves, salt marshes, sea-grass beds, sand dunes and coral reefs [12, 37, 39].

2.1.1 Location and background

The study area, named Uswetakeiyawa, is located about 10 km north of Colombo on the western coast of Sri Lanka. It is bordered to the north by Negombo Lagoon and to the south by the Kelani River (Fig. 1a). Uswetakeiyawa is a generally straight beach extending in the north-south direction. Kelani River is one of the main rivers in Sri Lanka

Fig. 1 **a** Map of Sri Lanka shows the location of the study area. **b** Google Earth satellite images (Digital Globe) show seven transects along this micro-tidal beach [blue lines represent the distance between the mean sea level and benchmark on 10 March 2010 and these line lengths are constant in the right-hand side (on 22 December 2015) photograph]. **c** Photos show waves breaking at beach rocks near location 6 (beach rocks are marked by black dots on the left-hand side photograph)

and falls a few kilometers to the south of the study area (Fig. 1a). The Kelani River can be identified as the main terrestrial sediment source on the western coast of Sri Lanka. However, Uswetakeiyawa beach has been subjected to severe coastal erosion since 2000, followed by a weakening of the sediment supply because of extensive sand mining in the Kelani River, construction of the Colombo fishery harbor and development of a saltwater barrier across the Kelani River. Previous studies clearly suggested that the coastal structures along with the sand mining in the rivers have reduced the supply of sand for developing a healthy system of beaches in the western coastal region of Sri Lanka [14, 31].

The Coast Conservation Department, the government arm for managing the coast, decided to artificially nourish the study area because of its potential as a tourist hub and use as a pilot project for future beach nourishment programs. Therefore, Sri Lanka's first beach nourishment program was carried out at Uswetakeiyawa (Fig. 1a). In this beach nourishment project, about 300,000 m^3 of offshore sand was pumped using a dredging vessel over a 1.8-km stretch at the Uswetakeiyawa coast in January 2012. The beach nourishment was carried out using offshore sand dredged from the nearby shelf area using a dredging vessel. The dredged sand was then pumped using pipelines onto the desired area as slurry and spread using land-moving machines. Beach nourishment was performed from the top of the berm to the water level using sediments with an average grain size of 0.50 mm. Three breakwaters were constructed (nearly 1 year after the beach nourishment program) along Uswetakeiyawa beach to dissipate the incoming wave energy and protect the nourished stretch.

2.1.2 Physiography

Sri Lanka experiences two main monsoon periods: the southwest monsoon (from May to September) and northeast monsoon (from December to February) [53]. There are also two inter-monsoon periods of the first inter-monsoon season (from March to April) and second inter-monsoon season (from October to November) [53]. The average annual rainfall in the study area is approximately 2025 mm [33], and the rainfall is mainly received during the southwest monsoon.

The southwest monsoon winds generate high-energy steep waves along the south to northwest coastlines of Sri Lanka [42, 44]. The high-energy steep waves reduce the beach width and flatten the inter-tidal beach face during the southwest monsoon. Therefore, the beaches along the south to northwest coasts of Sri Lanka tend to erode and deposit beach sediments in the wave breaker zone. The eroded narrow beaches generally consist of coarse-grained sand. In addition, the longshore currents carry sediments mainly toward the north during the southwest monsoon [10, 44]. The predominant northward sediment transport is characterized by many sand spits extending from south to north in the western and northwestern coastal regions in Sri Lanka. In contrast, the wave climate is much calmer during the northeast monsoon along the south to northwest coasts of Sri Lanka. In this period, the arrivals of low flat swells promote the accumulation of sand and the growth of the beach. Therefore, the resulting beach profiles are concave upward with broader berms and wider beaches. The longshore currents carry sediments mainly toward the south direction during the northeast monsoon [42, 44]. In contrast, the tide amplitude has no direct influence to change the coastal geomorphology of the study area as the maximum tidal range is < 50 cm in this micro-tidal region [32, 33, 36].

The initial beach geomorphology (i.e., before the nourishment project) of the study area was characterized by the presence of beach rock (calcareous sandstone) along the beach face extending a few meters toward the surf zone with some coarse sand beds in the backshore area. The study area is presently characterized by sandy beaches and exposed beach rocks in a few locations. Beach sediments are mainly composed of quartz with a few percentages of heavy minerals such as ilmenite, rutile, zircon, garnet and monazite. The grain size generally varies from fine to coarse-grained sand.

2.2 Materials and methods

2.2.1 Geomorphologic survey

The beach profile survey was carried out along seven transects spaced at approximately 150-m intervals over the nourished area. These survey lines were established perpendicular to the shoreline and surveyed at 1-m intervals on the beach and below the waterline, with the permanent benchmark located in the backshore (Fig. 1b). The dry beach was surveyed using a Leica Total Station instrument. The nearshore zone below the mean sea level was surveyed using a Leica Dumpy Level instrument. The elevation changes were estimated with respect to the permanent benchmark and wet-dry boundary (e.g., [38]). Positioning was carried out using the Navcom SF3040 GPS system with a continuously operating reference station system (SLCORSnet, service provider Sri Lanka Survey Department). The horizontal accuracy was 1 cm and vertical accuracy 2 cm. The beach profile surveys were conducted at the same locations over five field surveys covering all monsoon cycles from September 2014 to September 2015. These five field surveys cover all representative seasonal events (first survey during the southwest monsoon: September 2014; second survey during the second inter-monsoon: December 2014; third survey during the northeast monsoon: January 2015; fourth survey during the first inter-monsoon: March 2015; final survey again during the southwest monsoon: September 2015) (Table 1). These five consecutive field surveys were conducted nearly 32, 35, 36, 38 and 44 months after the beach nourishment program.

The gathered beach profile data were tabulated to obtain variations in elevation for each survey. The elevation data were exported to the Golden Software Surfer 10 software package. The volume of sand above the mean sea level and changes in sand volume were calculated. The present field data were compared with the Uswetakeyiyawa beach profile data before the nourishment (unpublished National Hydrographic Office Metric Sheet No. MISC. 004/11), conducted by the National Aquatic Resources and Research Development Agency (NARA), Sri Lanka.

Google Earth (Digital Globe) images ($n=17$) were also used to estimate beach width variations qualitatively over a longer time span, covering the pre-nourishment duration (from 2010 to 2011) and post-nourishment (from 2012) and after the construction of the breakwaters (from 2013 to 2015). A baseline was constructed on the master image to extract beach width data along each transect. The present results were compared with the actual field data (i.e., beach profile survey) for determining the validity of estimations. The high-resolution Google Earth images were productively used to calculate the distance from these baselines at different time periods along this micro-tidal coast. In addition, the large shoreline changes (> 10 m/year) could be more accurate compared with the minor shoreline changes (< 1 m/year). Therefore, the general trends of beach width variations before the beach nourishment and the breakwater construction and after the breakwater construction using the high-resolution Google Earth images were considered.

Surface sediments were collected along each transect at positions of the surf zone, mean sea level and berm top. Sediment samples were air dried for 48 h and then dried in an oven at 105 °C for 24 h. Dried samples were coned, quartered and sieved using a standard set, with sieve sizes ranging from 0.075 to 2 mm. Grain size statistics were analyzed using the GRADISTAT software package [7].

2.2.2 Wave data analysis

The Inter Ocean S4DW electromagnetic current meter was used to measure multiple wave parameters such as average wave height, peak wave period and wave direction on the western coast of Sri Lanka (e.g., [11, 50]). The current meter is designed to measure the true magnitude and direction of horizontal current motion (e.g., [11, 50]). The instrument was programmed to measure the wave-induced pressure at a frequency of 2 Hz with a sampling period of 20 min, which was carried out over 3-h intervals. The instrument was deployed at the outer surf zone (water depth = 16 m) covering all monsoon cycles from 1 June 2014 to 12 September 2015. The fundamental wave parameters such as average wavelength, wave celerity, maximum horizontal and vertical velocities, and energy flux were derived using the wave data analysis software of the SWELLBEAT numerical wave model (e.g., [52]).

Table 1 Measured and calculated summary of the wave data from 1 June 2014 to 12 September 2015 in the western coast of Sri Lanka

	First field survey (2014-09-24)	Second field survey (2014-12-05)	Third field survey (2015-01-28)	Fourth field survey (2015-03-04)	Fifth field survey (2015-09-14)
Mean wave length (m)	33.28	33.18	29.35	31.99	37.09
Wave celerity (m/s)	6.19	6.18	6.02	6.14	6.32
Maximum horizontal velocity (m/s)	0.51	0.35	0.24	0.18	0.55
Maximum vertical velocity (m/s)	0.38	0.26	0.19	0.13	0.38
Mass flux (kg/ms)	83.9	39.22	18.29	9.88	98.78
Energy flux (W/m)	2545.4	1187.17	500.04	290.66	3244.94
Average Hs (m)	0.91	0.622	0.419	0.311	0.998
Average Tp (s)	6.255	6.24	5.672	6.06	6.824
Monsoon period	Southwest monsoon	Second inter-monsoon	Northeast monsoon	First inter-monsoon	Southwest monsoon

Hs average wave height; *Tp* peak wave period

3 Results and discussion

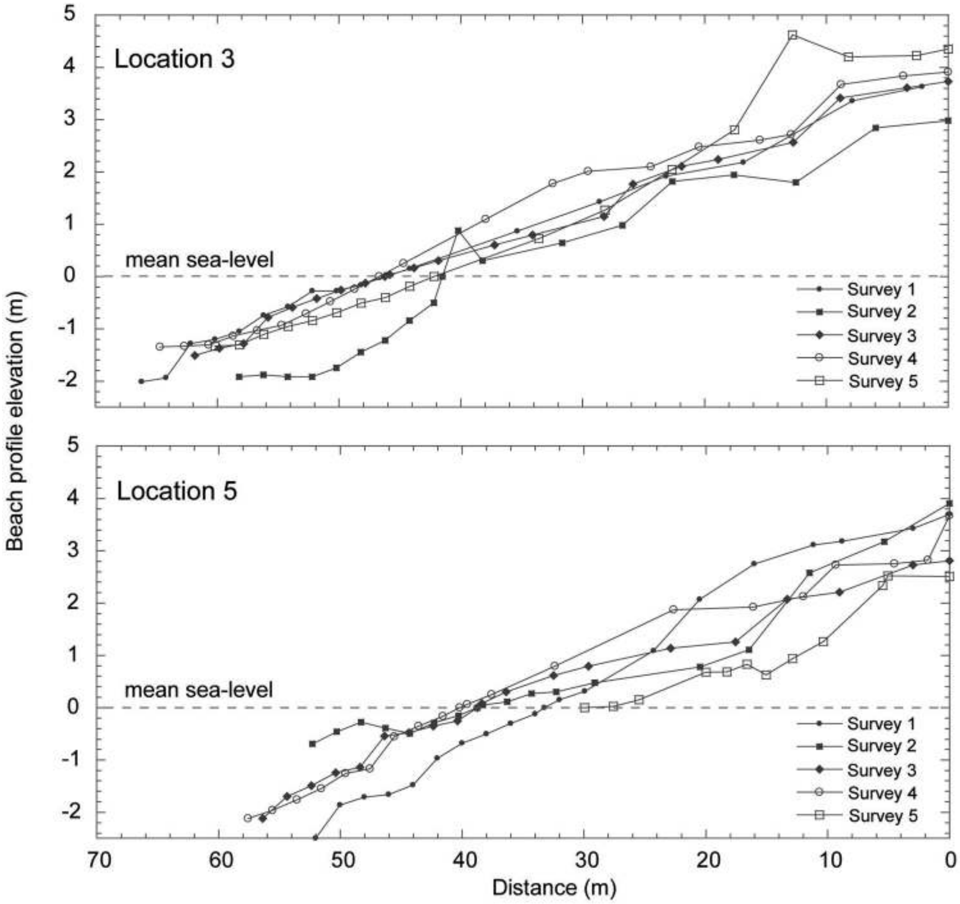
3.1 Geomorphologic changes

The geomorphologic processes in the coastal zone are primarily controlled by the magnitude of energy contained in waves (i.e., a hydrodynamic process) [15, 27, 28, 54]. Figure 1b illustrates the beach accretion and erosion events after the nourishment program and breakwater construction and prior to the nourishment program. Locations L1 and L6 are sheltered from breakwaters, whereas the other locations are exposed. The sheltered areas show the formation of salient features due to the sheltering effect of the breakwater structures. Similarly, Fig. 2 shows clear changes in the coastal geomorphology during the monitoring period. The spatial and temporal variations of beach profiles in the study area show irregular patterns of both erosion (e.g., location 5 in Fig. 2) and accretion (e.g., location 3 in Fig. 2) after analyzing the beach width and beach-face steepness variations with respect to the sheltering effect and monsoon seasonality. Therefore, each location indicates very distinct alongshore morphologic responses. Field surveys 1 and 5 indicate high-energy wave actions during the southwest monsoon. Most of the beaches on the west coast show narrower and steeper beaches during the southwest monsoon and wider and less steep beaches during the northeast monsoon [38].

The total values of measured beach widths (i.e., the distance between the benchmark and mean sea level) were calculated for all locations during each field survey and compared with the initial field survey as a reference (Fig. 3). The second survey shows a clear beach width reduction and relatively minor erosion during the next consecutive field surveys (Fig. 3) compared with the initial survey. Therefore, the net reduction of beach widths can suggest an overall beach degradation and/or changes in the regularity of the beach (Fig. 3).

Figure 4 shows a gradual decrease in the calculated sand volumes during the first three field surveys and then an increase in the fourth and fifth field surveys. However, sand volume changes (Fig. 4) are opposed to the overall beach width variations in the study area (Fig. 3). This is followed by the observed sand accretion (development of salient) and gap erosion at only specific locations (Fig. 1b). In addition, the final sand volume over the measurement period is greater than the calculated value for

Fig. 2 Representative beach elevation profiles for locations 3 and 5



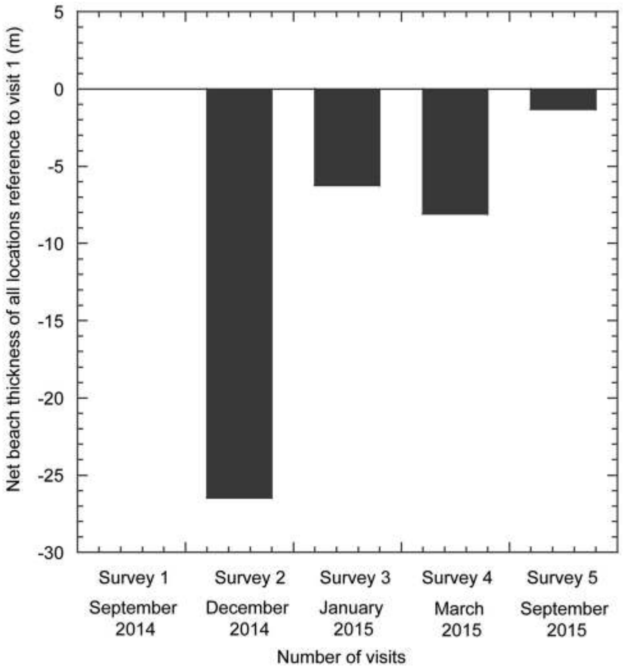


Fig. 3 Total values of measured beach widths for all locations with reference to the first field survey

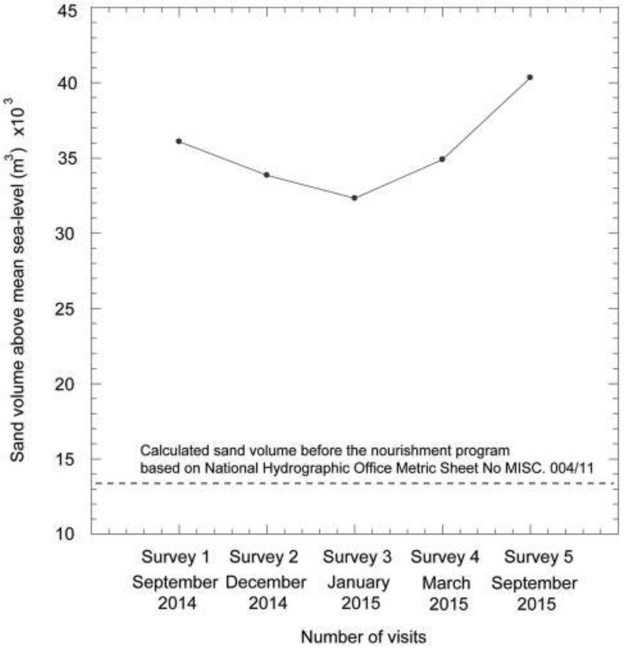


Fig. 4 The calculated sand volumes above the mean sea level based on beach profile survey data

the referenced survey (Fig. 4). Although the study area is subjected to irregular changes in coastal geomorphology, these calculations signify the overall enhancement of sand volume at the end of all field surveys. It is also consistent with long-term beach width evolution based on satellite images, as discussed below.

The long-term beach width evolutions based on satellite images show a slight increment in the beach width after the nourishment program (Fig. 5). However, the beach widths have shown irregular changes after the construction of breakwaters roughly 1 year after the completion of the nourishment program (Fig. 5). The irregular changes involve rapid erosion and/or sand accretion in certain locations (Fig. 5).

The variations of cross-shore grain sizes show that the average grain size at the berm top is clearly finer (average = 0.53 mm) than the samples from the mean sea level (average = 0.66 mm) and surf zone (average = 0.57 mm) (Fig. 6). The berm top is the topmost layer of the beach and remains undisturbed by waves and tides. Therefore, the berm top samples can indicate the sands used for the beach nourishment. It is generally accepted that the nourishing sands should be approximately equal to or coarser than the native beach grain size [9, 23, 51]. Therefore, the grain size of the nourished sand used in the project was partially ineffective. In addition, sand grains at the surf zone are in constant motion due to longshore currents. According to Ratnayake et al. [38], sand transportation in the southwest to the west coasts of Sri Lanka is mainly controlled by prominent longshore currents during the southwest monsoon.

3.2 Wave parameters and retention structures

Figure 7 shows the recorded wave heights for the complete annual monsoon cycle. The average wave height (Hs) is clearly high during the southwest monsoon compared with the northeast monsoon and inter-monsoon periods (Table 1 and Fig. 7). The maximum horizontal velocity (average = 0.53 ms^{-1}) and energy flux (average = 2895 Wm^{-1}) are also remarkably high during the southwest monsoon (Table 1). Similarly, Fig. 8 shows high wave action perpendicular to the west during the southwest monsoon. Therefore, the exposed areas of the breakwater are more vulnerable to coastal erosion. In addition, the prominent monsoon-derived longshore currents can rapidly erode both sheltered and exposed areas of the breakwater during the southwest monsoon. The comprehensive wave measurements (i.e., at least over a 1-year monitoring period) are required to design sand retention structures such as breakwaters to enhance the longevity of beach nourishment [17, 20, 27].

Different empirical relationships have been used in designing breakwaters such as the breakwater length/distance to shore (*L*/*D*) ratio, gap between breakwaters/

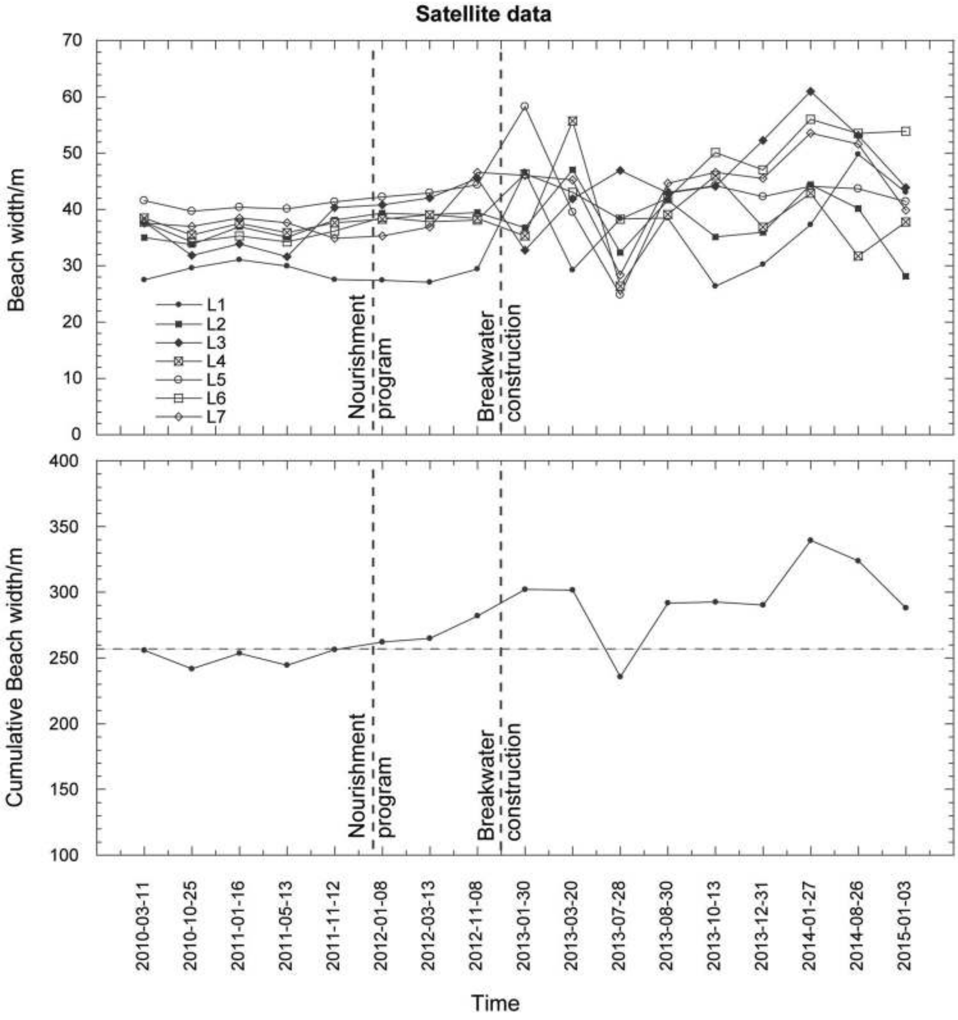


Fig. 5 Long-term individual beach width/cumulative beach width changes based on satellite images (from 11 March 2010 to 3 January 2015)

distance to shore (L_{gap}/D) ratio and distance to shore/water depth at structure (D/d) ratio [1, 30, 40, 43, 47]. These proxies can be used to predict depositional patterns (e.g., permanent tombolo, periodic tombolo, well-developed salients, subdued salients and no sinuosity) and erosional possibilities (e.g., no erosion, possible erosion and certain erosion) due to the breakwater structures [19, 25, 34, 45]. The parameters of the length of breakwaters (L), distance to shore (D) and gap between breakwaters (L_{gap}) are 60, 95 and 200 m, respectively. In addition, the average water depth at the breakwaters and calculated annual average wavelength are 5 and 32.98 m, respectively.

The calculated L/D value of 0.63 suggests a weak to well-developed landform projecting outwards/upwards from its surrounding (termed a salient) (e.g., [40, 45]), as observed in this study. The beach response index (I_S) is calculated to be 3.97 according to the Ahrens and Cox [1] equation of $I_S = \exp\ (1.72–0.41\ (L/D))$, suggesting a subdued salient. The ($L/L_{gap} = 0.30$) and ($D/d = 19$) relationships also show occurrence of a salient. Seiji et al. [43] developed erosional relationships after observation of over 1500 breakwaters in Japan. Therefore, the L_{gap}/D ratio of 2.11 suggests major erosion opposite to the gap of breakwaters, as observed in this study. The above-calculated proxies suggested that no major depositional features such as a permanent or periodic tombolo can be formed in the study area (e.g., [13, 43, 48, 49]). Therefore, all these interpretations are very closely consistent with the observed present physical geomorphology of the study area (Fig. 1b).

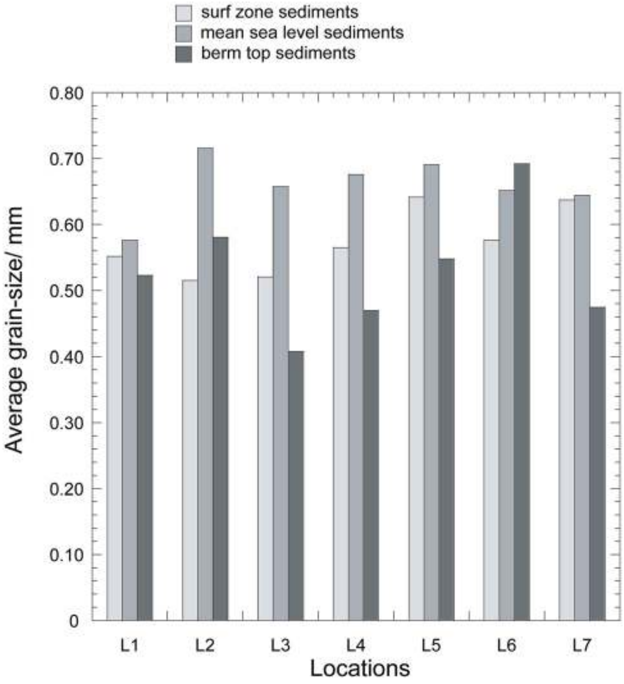


Fig. 6 Comparison of average grain sizes at the surf zone, mean sea level and berm top sediments

4 Conclusions

Beach profile variations showed both sand accretion and erosion. The cumulative sand volume variations showed an enhancement of sand volume at the end of last field survey. Similarly, the long-term beach width evolution demonstrated irregular variations after the construction of the breakwaters along this coast. The longshore currents and sediment transport play an important role in the beach morphologic equilibrium. The accretion/erosion patterns observed in the profiles are likely to be related to calm/energetic wave conditions, while the different responses observed in the profiles due to the alongshore variability of the beach were related to the presence of the breakwaters. The shoreline response suggested that development of a subdued salient opposite the breakwaters and certain erosion opposite to the gap of breakwaters. By observing historical Google Earth images at this location, it is possible to identify that the region in the south of the study site has been suffering severe modifications such as the construction of large engineering structures (breakwaters, jetties and ports). The changes observed at the study site are thus related to the blocking of longshore sediment transport during

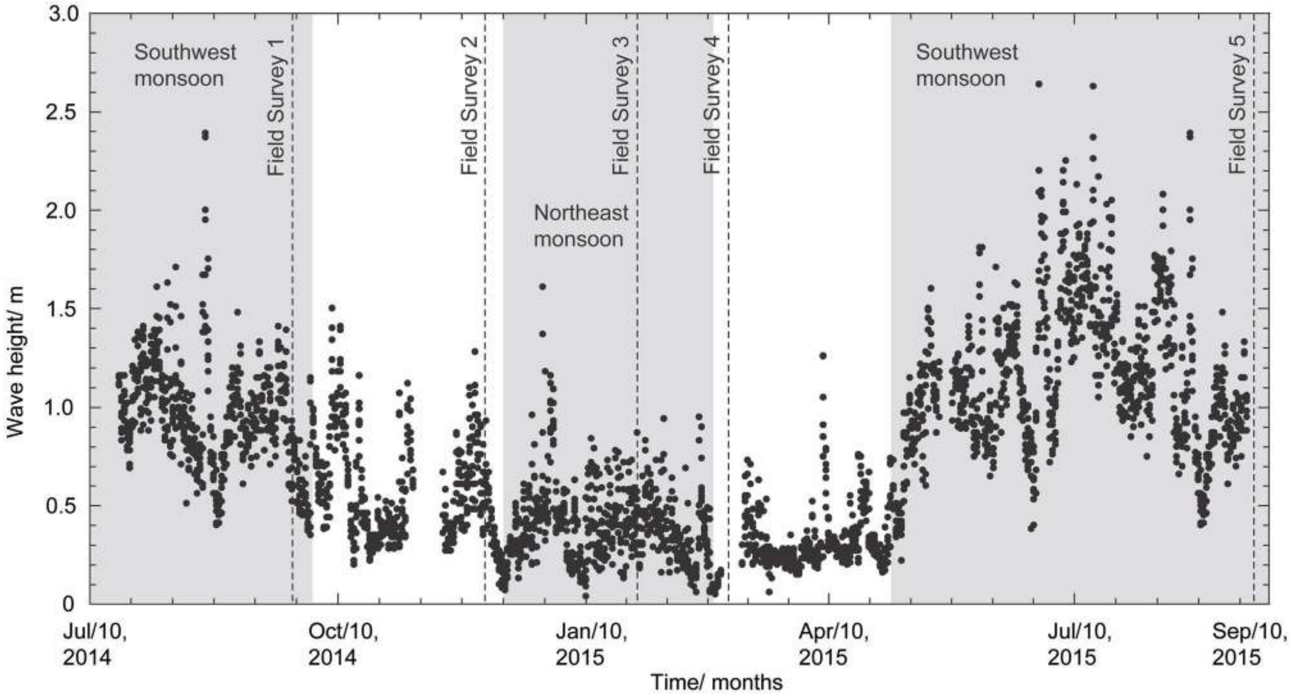


Fig. 7 Wave height variations from 1 June 2014 to 12 September 2015 on the west coast of Sri Lanka

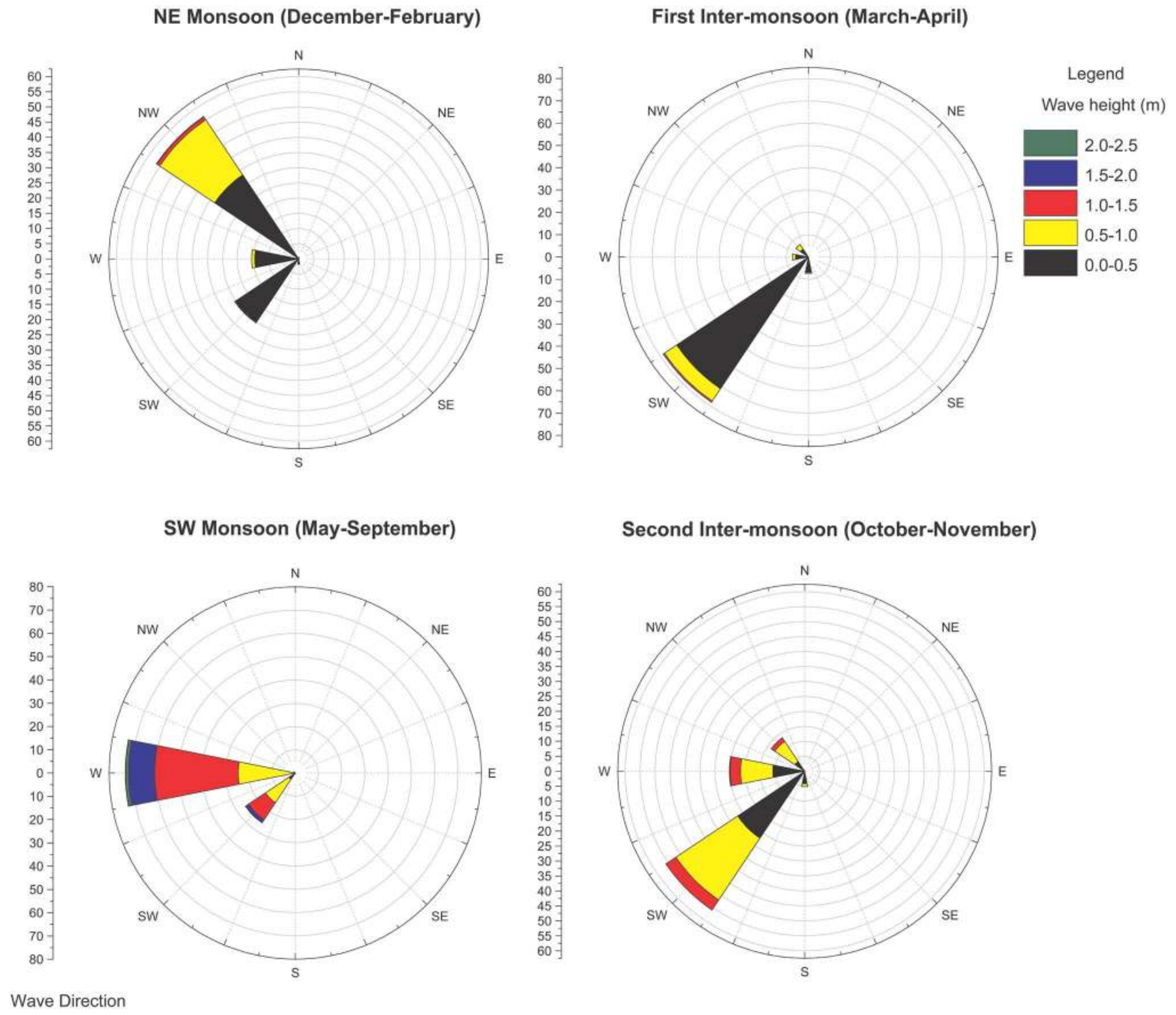


Fig. 8 Direction and frequency of wave data from 1 June 2014 to 12 September 2015

the most energetic southwest monsoon waves due to the presence of impermeable structures.

Funding This study was financially supported by the University of Moratuwa Senate Research Capital Grant (grant no. SRC/CAP/14/03) to the first author. We thank Bandula Wickramarachchi, Ranjani Amarasinghe and Sadun Silva for coordinating the research project. We also extend our gratitude to R. Saranya, P. Thenugaadevy, G.S.M. Gamage, R. Chandrajith and P. Weerakoon for assisting with the field and laboratory work. We greatly acknowledge the Coastal Conservation Department, National Aquatic Resources and Research Development Agency (NARA) and Irrigation Department, Sri Lanka. We acknowledge two anonymous reviewers for their very constructive and helpful comments on an earlier draft of this manuscript. We also acknowledge Dr. Benjamin Shannon (Monash University, Australia) for valuable comments and editorial suggestions.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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