Wave characteristics off Visakhapatnam coast during a cyclone

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Waves were measured using a directional waverider buoy off Visakhapatnam, east coast of India during the passage of a cyclone in November 1998. The maximum wave height observed during the passage was 5.74 m, whereas this height 24 h before and after the passage were 1.54 and 1.24 m. Wave spectra during the cyclone were single-peaked with peak period varying from 8 to 10 s and direction from 125° to 170° with respect to north. Before and after the cyclone, the spectra were multi-peaked with the predominant peak period varying from 12 to 18 s.

EVALUATION of wave characteristics during severe sea states is essential for the adequate design and construction of coastal structures. The significant wave height is the generally used wave height parameter and is comparable to the statistically determined average of the highest one-third wave in a record. Significant wave height (H_s) is the wave height value approximately observed and recorded by a human when making a visual observation. The maximum value of wave height in a record is called the maximum wave height (H_{max}). The data available on wave characteristics off Visakhapatnam coast are visual data[1] observed from ships of opportunity and reported in Indian Daily Weather Reports (IDWR). Since the ships usually avoid the cyclone track, the wave conditions during cyclone are missed. In the present study, the characteristics of waves measured during the passage of a cyclone, which occur frequently along this coast during the northeast monsoon (October to January) are presented.

The wave climate of this region varies from the southwest monsoon (June to September) to the northeast monsoon. IDWR results show that H_s has a range of 1–3 m during May–September, 0.5–2 m during October to December (except during the cyclone periods), and generally less than 1.5 m in the remaining period. The average wave period varies from 9 to 12 s for the greater part of the year. The waves predominantly approach the coast from the south during March to September and from the east during December to February. The wave direction is transitional, shifting from south to east during October to November. The tides in this region are semi-diurnal. As reported in the Indian Tide Table for Visakhapatnam, the mean spring tidal range is 1.43 m and the neap tidal range is 0.54 m.

Data measurement and analysis

A low pressure area formed over the central Bay of Bengal developed into a deep depression by 0300 h GMT on 14 November 1998. The cyclone turned into a severe cyclonic storm by 1800 h on 14 November 1998 and crossed over the coast on 15 November 1998 between 1100 and 1200 h. The wind information recorded at Visakhapatnam, the nearest meteorological observatory of the India Meteorological Department is given in Table 1 along with the position of the cyclone. The maximum wind speed recorded was 25.74 m/s. The maximum wind gust recorded was 73 knots (37.57 m/s) north-easterly at 1000 h on 15 November 1998.

Wave measurements were carried out using a Datawell directional waverider buoy[2] in 12 m water depth from 10 to 19 November 1998. The measurement site is off Tikkavanipalem along the east coast of India and is 30 km southwest of Visakhapatnam in Andhra Pradesh (Figure 1). The coast along this region is straight and has an average orientation of about 72° with respect to north. The data were recorded for 20 min duration at every 3 h interval. Data were sampled at a frequency of 1.28 Hz and Fast Fourier Transform of 6 series, each consisting of 256 data points was added to give spectra with 16 degrees of freedom. The high frequency cut off was set at 0.6 Hz and the frequency resolution was 0.005 Hz. The directional wave parameters at each frequency were obtained directly from Fourier coefficients[3]. Fourier coefficients were estimated from auto, co- and quadrature spectra of the collected three translational motions of buoy (vertical, north-south and east-west). The significant wave height (H_s) and the average wave period (T_{02}) were obtained from the spectral analysis. Other parameters obtained were wave period corresponding to the maximum wave height ($T_{H_{max}}$), wave period corresponding to maximum spectral energy (T_p), spectral peakedness parameter[4], Q_p spectral width parameter[5], ε and spectral narrowness parameter[6], ν. The sharpness or flatness in the shape of the wave spectrum is judged through the spectral peakedness parameter. Spectra with sharper peaks will have larger values of the peakedness parameter. The width of the spectra is defined by using the spectral width parameter, ε and spectral nar-

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Table 1. Wind information recorded at Visakhapatnam along with position of cyclone

Time (GMT) (h)	Recorded values at Visakhapatnam			Position of cyclone	
	Speed (m/s)	Wind direction (°)	Pressure (mbar)	Latitude (°N)	Longitude (°E)
14 Nov 98					
0000	4.12	360	1007.4		
0300	4.12	360	1010.1	13.5	86.5
0600	6.18	360	1008.9		
0900	5.15	360	1006.1	14.0	86.0
1200	9.26	360	1006.2	14.5	85.5
1500	6.18	360	1006.8		
1800	8.24	360	1006.5	15.0	85.0
2100	9.26	360	1005.4		
15 Nov 98					
0000	10.29	360	1002.5		
0300	14.41	360	1003.5	16.0	84.0
0600	14.41	360	999.4		
0900	20.59	50	991.9		
1000	25.74	20	986.5		
1200	10.81	180	988.9	17.5	83.0
1500	8.24	230	1000.5		
1800	6.18	230	1004.3		
2100	3.09	270	1004.3		
16 Nov 98					
0000	3.09	270	1005.1		
0300	1.54	230	1008.7	20.5	82.0
0600	4.12	230	1007.4		
0900	4.12	200	1005.1		
1200	5.15	230	1005.8		
1500	3.09	230	1008.3		
1800	3.09	270	1008.7		
2100	1.54	270	1007.3		

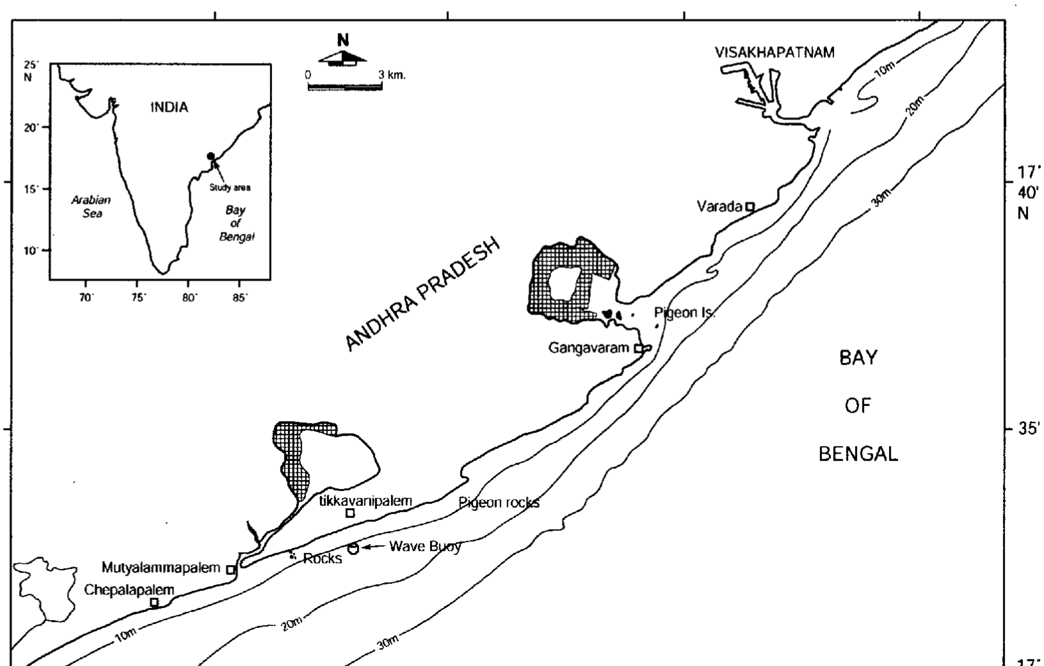

Figure 1. Map showing the study region with local bathymetry.

rowness parameter, ν. Small values of ε, ν represent narrow band spectra, while larger values represent broad band spectra.

Results and discussion

Wave height

Heights of the waves depend on characteristics of the wind responsible for generating them. During the observation period, the highest significant wave height of 3.29 m and maximum wave height of 5.74 m were recorded on 15 November 1998 at 0930 h, when the storm crossed very close (within 13 km distance) to the measurement location. The maximum, minimum and the average values of the wave parameters are presented in Table 2. The variation of H_s and H_{max} along with the recorded wind speed is shown in Figure 2. The maximum wave height was 1.54 and 3.21 m when the cyclone was 500 and 200 km away from the measurement location. Twenty four hours before and after the passage of the cyclone, the H_{max} was 1.54 and 1.24 m respectively. The low value (5.74 m) of the H_{max} obtained for the cyclone is due to the shallow water effects as the waves were recorded at 12 m water depth. Even though theoretically, a maximum wave height of 9.36 m (0.78 times the water depth) can occur at 12 m water depth, the laboratory experiments have shown that the maximum height will be 0.55 times the water depth[7]. The variation of maximum wave height with significant wave height is shown in Figure 3. H_{max} observed from each 20 min record shows that it is approximately 1.65 times H_s with a correlation coefficient of 0.88 having a confidence limit of 0.85. The H_{max} estimated, based on Rayleigh distribution also shows that this relationship holds good, similar to the conclusion drawn for the normal sea states based on the wave data collected in the intermediate and shallow water along the Indian coast[8,9]. The present study shows that the Rayleigh distribution predicts the wave heights distribution very well during the severe sea states also.

Table 2. The minimum, maximum and average value of wave parameters

Parameter	Minimum	Maximum	Average
Significant wave height, H_s (m)	0.52	3.29	1.16
Maximum wave height, H_{max} (m)	0.78	5.74	1.98
Mean wave period, T_{02} (s)	4.4	8.8	6.3
Peak wave period, T_p (s)	7.0	17.3	12.2
Wave period corresponding to maximum wave height, $T_{H_{max}}$ (s)	5.5	15.6	10.5
Maximum spectral energy, E_{max} (m^2/Hz)	0.38	24.07	2.97
Spectral width parameter (ε)	0.73	0.93	0.85
Spectral narrowness parameter (υ)	0.43	0.92	0.62
Spectral peakedness parameter (Q_p)	1.00	4.11	2.06

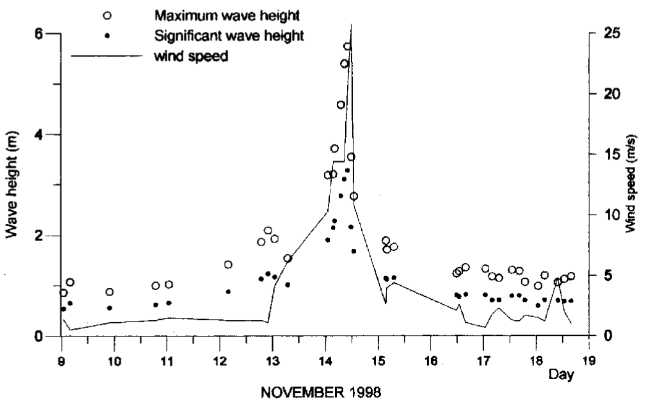

Figure 2. Variation of maximum wave height (H_{max}), significant wave height (H_s) and recorded wind speed with time.

Wave period

The variation of average wave period (T_{02}), period corresponding to maximum wave height ($T_{H_{max}}$) and wave period corresponding to maximum spectral energy (T_p) during the observation period are shown in Figure 4. During the cyclone period, the wave energy increases and hence the wave height, but the wave period reduces due to formation of more young waves with shorter period. Hence T_p and $T_{H_{max}}$ were low during the cyclone period compared to other period. In general, normal short-term sea states are characterized by the significant wave height and average wave period and extreme sea states by significant wave height and peak period. From a practical point of view, it is therefore of some interest to calculate T_p from H_s using a regression function. For the present data

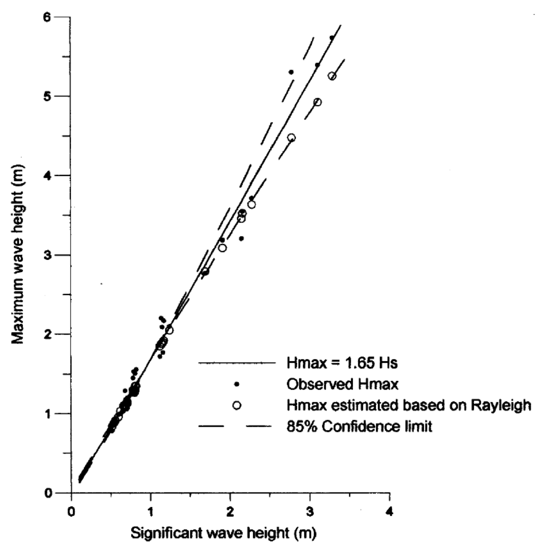

Figure 3. Variation of maximum wave height (H_{max}) with significant wave height (H_s).

analysed, the correlation between H_s and T_p with a correlation coefficient of 0.6, was better than H_s and T_{02} with a correlation coefficient of 0.1 (Figure 5). Good correlation between significant wave height and average wave period with correlation coefficient of 0.79 was observed for the shallow water waves along the west coast of India[9,10].

Wave groups

Wave group can excite low frequency responses in floating and compliant marine structures. Wave groups are usually characterized in terms of the number of consecutive waves that exceed some specified threshold height. The number of consecutive waves having heights more than the threshold height is called the run length. In the present study, the threshold height considered was H_s and the run length estimated was for $H > H_s$. Wave group statistics for the waves off the west coast of India have been investigated and the results have been reported[11–13]. Wave group formation among storm waves was studied based on the data collected in the North Sea and it was found that wave group formation among large waves is larger than would be expected from an estimate based on a completely random succession of the wave heights[14]. Based on the present data, the longest runs identified contained six waves for $H > H_s$. Grouping of high waves (H_s = 2 m) in a long-travelled swell recorded at a shallow water location of west coast of India was studied and found 6 and 16 run[12]. The average run length for $H > H_s$ were 1.34, 1.35, 1.42, 1.38, 1.39, 1.25 for the data analysed off Mangalore[11], Utsira[14], Japan[15], Bombay High[16], Karwar[17] and Vizhinjam[17] respectively. For the present data average run length is 1.44 whereas the theoretical value is 1.16. The average run length for the data analysed is shown in Figure 6. The higher value obtained during the cyclone period shows that as the wave height increases, the groupiness increases. The mean length of run containing maximum wave height (H_{max}) in all records for the present data is 2.32.

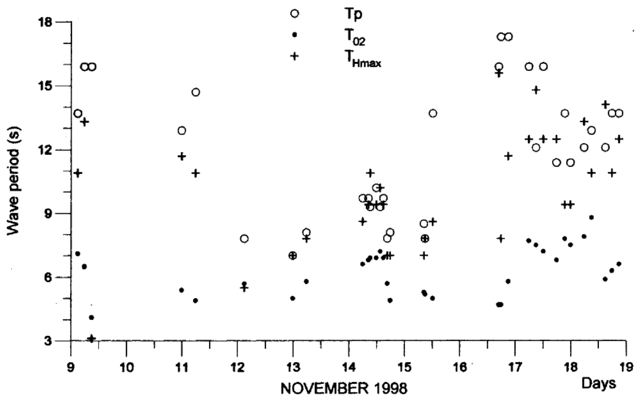

Figure 4. Variation of peak period (T_p), average period (T_{02}) and period corresponding to maximum wave height ($T_{H_{max}}$) with time.

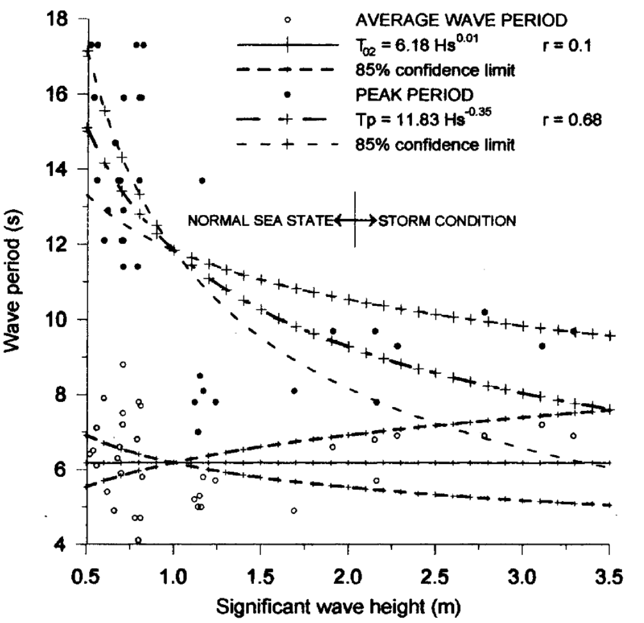

Figure 5. Variation of peak period (T_p) and average period (T_{02}) with significant wave height (H_s).

Wave spectrum

Many times, it becomes necessary to know the range of wave frequencies where most of the wave energy is concentrated and this can be easily identified from a wave spectrum. Also, the wave spectrum is required for determination of the transfer function while estimating the response of the marine structures.

Of the 32 analysed wave spectra, 17 were single-peaked and 15 were double-peaked. The double-peaked spectra were swell-dominated. The wave spectra during extreme sea states (14 to 16 November) were mainly single-peaked (Figure 7) with peak period varying from 8 to 10 s. The

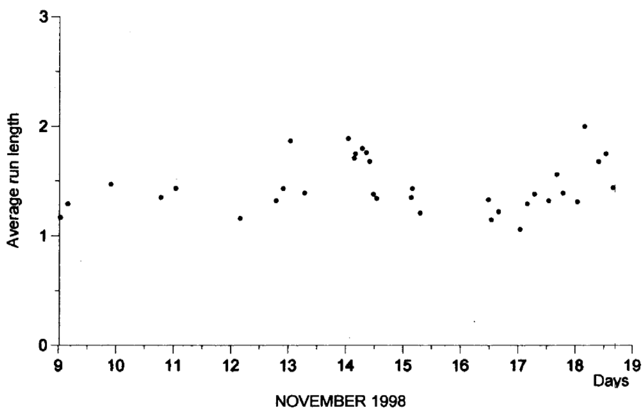

Figure 6. Variation of average run length for $H > H_s$.

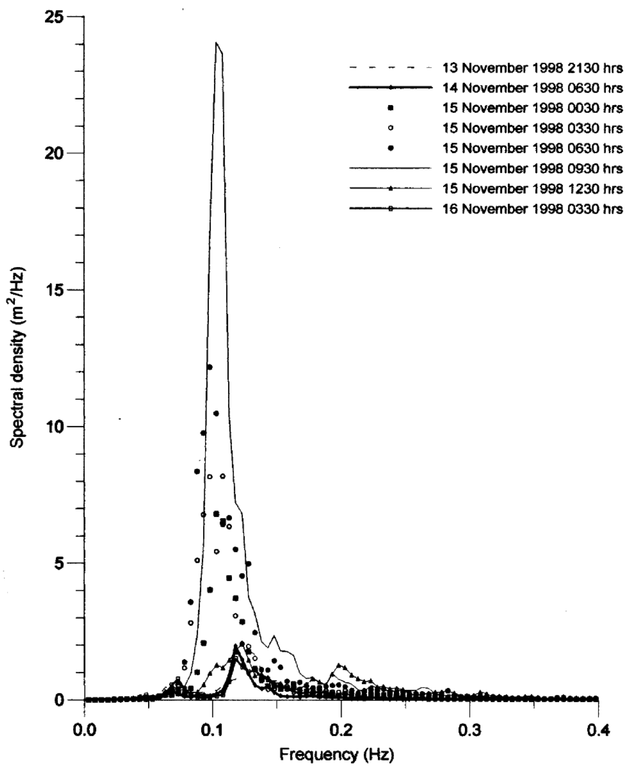

Figure 7. Wave spectra for the period from 13 November 1998 2130 h to 16 November 1998 0330 h.

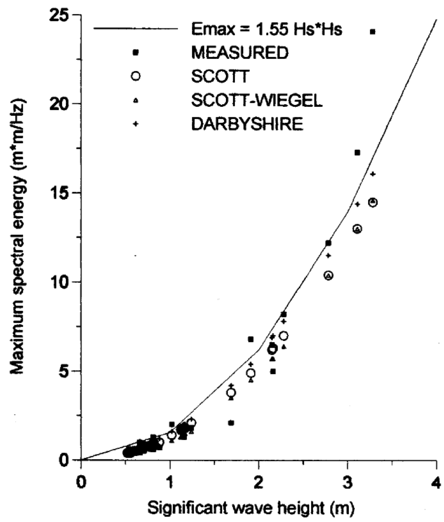

Figure 8. Variation of maximum spectral density measured and estimated based on Darbyshire, Scott and Scott-Wiegel with significant wave height.

percentage occurrence of the double-peaked spectra was higher for low sea states and lower for storm conditions. The maximum spectral density varied from 0.4 to 24.2 m^2/Hz and the mean wave direction varied from 125° to 170° with respect to north. The spectrum computed from measured data shows that storm data can be satisfactorily represented by Darbyshire[18], Scott[19] and Scott-Wiegel[20] spectra. Similar observations have been made for the normal sea states seen along many sites along the Indian coast[9,21–23]. The maximum spectral density computed from the measured data and from the Darbyshire, Scott and Scott-Wiegel spectra are presented in Figure 8. This shows that the better representation of peak is obtained by the Darbyshire spectra. During the cyclone period, the correlation coefficient between the measured and theoretical spectral estimate was greater than 0.9. The variation of maximum spectral density (E_{max}) with significant wave height (H_s) shows that the following empirical relationship proposed for normal sea states[9] can be used for the storm data also.

$$E_{max} = 1.55H_s^2. \quad (1)$$

The spectral peakedness parameter (Q_p) was 4.1 when the cyclone was close to the measurement location. For normal sea states the value of Q_p varies from 1 to 2.2. The larger value indicates that the wave spectrum has sharper peak during high sea state. The range and the average value of spectral width parameter based on spectral and zero crossing analyses and spectral narrowness parameter is presented in Table 2. There is a good correlation between the spectral width parameter estimated based on spectral analysis and the zero crossing method with a regression coefficient of 0.73. The spectral narrowness parameter is around 0.5 during the severe sea states, indicating that all the wave energy is concentrated in one frequency. ν is apparently 0.5 ε for a narrow band spectrum[6] and holds good for the data collected off Mangalore[8], but in that work the spectral width parameter was estimated directly from the records by the number of crests and zero crossings rather than spectral analysis. For the present data it was found that $\nu = 0.85\ \varepsilon^{1.9}$.

Conclusions

- The low value of the significant wave height of 3.29 m obtained for the cyclone was due to the shallow water effects as the waves were recorded at 12 m water depth.
- Significant wave height was well correlated with the peak wave period with a correlation coefficient of 0.6, rather than with the average wave period.
- Wave spectra during cyclone were single-peaked with spectral periods from 8 to 10 s and direction from 125° to 170° with respect to north. The percentage occurrence of the double peaked spectra was higher for low sea states and lower for storm conditions.
- The longest run identified contained 6 waves for $H > H_s$ and the mean length of run considering all records was 1.44.

- Most of the earlier studies along the Indian coast were based on the data collected during the normal sea states. Since the design parameters are to be estimated based on the extreme conditions (such as the cyclonic conditions), in the present study the proposed relations/findings of the earlier study for normal sea states were examined and the following observations were noticed: (i) The maximum wave height was 1.65 times the significant wave height and the wave heights follow the Rayleigh distribution; (ii) The wave spectrum can satisfactorily be represented by Darbyshire, Scott and Scott-Wiegel spectra with a better representation of peak by the Darbyshire spectrum.

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