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ORIGINAL PAPER

Significance of nearshore wave parameters in identifying vulnerable zones during storm and normal conditions along Visakhapatnam coast, India

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Abstract The nearshore parameters, viz., wave runup, wave setup, and wave energy have been estimated during storm and normal conditions of SW monsoon (June–September) and NE monsoon (November–February) by empirical parameterization along Visakhapatnam coast. These results were compared with the field observations during three storms of SW monsoon season in the year 2007. The higher nearshore wave energies were observed at R.K. Beach, Jodugullapalem beach, and Sagarnagar beach during both the seasons. During storm events, the higher wave energies associated with higher wave runups cause severe erosion along the wave convergence zones. The storm wave runups (SWRUs) were higher at R.K. Beach, Palm beach, Jodugullapalem beach, and Sagarnagar Beach. The yearly low wave energy was observed at Lawson's Bay with lowest wave runup, considered as safest zone. R.K. Beach, Palm beach, and Jodugullapalem beach are identified as vulnerable zones of wave attack. It is noteworthy that in addition to wave energies, wave runups and wave setups also play a vital role in endangering the coast.

Keywords Wave energy · Wave runup · Wave setup · Vulnerable zones · Erosion · Storms · Monsoon

1 Introduction

Sandy beaches along most of the shorelines of the world exhibit variations in their geometric form over different time scales in response to the prevailing dynamic forces due to

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waves, tides, and associated currents. They function as a natural sediment buffer for coastal systems. The periods and intensity of erosion and accretion alternate over time and are generally coupled to nearshore wave conditions. The wave action on the coast depends on deep-water wave climate and its complex transformation processes in the nearshore. Depth-induced shallow water wave refraction has significant influence in wave attenuation and in turn the distribution of wave energy. One of the significant wave parameters, the wave runup, is defined as the maximum vertical extent of wave uprush on a beach or structure above the still water level (SWL) (Sorenson 1997). The wave runup on dissipative beaches depends primarily on the deep-water significant wave height, wave period, and beach slope (Ruggiero et al. 2001). The impact of wave parameters was studied by many researchers (Hunt 1959; Battjes 1974; Mase 1989; Nielson and Hanslow 1991; Ahrens and Seelig 1996; Stockdon et al. 2006, 2007) and developed empirical equations to wave runup in laboratory and/or natural conditions. The estimation of wave runup on natural beaches is important in the design of artificial fill beaches as well as to estimation of flood structural damages on existing beaches (CERC 1995) and harbor-armored structures. Intensive work had been done (Bowen et al. 1968; Dolan and Hayden 1981; Leatherman 1981; Dolan and Davis 1994; Lee et al. 1998; Cleary et al. 1999; Sallenger 2000; Ruggiero et al. 2001; Elko et al. 2002; Doughty et al. 2004; Sallenger et al. 2004; Fauver 2005; Stockdon et al. 2006, 2007) in bringing out storm-driven variability over the natural beaches in terms of wave runup, extreme water levels, and erosional features. During storms, increased water levels shift runup and the location of wave attack higher on the profile, making berms and dunes more vulnerable to erosion and over-tapping (Stockdon et al. 2007). The storm-induced water levels are the sum of astronomical tide, storm surge, and wave runup (Sallenger 2000).

The frequency of tropical cyclones in the north Indian Ocean has registered increasing trends (Singh et al. 2001; Bhaskar Rao et al. 2001) during November and May, which account for maximum number of intense cyclones and are diminished considerably during June and September. The possibility of occurrence of cyclones is more over Bay of Bengal than that of the Arabian Sea (Table 1). The premonsoon month May and postmonsoon months October and November are most susceptible to severe cyclones. Deep depressions and Depressions will be occurred frequently during SW monsoon with a maximum occurrence during August month. The NE monsoon season can be treated as calm season with fewer occurrences of storms. During spring (April–May) and fall (October–December) seasons, the region between 10° and 15° N gives rise to several depressions; some develop into storms, while few intensify into severe storms. Usually they move toward northwest and strike the coasts of Andhra Pradesh and Orissa (Mohanty et al. 2008). During postmonsoon (October–November) season, most of the storms cross 17° N and move north to north-east. Hence, a major part of the east coast is vulnerable to storms during most part of the year except during calm conditions. The nearshore region is more susceptible to dangerous waves during storm events. Moreover, because of the complexity arises in the wave and current patterns, this region is difficult to study and interpret. Hence, the wave conditions can be estimated using empirical parameterization which reduces the complexity to some extent and helps in understanding the phenomena. The aim of this article is to estimate nearshore wave parameters and to identify the vulnerable zones by applying empirical approaches of wave runup during storm and normal conditions in south-west (SW) monsoon and north-east (NE) monsoon seasons along Visakhapatnam coast.

Table 1 Number of depressions (D), storms (S) and severe storms (SS) over Bay of Bengal and Arabian Sea from 1877 to 2000

Month	Bay of Bengal			Arabian Sea		
	D	S	SS	D	S	SS
January	8	4	1	1	1	9
February	3	1	2	9	9	9
March	2	2	3	9	9	9
April	8	11	9	2	2	4
May	29	17	39	5	6	15
June	75	39	7	15	7	11
July	119	41	8	4	1	9
August	157	29	5	1	2	9
September	135	31	18	1	5	2
October	97	54	39	3	15	10
November	48	51	70	11	4	16
December	34	26	22	3	4	3

Sources: IMD (1979) and Mausam journals from 1980 to 2000

2 Study area

Visakhapatnam coast (17°41′34″ N and 83°17′45″ E) located in the northern part of Coastal Andhra Pradesh, India, is selected for this study (Fig. 1). The study area comprises of 12-km long stretch from Coastal Battery to Rushikonda beach, which is a main zone for recreational activity. About 35 stations are selected with equal spacing along this stretch to observe the impact of waves with the varying nearshore and shoreline characteristics on the beach. The coastline is aligned WSW–ENE direction with almost parallel bathymetry contours offshore. It has Visakhapatnam harbor in the southernmost part constructed for shipping, trade, and defense purposes. The harbor was protected from strong swell by a rocky promontory known as Dolphin's nose in the south, acting as a natural breakwater to the harbor. Half-a kilometer away toward north, there is Coastal Battery where huge concrete rocks were laid to protect the beach road from storm surge. The popular R.K. Beach is a straight (∼2 km) beach with plunging breakers and dangerous rip currents. Scattered rocky outcrops exist at Coastal Battery, R.K. Beach, and Palm beach. Toward north, there is Lawson's Bay beach which has concave shape with low energy waves throughout the year. Still ahead, a beach with rocky outcrops exists near the foot of Kailasa hill range scattering ∼200 m along the beach. A natural rocky protrusion exists at the Jodugullapalem beach that extends perpendicular to the beach up to 50 m seaward; acts as sediment barrier. Further north, near Sagarnagar beach, there is a band of stabilized sand dunes. Rushikonda beach in the farthermost part is well known for surfing and fishing. In general, Visakhapatnam beach undergoes seasonal change with erosion during SW monsoon season and deposition during NE monsoon season. The predominant offshore wave height is 1.0–1.25 m during storm wave events and 0.5–0.75 m during normal conditions. The spring tide range is around 1.5 m and the beach is composed of fine-coarse sand of mean grain size ∼0.35 mm.

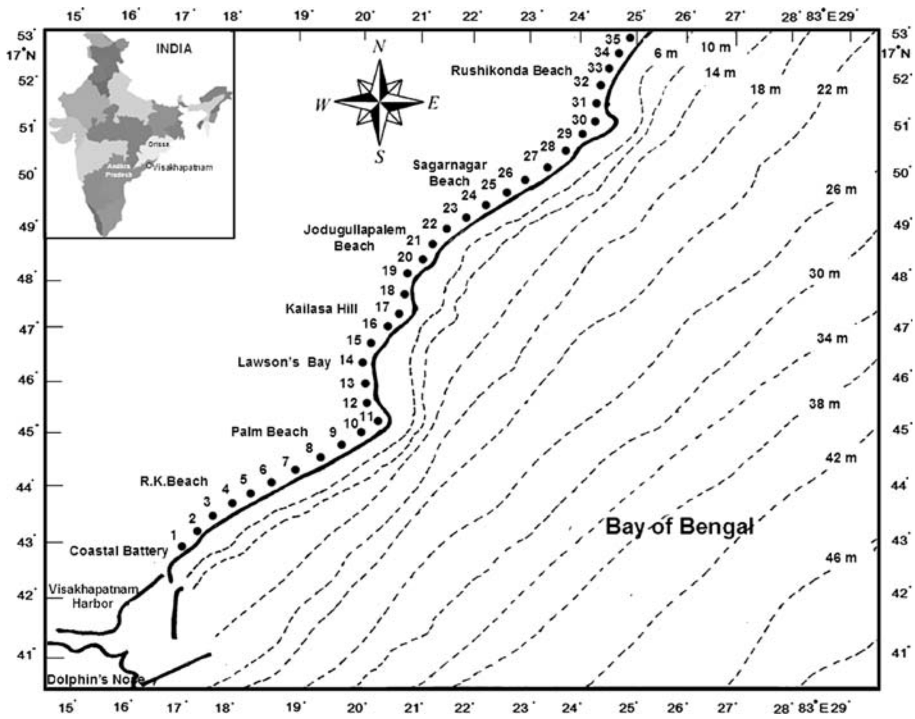

Fig. 1 Location map. The stations are denoted by numbers (1–35) along the coast

3 Methodology

The deep-water wave statistics are obtained from raw Indian Daily Weather Reports (IDWR) visual ship estimates over 16–19° N and 82–85° E. The swell waves are having periods 5–8 s (Chandramohan et al. 1991) with the predominant period of 6 s approaching from SSE and E directions during SW monsoon and NE monsoon, respectively. During storm conditions, the wave periods of 14 s (Sarma 1986) are also observed in both the seasons. Wave refraction diagrams were constructed for most predominant wave directions, i.e., SSE and E waves and the most predominant wave periods, i.e., 6 and 14 s periods based on Arthur et al. (1952) method using the bathymetry survey chart off Visakhapatnam, published by Naval Hydrographic Office, Survey of India (No. 3002).

3.1 Estimation of wave setup

Wave setup is the elevated sea level above the SWL that occurs in the nearshore zone as a result of onshore momentum flux as waves transform and propagate toward the shore. The sea level becomes elevated to compensate for a loss of momentum in the nearshore zone. Wave setup (h_{setup}) has been estimated from the following equation suggested by de Lange (2003).

$$h_{\mathrm{setup}} = 0.19\left(1 - 2.82\sqrt{\frac{H_{\mathrm{b}}}{gT^2}}\right)H_{\mathrm{b}} \tag{1}$$

where H_b is breaking wave height in meters, T is the wave period in seconds, and g is the gravitational acceleration in meters/second^2.

3.2 Estimation of wave runup

Wave runup is the sum of the setup, the time averaged water-level elevation at the shoreline due to waves (excluding tides and surge), and the surge is the time varying vertical fluctuations about the temporal mean (Fig. 2). The elevation of runup maxima has been shown to be dependent on deep-water wave height (H_o), wave period (T_o), and the foreshore beach slope (β_f).

Various formulae were developed by different researchers in laboratory and/or field for different beach and wave types. The laboratory methods proposed by Hunt (1959), Battjes (1974), CERC (1984), and Mase (1989) for estimating wave runups are applicable only for smooth and impermeable slopes under regular/irregular wave conditions which practically do not exist on natural beaches, whereas method suggested by Ahrens and Seelig (1996) is applicable for sand and gravel beaches. Since Visakhapatnam beach is sandy with a mean grain size of 0.35 mm, the Nielson and Hanslow method (1991) is appropriate for this coast given as follows:

$$
\begin{aligned}
&R = cL_{\mathrm{zwm}} \\
&R_{2\%} : c = 1.98 \\
&\bar{R} : c = 0.89 \\
&L_{\mathrm{zwm}} = 0.6(H_{\mathrm{orms}}L_{\mathrm{o}})^{0.5} \tan \beta_{\mathrm{f}} \quad \text{for } \tan \beta_{\mathrm{f}} \geq 0.10 \\
&L_{\mathrm{zwm}} = 0.05(H_{\mathrm{orms}}L_{\mathrm{o}})^{0.5} \quad \text{for } \tan \beta_{\mathrm{f}} < 0.10
\end{aligned}
\tag{2}
$$

where R is the mean runup for irregular waves or runup for regular waves, $R_{2\%}$ is the two-percent wave runup, L_{zwm} is the vertical scale for Rayleigh distributed wave runup values, and H_{orms} is the root mean square deep-water wave height.

But the above method is not effective for the foreshore beach slopes lesser than 0.1 (Fig. 3). Hence, we have used the empirical parameterization suggested by Stockdon et al. (2007) for computing 2% exceedence level for runup ($R_{2\%}$) for the predominant wave period and direction. It is given by

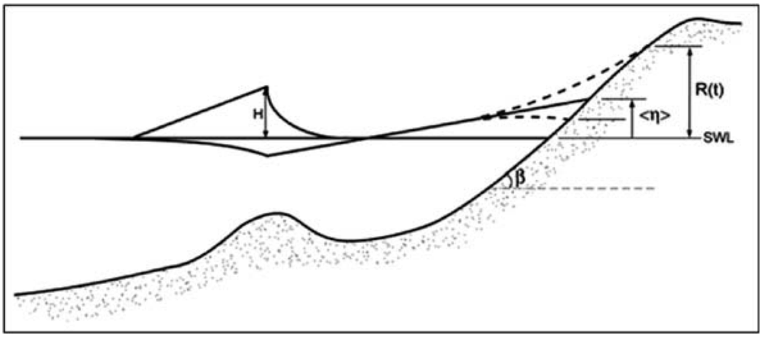

Fig. 2 Wave runup (R) is the time-varying elevation of water level at the shoreline, measured here with reference to the SWL. The schematic shows wave runup (R) and its components, time-averaged wave setup (η), and time-varying swash (*dashed lines*), as a function of wave height (H) and beach slope (β). *Source*: http://coastal.er.usgs.gov/hurricanes/impact-scale/image/runupLG.gif

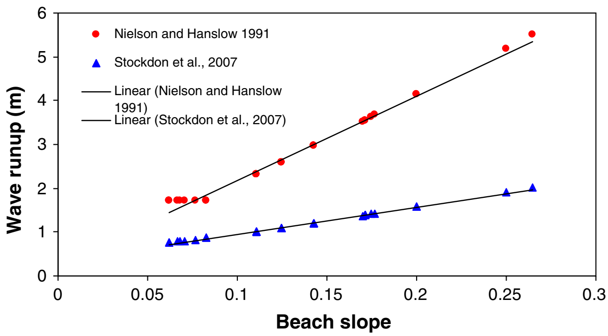

Fig. 3 Relation between wave runup (m) and beach slope (*dots* in *red* are based on Nielson and Hanslow 1991 and *triangles* in *blue* are based on Stockdon et al. 2007)

$$R_{2\%} = 1.1\left(0.35\beta_{\mathrm{f}}(H_{\mathrm{o}}L_{\mathrm{o}})^{1/2} + \frac{\left[H_{\mathrm{o}}L_{\mathrm{o}}\left(0.563\beta_{\mathrm{f}}^{2} + 0.004\right)\right]^{1/2}}{2}\right) \tag{3}$$

which includes both wave-induced setup and swash, where L_{o} is the deep-water wave length, defined as $gT^2/2\pi$. Foreshore beach slope used in Eq. 3 is defined over the area of significant swash activity (Stockdon et al. 2006). The mean beach slope was thought to provide a more stable measure profile slope that was less sensitive to daily changes in wave energy (Stockdon et al. 2007). We applied the Eq. 3 to predict the wave runup elevations along the 35 stations of known beach slopes under normal conditions.

3.3 Estimation of storm wave runup (SWRU)

SWRU is the term used to describe inundation caused by the combination of super elevated sea levels and overtopping by waves riding on elevated sea levels. Maximum inundation from SWRU occurs when high astronomical tides coincide with intense low pressure weather systems causing storm surge and large waves to inundate low-lying areas. We estimated the maximum SWRU elevations from a combination of contributing factors, such as mean astronomical tide, storm surge, and wave runup (Stockdon et al. 2007). The sea-level variations are not considered to reduce the complexity.

Equations 4–6 summarize the factors used in estimating the maximum SWRU elevation levels:

$$\mathrm{SWRU} = \mathrm{surge} + W_{\mathrm{runup}} \tag{4}$$

where

$$\mathrm{surge} = \mathrm{ATide_{MHWS}} + \mathrm{SS} + \mathrm{SL_{rise}} + (\mathrm{ATide_{MHWS}} + \mathrm{SS} + \mathrm{SL_{rise}})\mathrm{SF} \tag{5}$$

and

$$W_{\mathrm{runup}} = W_{\mathrm{runup}} + \left(W_{\mathrm{runup}}\right)\mathrm{SF} \tag{6}$$

where SWRU is the storm wave runup elevation in meters above mean sea level, $\mathrm{ATide_{MHWS}}$ is the astronomical tide elevation at the mean high water springs level in meters, SS is the storm surge elevation (inclusive of inverse barometric pressure response and wind stress) in meters, W_{runup} is the wave runup elevation (inclusive of wave setup) in meters, $\mathrm{SL_{rise}}$ is the sea-level rise in meters for the selected location, and SF is the safety factor (coefficient ranges from 1 to 0).

4 Results and discussion

4.1 Wave refraction

The coast is exposed to SSE waves during March–October. The wave refraction diagram (Fig. 4a) for 6-s waves shows the convergence zones at stations 7, 8, 20, 21, 26, and 34. Wide divergence patterns are observed around R.K. Beach (stations 4–7), Palm beach (stations 6 and 7), Lawson's Bay beach (stations 12–14), and Jodugullapalem beach (stations 17–20). But for 14-s (Fig. 4c) waves which occur during cyclone periods, the zones of convergence has shifted toward R.K. Beach and thus R.K. Beach is vulnerable to severe erosion during storm periods. Whereas the wave refraction diagrams for E waves (Fig. 4b, d) show a general trend of divergence all along the coast. The convergence is however noticed at the Palm beach (station 8) and Lawson's Bay (station 15) for 6-s period waves. The convergence noticed at station 8 for 6-s waves has shifted to stations 10 and 11 for 14-s waves. Strong convergence is noticed near the Kailasa Hill (stations 14–17). The northern parts (stations 20–35) of the coast also experience wave convergence during E waves.

4.2 Nearshore wave energy and wave runup

During SW monsoon (SSE waves), the average nearshore wave energy along the coast is higher for the stations 3 and 20 with values 4.3×10^3 J/m^2. From the southern end of the

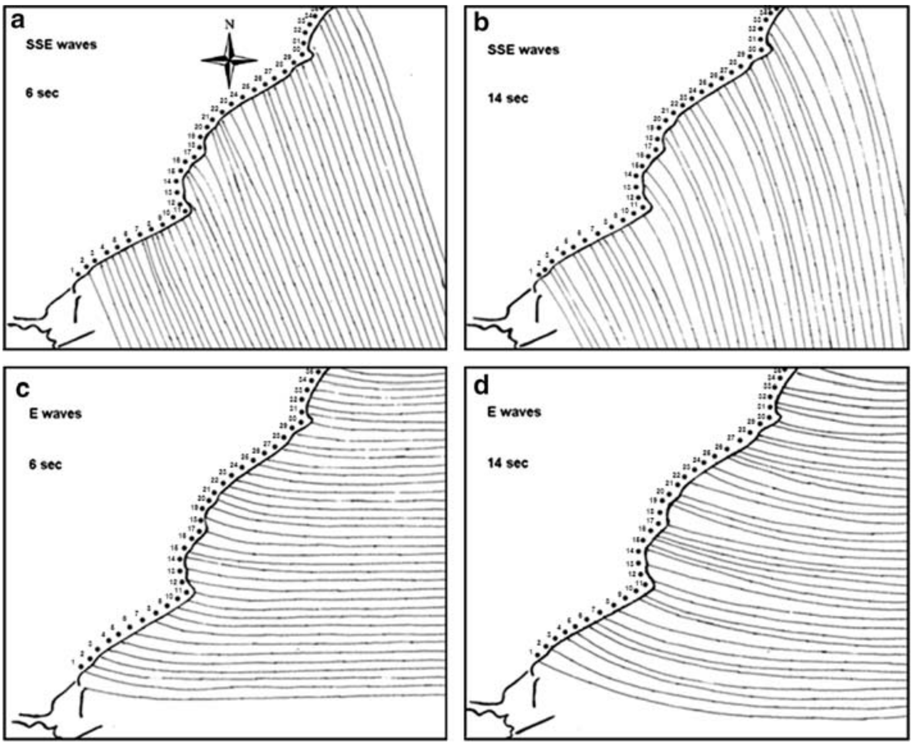

Fig. 4 Wave refraction diagrams for SSE and E waves (6 s: **a**, **b**; 14 s: **c**, **d**) along Visakhapatnam coast

coast, the wave energy is decreasing having a least value of 2.2 × 10^3 J/m^2 in the Lawson's Bay (station 13). The secondary high energy zone resides at the stations in the northern part of the coast (stations 27 and 31). Hence, during this season, R.K. Beach, Jodugullapalem beach, and Sagarnagar beach are high energetic zones, and so there is a possibility of erosion at these places. During NE monsoon (E waves), the breaker energies are lower compared to previous season all along the coast. The seasonal maximum occurs at station 15 with value 4.1 × 10^3 J/m^2, and thereafter, the stations along the northern extension are potential zones of higher wave energies (Fig. 5). In the southern part, the wave energy is lesser at stations 9 and 10 (~1.5 × 10^3 J/m^2). This shows that during NE monsoon, the southern part of the coast is less vulnerable to wave attack except the stations 4 and 6. The mean minimum energy occurs at station 18 (1.8 × 10^3 J/m^2). On a yearly average, stations 4, 15, and 31 are the higher wave energy zones with values 3.9 × 10^3, 3.6 × 10^3, and 4.0 × 10^3 J/m^2, respectively. The lower energies reside at Lawson's Bay (station 12) and station 18. Hence, in a year maximum possibility of erosion takes place at R.K. Beach, Palm beach, Jodugullapalem beach, and Rushikonda beach.

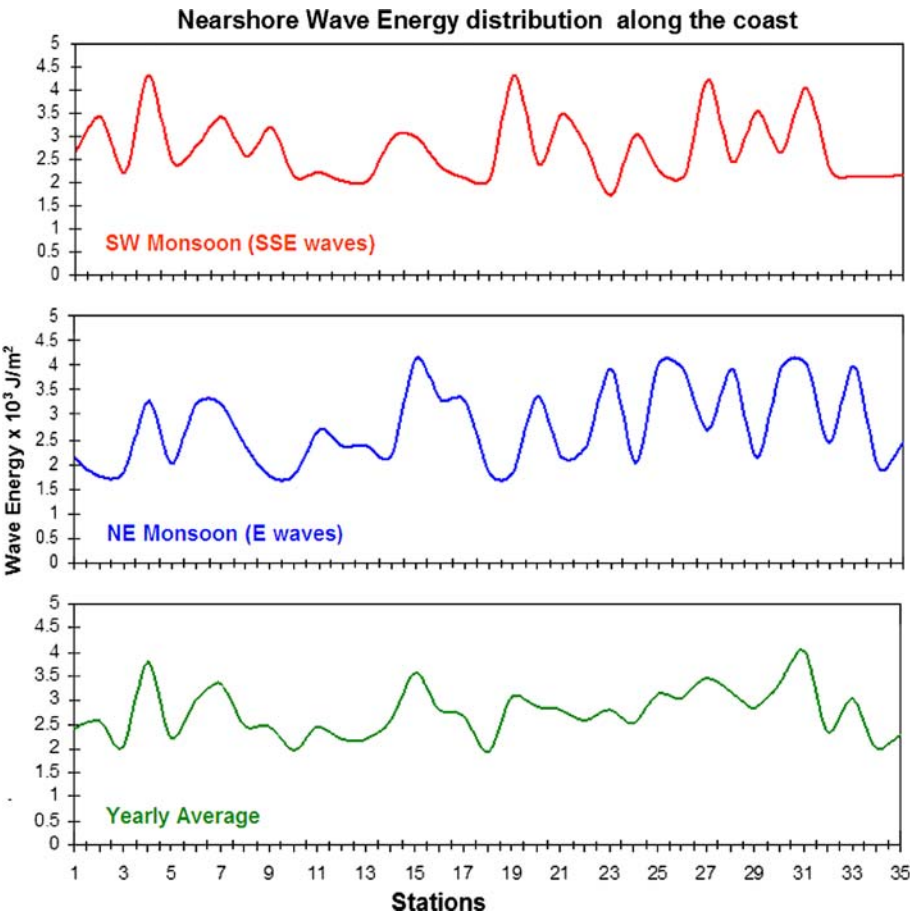

Fig. 5 Nearshore wave energy distribution in SW monsoon, NE monsoon, and yearly average along the coast

But in the natural conditions, the erosion at the above locations may not severe. The severe erosion also depends upon the extent of maximum wave runup during storms. As the cut in the beach takes place mainly in the foreshore of the beach, it should include wave runup factor in addition to wave energy. An assumed storm surge elevation of 1 m and the mean high water spring ($ATide_{MHWS}$) of Visakhapatnam, +1.52 m Indian Tide Tables 2007, were considered. During normal conditions, the wave runups are computed directly by using the method suggested by Stockdon et al. (2007). The estimated wave runup is plotted along with breaker wave energy during storm (Fig. 6a, b) and normal (Fig. 6c, d) conditions for alternate stations along the study area.

During storm conditions, the maximum wave runup ($R_{2\%}$) ranges between 5–6 m and wave energy (E_b) is around 5.0×10^3 J/m^2. During these conditions for SSE waves (SW monsoon), SWRUs are higher at the stations R.K. Beach (station 5) and Jodugullapalem beach (station 21) with magnitudes 5.13 and 5.52 m, respectively. SWRU lows are occurring all along the Lawson's Bay beach (stations 12–16) and along Rushikonda beach (stations 33–35). Lower runups are associated with lesser foreshore beach slopes, whereas during storms of NE monsoon season the higher wave runups occur at the above places with lesser magnitudes. The wave energies are having higher magnitudes from stations 7 to

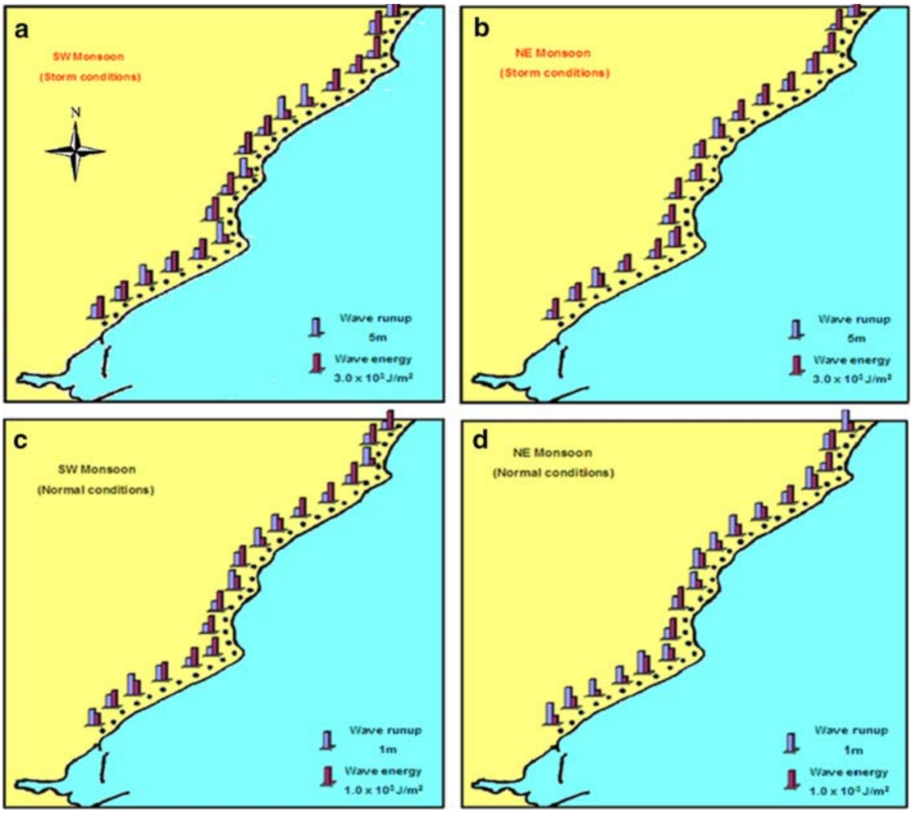

Fig. 6 Wave runup (in *blue*) and breaker wave energies (in *brown*) during south-west and north-east monsoon seasons in storm (**a**, **b**) and normal conditions (**c**, **d**), respectively

15 of around 1.3×10^3 J/m^2, but taking runups into consideration the stations from 11 to 15 are less vulnerable to erosion.

During normal conditions the estimated wave runups and energies are of lesser ranges ($R_{2\%} \sim$ 1–2 m and $E_b \sim 10^3$ J/m^2). For the most frequent 6-s period waves, during SW monsoon (SSE waves) and NE monsoon (E waves), the results are quite noticeable that the stations 3, 4, 7, 9 in the southern part and the stations 20 and 25 in the northern part are vulnerable for erosion during SW monsoon season (Fig. 6c) and the stations 8, 11, and 22 are vulnerable for erosion during NE monsoon season (Fig. 6d). Hence, it is worth mentioning that in addition to higher wave energies, the higher wave runups also should take into account for identifying the vulnerable zones of erosion along the coast.

4.3 Response of the beach to nearshore parameters

The breaker heights during storms of SW monsoon 2007 (Tables 2 and 3) are observed visually and compared with that of Reddy et al. (1984) and Prasad (2002) at the stations 3,

Table 2 Breaker wave characteristics along four stations during three storm events (June–August 2007)

Date	Wave direction	Wave period (s)	Breaker wave height (m)			
			Station 3	Station 4	Station 9	Station 13
20 June	E	13	0.5	0.75	1.25	0.75
21 June	E	14	0.5	1.5	1.75	1.25
22 June	EES	15	1.0	1.75	1.75	1.5
23 June	EES	15	1.0	2.25	1.75	1.5
24 June	SE	10	0.5	1.5	1.25	1.75
25 June	SE	10	0.5	1.5	1.0	1.5
26 June	SE	10	0.5	0.5	1.0	1.25
27 June	SE	10	0.75	0.75	1.25	1.25
28 June	E	12	1.25	1.25	1.5	1.25
29 June	E	11	1.75	1.55	1.5	1.5
30 June	E	10	1.75	1.75	1.75	1.5
1 July	E	10	2.0	2.0	1.75	1.75
2 July	E	9	2.25	2.0	2.0	1.75
5 August	E	10	0.5	0.8	1.5	1.75
6 August	EES	12	0.75	1.75	2.0	1.75
7 August	EES	15	1.75	2.25	1.75	1.25
8 August	E	13	1.5	2.0	1.75	1.5
9 August	E	12	1.5	2.25	2.0	1.75

Table 3 Storms over Bay of Bengal during SW monsoon 2007

Event	Type	Cyclogenesis date	Cyclolysis date	Maximum 6-h sustained wind (kt)
I	TC	21 June 2007	26 June 2007	50
II	TC	28 June 2007	1 July 2007	45
III	DD	5 August 2007	8 August 2007	22

DD deep depression, *TC* tropical cyclone

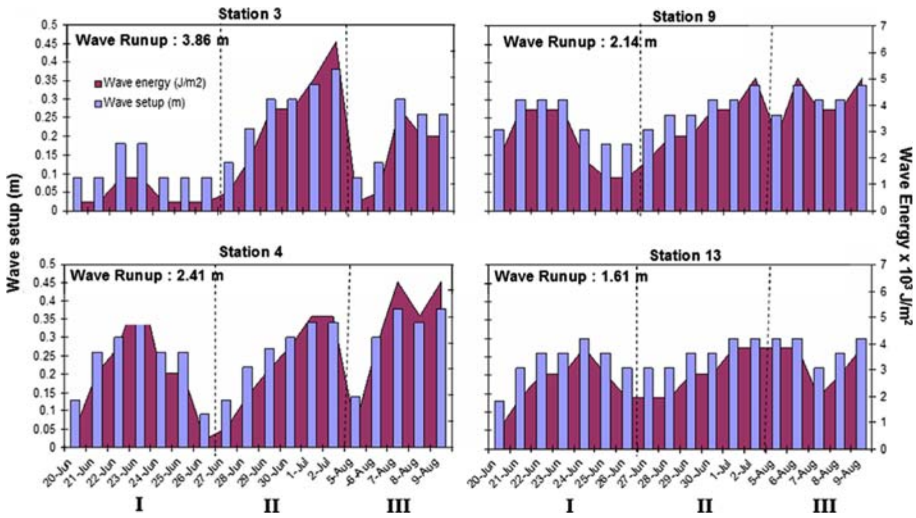

Fig. 7 Wave energy, wave setup, and wave runup at stations 3, 4, 9, and 13 for storm events I, II, and III during SW monsoon 2007

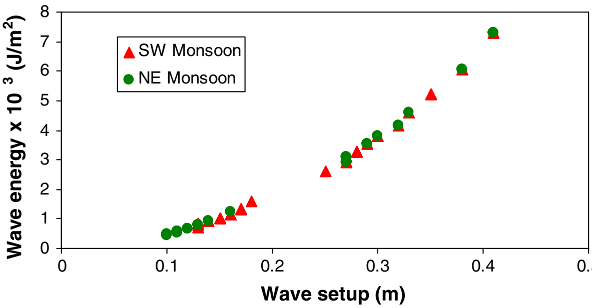

Fig. 8 Mean wave energy (J/m^2) versus wave setup (m) (*circles* represent NE monsoon and *triangles* represent SW monsoon)

4, and 9. The wave energy, setup, and wave runup are computed for the stations 3, 4, 9, and also for 13 (Lawson's Bay) to understand the variations alongshore (Fig. 7). Wave energy is observed to be in perfect correlation with the wave setup. It is more clearly observed in the Fig. 8. At station 3, the maximum SWRU is 3.86 m. Of the three events, the wave setup during the second event is significant with magnitudes ranging from 0.2 to 0.4 m. The peak energy of 6×10^3 J/m^2 is observed at this station during the II event. At station 4, the maximum SWRU reaches up to 2.41 m. The peak energy is around 5×10^3 J/m^2 which is 10^3 J/m^2 lesser than in the previous station. There is a possibility of erosion at these two stations because for higher energies and higher wave runups. At station 9, the wave energy is lesser ($\sim 4.5 \times 10^3$ J/m^2) with a maximum SWRU of 2.14 m. The wave setup reaches maximum during the III event (Fig. 7). The station 13 (Lawson's Bay) is also considered to understand the effect of beach slope on the wave parameters. Here, the average wave energy is around 3×10^3 J/m^2, and the wave runup is observed just only 1.61 m which is far lesser than the previous stations. It is because of lesser beach slope and concave shape shoreline where divergence is possible during wave refraction. This suggests that beach slope and shoreline configuration influence the natural sediment movement in addition to the other nearshore parameters.

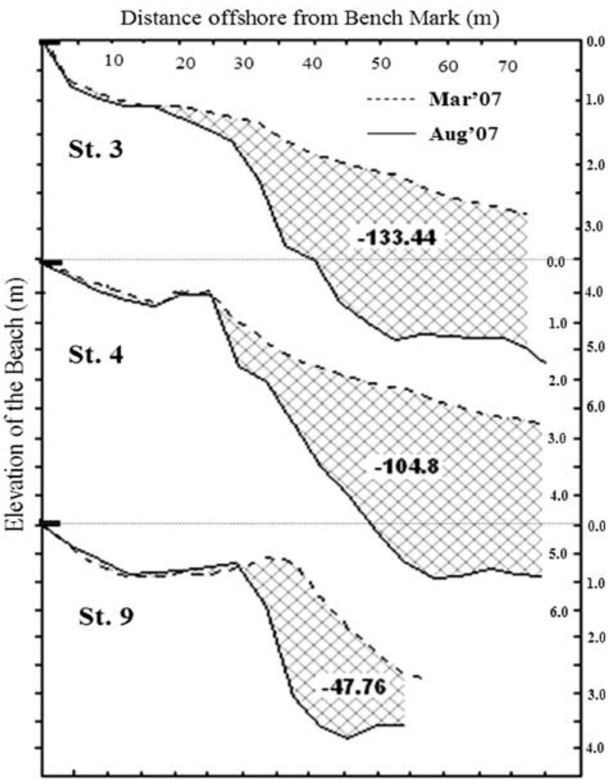

Fig. 9 Beach profiles at stations 3, 4, and 9 between March 2007 and August 2007 showing intensity of erosion (volumes in m^3/m of shoreline) due to storm waves

These results were compared with the beach profiles taken prior (March) to and after (August) the storm events at stations 3, 4, and 9 (Fig. 9) in order to observe the response of the beach due to combined affect of wave energy, wave runup, and wave setup. It is observed that net seasonal erosion takes place at all the above stations with the maximum being noticed at station 3 of magnitude 133.44 m^3/m of shoreline. At station 4, it is around 104.8 m^3/m and at station 9, it is still lesser 47.76 m^3/m. The erosion was mainly observed at the foreshore zone and it is a short-term effect. The erosion was observed to be severe for the stations where wave runup is higher. In addition to wave energies, the wave runups and wave setups also play a vital role in endangering the coast. Even though some of stations are having higher energies, but erosion may not possible affectively without much slope (wave runup). Severe erosion is possible for steeper foreshore beach slopes (higher wave runups) even for moderate breaker wave energy during storm conditions.

5 Conclusions

During storm conditions in SW monsoon, the SWRUs are higher at the stations R.K. Beach and Jodugullapalem beach with magnitudes 5.47 and 5.59 m, respectively. Higher SWRUs are also observed at the above stations during storms of NE monsoon, with magnitudes

5.13 and 5.52 m, respectively. SWRU is observed to be smaller all along the Lawson's Bay beach with magnitudes 0.64 m. The higher nearshore wave energies are observed at R.K. Beach, Sagarnagar beach, and Jodugullapalem beach with magnitudes around 4×10^3 J/m^2 during both the seasons. The yearly low wave energy (1.8×10^3 J/m^2) is observed at Lawson's Bay with lowest wave runup (0.56 m), considered as safest zone. R.K. Beach, Palm beach, and Jodugullapalem beach are identified as vulnerable zones due to waves. In addition to wave energies, the wave runups and wave setups also play a vital role in endangering the coast. Even though some of the stations are having higher energies, erosion may not be possible affectively without much slope (wave runup). Severe erosion is possible for steeper foreshore beach slopes (higher wave runups) even for moderate breaker wave energy during storm conditions.

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