WAVE MEASUREMENT AND EVALUATION TECHNIQUES ADOPTED AT DAMAN ON THE WEST COAST OF INDIA

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ABSTRACT

This paper presents the results of analysis carried out on time series data on waves measured off Daman on the West Coast of India. Wave variability in the south-west monsoon period and non-monsoon period including that observed during the occurrence of a severe cyclone has been discussed. Results obtained from the analysis by the Tucker's, zero upcrossing and spectral methods have been compared. A comparison of the observed spectra with the theoretical spectra indicated that the Scott's spectra in general gave a better overall fit whereas the JONSWAP spectra fitted well at the peak frequency region of the observed spectra. Correlation between significant wave heights estimated by different methods is found to be very good where as the estimated zero crossing wave periods by different methods do not show very good relationship.

1. INTRODUCTION

Understanding of the wave climate is very essential for designing, constructing and operating various coastal and offshore facilities. In particular, wave data measured during cyclones and storms would provide very valuable information for establishing design criteria for marine structures.

The surface of the sea is a complex and irregular function of space and time and can therefore, be best described by non-deterministic techniques. Instrumentally measured data in conjunction with the ship observed and/or the hind cast data on waves are generally used for the realistic estimation of design wave heights for different return periods.

Worst wave conditions in the Arabian Sea adjoining the West Coast of India occur in the south-west monsoon (June to August/September) as well as during the severe cyclones which may occur in October-November. This paper presents the results of analysis carried out on the time series records of waves collected from May to November 1982. The results obtained by analyzing the wave records by the Tucker's, zero up-crossing and spectral methods have been discussed and compared.

In view of the importance of the cyclone waves, special effort has been made in the paper to present the results of analysis of wave spectra during the growing and decaying stages of the cyclone which hit the Gujarat coast on the northern part of the west coast with a wind speed of 170 to 180 km per hour on 8 November 1982 at about 2100 hrs Indian Standard Time (I.S.T). The land fall point was about 220 km distance from the wave measurement station.

2. WAVE DATA COLLECTION

A wave rider buoy was installed in May 1982 at a distance of about 20 km from the shoreline at Daman on the west coast of India where the water depth was about 27 m. 20 min time series records of waves at normal intervals of 3 hours were obtained at the recording station installed on the shore. During the occurrence of a severe cyclone, records were obtained at closer intervals of 1½ hours. Analog records on chart paper rolls were obtained by using WAREP Mark II receiver system with a programmable strip chart recorder which can switch-on the unit at a given interval of time and start recording data for a desired duration. A digital magnetic (DIMA) tape recorder was interfaced with WAREP unit to digitize the analog wave signals at 0.5 sec interval for recording on a digital magnetic tape cassette. These data were further transferred on to computer compatible magnetic tapes to facilitate computer-aided data analysis.

3. WAVE DATA ANALYSIS

Three different methods were used for analyzing the wave records. Good quality analog data on chart paper rolls were analyzed by using the Tucker's method (Tucker 1963). The digital wave records contained in the magnetic tapes were first checked for various errors and good quality data were analyzed by zero up-crossing (statistical) and spectral methods.

3.1 Tucker's Method

Tucker's method consists of measuring highest crest (A), second highest crest (B), lowest trough (C) and second lowest trough (D) and the number of zero up-crossings (Nz) with reference to the mean water line (MWL). Maximum wave height (H_{max}) and the wave period (TH_{max}) associated with (H_{max}) as well as the number of wave crests (Nc) in each wave record were obtained. The following equations were used to compute root mean square of the water surface elevation (m_{oT}):

$$\frac{H_1}{\sqrt{m_{oT}}} = 2\,(2\ \ln Nz)^{\frac{1}{2}} \left[1 + \frac{0.289}{\ln N_z} - \frac{0.247}{(\ln N_z)^2} \right] \quad .. \quad (1)$$

$$\frac{H_2}{\sqrt{m_{oT}}} = 2\,(2\ \ln Nz)^{\frac{1}{2}} \left[1 - \frac{0.211}{\ln N_z} - \frac{0.103}{(\ln N_z)^2} \right] \quad .. \quad (2)$$

where $H_1 = A + C$, $H_2 = B + D$.

The highest value of m_{oT} obtained from the above two equations was used to compute the significant wave height H_{sT} by the statistical relationship

$$H_{sT} = 4\sqrt{m_{oT}}$$

The zero crossing wave period T_{zT} was computed from

$$T_{zT} = \frac{\text{Period of each record in secs.}}{N_z} = \frac{1200}{N_z} \text{ sec} \quad .. \quad (4)$$

Spectral width parameter e_T was calculated using the relationship

$$e_T = \left[1 - \left(\frac{N_z}{N_c}\right)^2 \right]^{\frac{1}{2}} \quad .. \quad (5)$$

3.2 Zero Up-crossing (Statistical) Method

The digital wave records on computer compatible tapes were analyzed by zero up-crossing and spectral methods using a specially developed computer program which is so designed that simple errors are corrected whereas certain serious errors cause rejection of the wave record by the computer. The raw data were subjected to various checks on spikes, steepness, constant signals, same sign etc. Only samples with 2048 data points are included. Samples with number of waves less than 40 or greater than 600 or significant wave height greater than 0.9 times maximum wave height are rejected.

The zero up-crossing analysis is based on the determination of wave heights and the corresponding wave periods by identifying the location at which the time series record of waves crosses the zero level from negative to positive values. The problem is not a simple one as the noise and interference with other signals greatly affect the result. Provision has been made in the computer program to neglect certain very small wavy fluctuations. Significant wave height (H_{SS}) defined as the average of the one-third highest waves, height of maximum wave (H_{max}), zero crossing wave period (T_{ZS}) defined as the average of zero up-crossing periods of individual waves, period of the highest wave (T_{Hmax}) etc. were computed for each wave record.

3.3 Spectral Method

Spectral analysis is based on the assumption that the wave surface is formed as a result of the linear superposition of a number of sinusoidal waves each having different amplitude and random phase. Spectral analysis consists of the calculation of the frequency spectrum of a time series. In the discrete case, this concerns with the computation of wave energy distributed at various frequency components.

The energy of a particular discrete frequency component is proportional to the square of the amplitude of the frequency component. Once we know the amplitudes of all the discrete frequency components, the spectrum S(f) is obtained by calculating the Fourier Coefficients, squaring and adding these in pairs. The periodogram (or raw spectrum) is computed from the time series each of 1024 sec duration with 2048 data points by using Fast Fourier Transform (FFT) alogorithm. If the time series is defined as

$$\left[x(j) \right]_{j=0}^{j=N-1}$$

the spectrum is computed using the equation:

$$S(f) = \frac{1}{N f_o} \left[\sum_{j=0}^{j=N-1} x(j)\, e^{-ij\lambda} \right]^2 \qquad \ldots \quad (6)$$

where $\lambda = \frac{2\pi f}{f_o}$ and $f = 0, f_o/N, 2f_o/N, \ldots\ldots (N-1)f_o/N$

f = frequency

f_o = sampling frequency = 2 H_z and

N is a power of 2 in order to gain maximum efficiency in FFT algorithm. In this case N = 2048 (= 2").

A smoothed spectrum is computed by taking moving average of 8 spectral estimates of the raw spectrum. Moments of the spectrum about the origin (m_o, m_1, m_2 & m_4), spectral estimate of the significant wave height (H_{4rms}), period of the spectral peak (T_p), spectral estimate of zero crossing wave period (T_{mo1} and T_{mo2}) etc. were computed. T_{mo1} is defined as m_o/m_1 and $T_{mo2} = (m_o/m_2)^{½}$.

4. RESULTS OF ANALYSIS AND DISCUSSIONS

4.1 Time Variation Of Wave Heights

Variations in the daily maximum significant wave height (H_s) and highest wave height (H_{max}) which occurred during the measurement period are shown in Figure 1. The significant wave height varied from 0.62 m to 1.13 m in May, 1.13 m to 3.08 m in June, 1.61 m to 3.22 m in July, 1.62 m to 2.99 m in August, 0.56 m to 1.45 m in September, 0.37 m to 0.74 m in October and 0.25 m to 0.88 m during the non-cyclonic period of November. During the cyclonic period of 7-9 November 82 H_s, varied from 1.00 m to 5.97 m with the corresponding highest wave heights measured ranged from 1.50 m to 8.40 m. In general waves were severe in the south-west monsoon period of June to August. The maximum significant wave height of 3.22 m occurred in July with the corresponding highest wave being 5.15 m. When severe cyclones occur, severe sea-state conditions may be generated in the area as observed during this measurement period.

4.2 Time History Of Wave Period

Variation of zero crossing wave period corresponding to the daily maximum significant wave height is plotted in Figure 2. It varied from 4.1 sec to 11.9 sec in May, 4.4 sec to 7.5 sec in June, 4.6 sec to 7.7 sec in July, 5.5 sec to 7.5 sec in August, 4.9 sec to 9.5 sec in September, 4.8 sec to 16.7 sec in October and

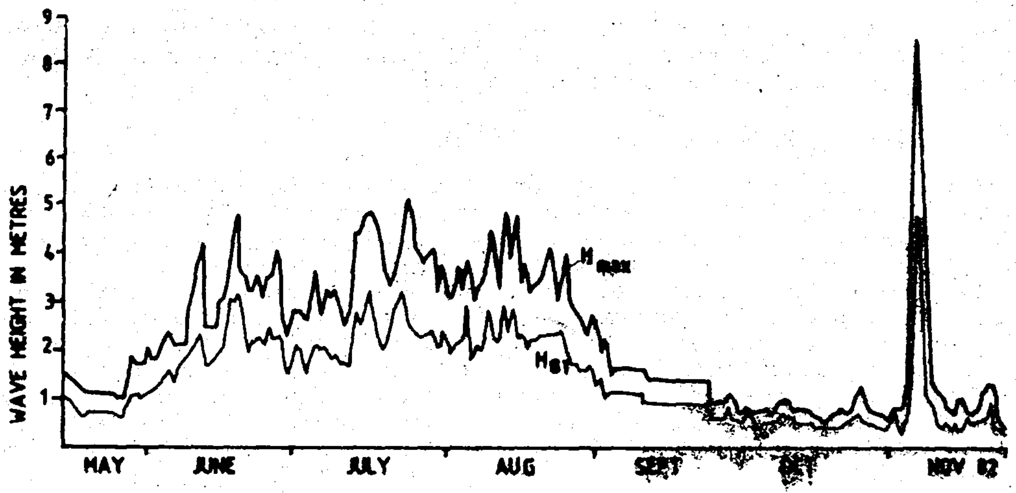

FIG. 1 TIME HISTORY OF DAILY WAVE HEIGHT H_{ST} AND H_{max}

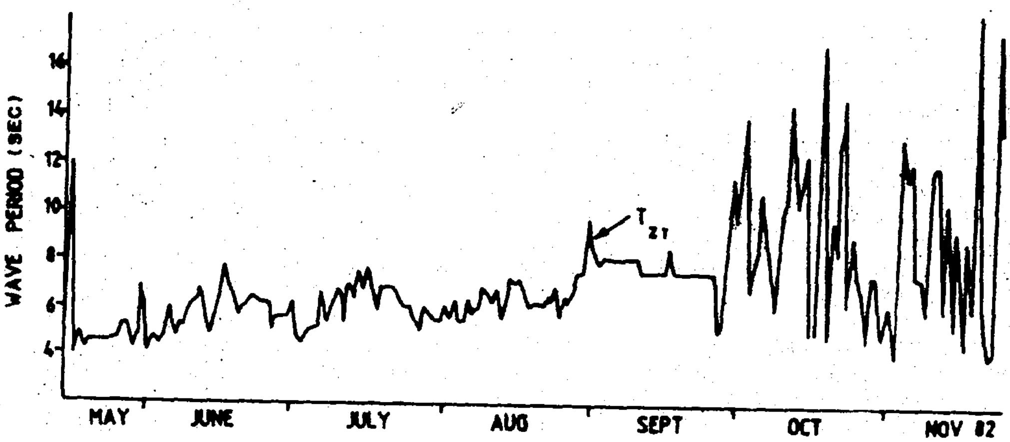

FIG. 2 TIME HISTORY OF ZERO CROSSING WAVE PERIOD T_{ZT}

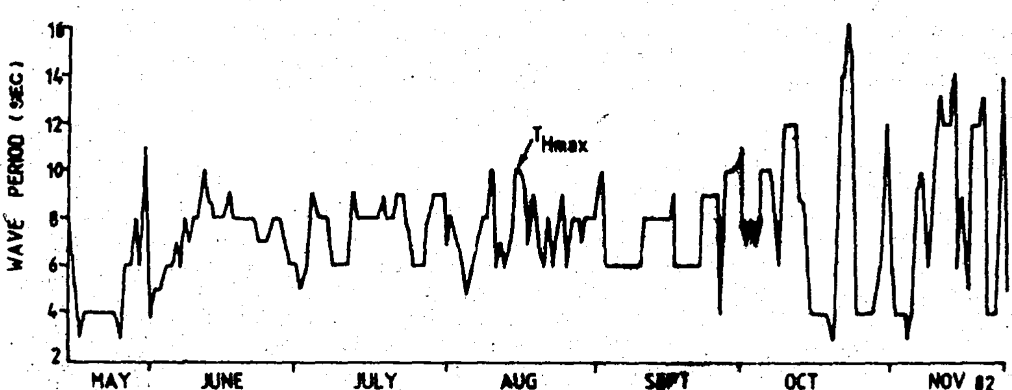

FIG. 3 TIME HISTORY OF WAVE PERIOD T_{Hmax}

4.0 sec to 18.2 sec in November. Figure 3 presents the time variation of wave period associated with daily highest wave height observed during the measurement period.

4.3 Joint Distribution Of H_S and T_Z

Joint distribution of significant wave height H_S and zero crossing wave period T_Z for the south-west monsoon period (June-Sept) and for the non-monsoon period are shown in Figure 4 in the form of scatter diagrams. In the monsoon season, the waves were relatively steeper as can be expected and they were mostly distributed around the steepness parameter (H_S/T_Z^2) ranging from 0.02-0.5. In the non-monsoon period, the waves were comparatively flatter with predominant distribution lying around the steepness parameter of about 0.002. However, the waves measured during the occurrence of the cyclone were higher and steeper when compared to the waves observed during the rest of the measurement period as indicated in Figure 4.

4.4 Growth and Decay of Waves During the Cyclone

4.4.1 Variability of wave spectra

Wave spectra of 20 selected wave records have been plotted in Figure 5A to indicate how the shape and size of the spectrum vary at the measurement station (Figure 5B) as the cyclone passes the area at a distance along the track (Figure 5C). An examination of the variability of the shapes of wave spectra during the stages of growth and decay of the cyclone indicate that there are 2 major peaks which become sharper as severety of wave conditions increase. Three well defined peaks with spectral densities 25.87, 33.17 and 22.88 m^2 sec respectively can be seen in the wave spectra computed for the wave record of 1928 hrs on 8 November 82. The chart paper record, however, showed that the highest wave of about 8.40 m height occurred at 2100 hrs. The digital record obtained at this time contained more spikes and therefore, rejected by the computer. The multi-peaks in the spectra seem to be due to the interference of the wave trains arriving at the measurement station from different directions.

4.4.2 Variability of the wave parameters

Table 1 gives some of the important wave parameters computed by the three different methods using the same 20 wave records whose energy spectra are plotted in Figure 5A. It is interesting to note that the spectral peak frequency in the decaying stage is slightly higher than that in the growing stage. This trend can be observed throughout the period of the cyclone as indicated in Figure 5A and Table 1. Zero crossing wave periods computed by the three different methods also show this trend as the periods are slightly lower in the decaying stage than that in the growing stage of the cyclonic waves. Ochi & Chiu (1982) have observed similar trend for waves measured at a station off Florida coast in the case of a hurricane moving shoreward or inland of the point of measurement. Figure 5B shows the temporal variation of significant wave height and the radial distance from the cyclone centre to the wave rider station. It can be seen from the figure that the significant wave height decreases relatively faster in the decaying stage in comparison with the somewhat slow increase in the significant wave height

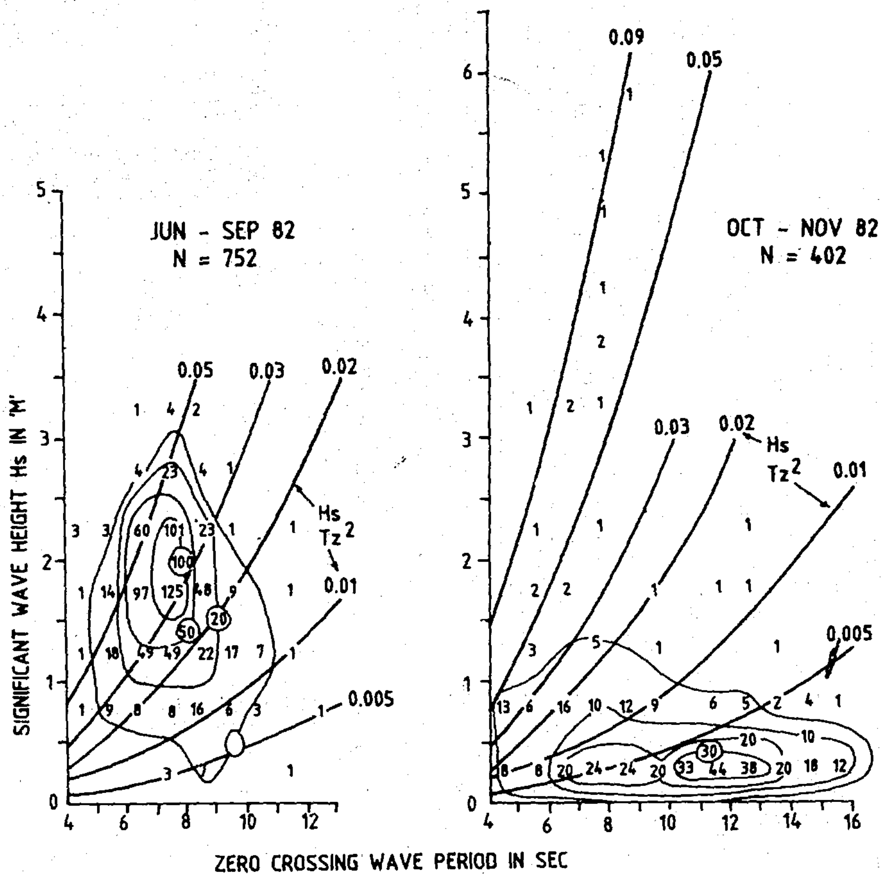

FIG. 4 JOINT DISTRIBUTION OF SIGNIFICANT WAVE HEIGHT VERSUS ZERO CROSSING WAVE PERIOD

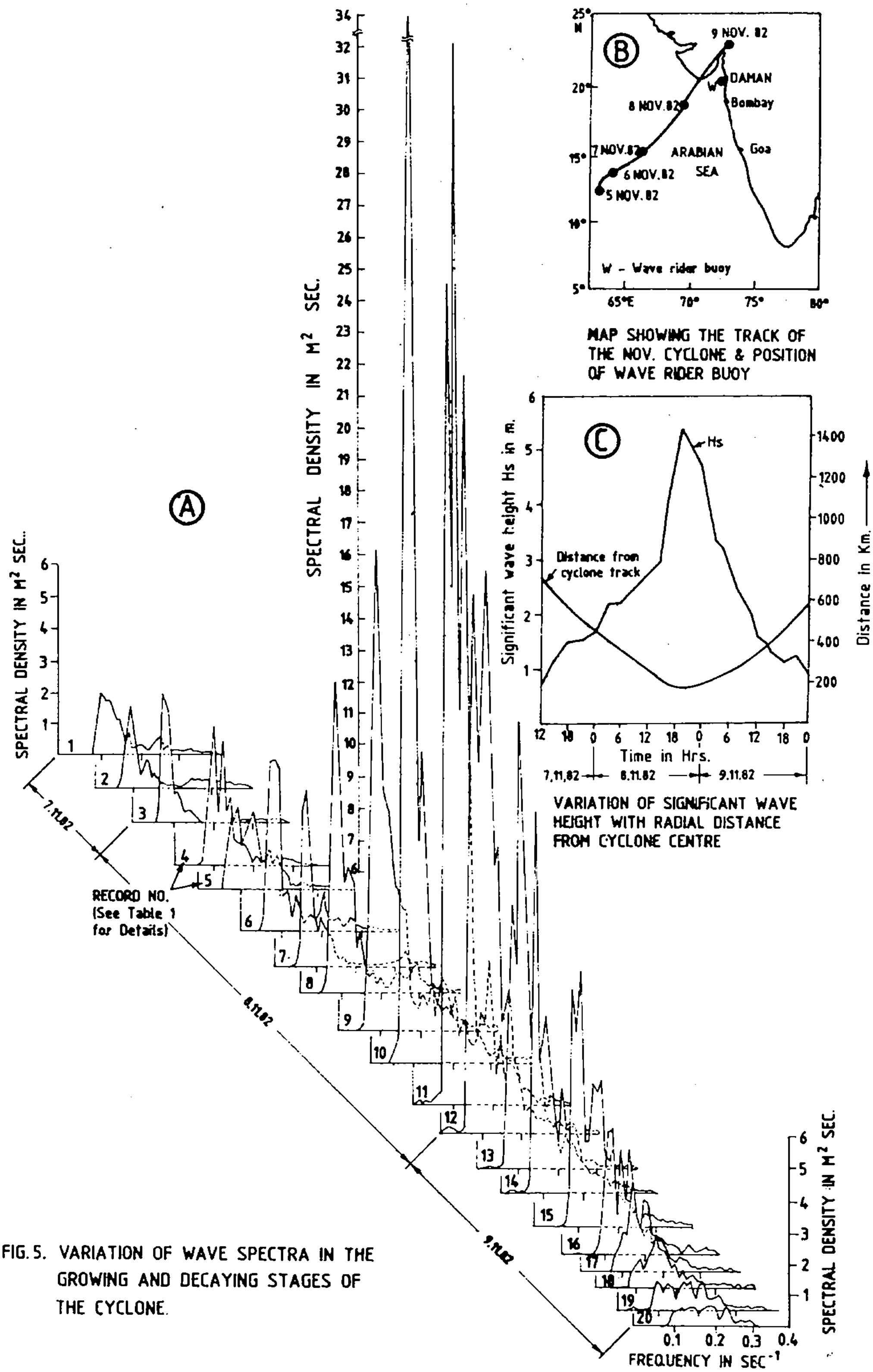

FIG. 5. VARIATION OF WAVE SPECTRA IN THE GROWING AND DECAYING STAGES OF THE CYCLONE.

Table 1. VARIATION OF WAVE PARAMETERS DURING THE CYCLONE

Record No.	Date & Time I.S.T.	Sig. Wave Height Hs in 'm'			Zero Crossing Wave Period 'Sec'			Peak Spectral Period 'Sec'	Spectral width Parameter	
		H_{ST}	H_{SS}	H_{4rms}	T_{ZT}	T_{ZS}	T_{mo2}		ϵ_T	ϵ_{sp}
	7.11.82									
1	1804	1.75	1.56	1.50	7.55	5.6	5.31	9.31	0.85	0.81
2	2103	1.58	1.56	1.50	7.08	4.98	4.87	11.51	0.85	0.85
	8.11.82									
3	0009	1.68	1.69	1.59	7.53	5.93	5.61	12.34	0.84	0.90
4	0310	2.05	2.21	2.04	8.66	6.27	6.08	8.68	0.76	0.84
5	0612	2.23	2.23	2.09	7.34	6.55	6.15	10.56	0.74	0.82
6	0859	2.52	2.49	2.34	6.79	6.55	6.21	12.96	0.86	0.87
7	1202	2.11	2.23	2.06	6.54	6.33	6.23	12.96	0.84	0.90
8	1457	3.19	3.08	2.80	7.02	6.55	6.30	11.01	0.80	0.85
9	1636	3.64	4.14	3.83	7.81	6.98	6.68	11.51	0.73	0.84
10	1801	4.21	4.67	4.31	8.10	7.40	6.87	11.13	0.70	0.82
11	1928	5.18	5.41	4.96	7.60	7.58	7.19	9.06	—	—
	9.11.82									
12	0007	3.91	4.72	4.32	8.30	7.44	7.41	10.78	0.59	0.77
13	0133	3.48	3.94	3.56	6.89	6.85	6.78	8.75	0.67	0.79
14	0310	3.32	3.35	3.03	6.87	6.37	6.17	10.89	0.64	0.79
15	0434	3.04	3.23	2.98	6.33	5.78	5.66	9.48	0.66	0.79
16	0734	2.32	2.46	2.27	5.61	5.28	5.16	8.61	0.67	0.78
17	1033	1.88	2.10	1.91	7.43	5.31	5.02	6.06	0.67	0.78
18	1206	1.65	1.65	1.60	5.52	5.16	4.86	5.75	0.56	0.77
19	1336	1.42	1.56	1.46	5.92	4.93	4.61	10.45	0.59	0.77
20	1456	1.33	1.32	1.28	5.79	5.07	4.66	5.63	0.60	0.77

Legend : H_{ST}, H_{SS}, H_{4rms}, : Significant wave heights and T_{ZT}, T_{ZS}, T_{mo2}, corresponding average wave periods (zero upcrossing period) by Tucker's, zero upcrossing and Spectral methods respectively. ϵ_T & ϵ_{sp} denote spectral width parameters computed by Tucker's and spectral methods respectively.

during the growing stage of the cyclone.

4.4.3 Comparison between measured and theoretical spectra

The measured spectra during the cyclone are fitted by the method of least squares with the commonly used theoretical spectral formulations to examine how well the cyclone generated nearshore wave spectra can be represented by currently available theoretical formulae. These include one-parameter Pierson-Moskowitz spectrum (1964), two-parameter Bretschneider spectrum (1959), two-parameter Scott spectrum (1965) and five-parameter JONSWAP spectrum (Hasselmann et al., 1973). Figures 6 and 7 present typical examples indicating that the Scott as well as the JONSWAP spectral formulations fit the measured spectra satisfactorily. However, it may be seen that the JONSWAP spectra fits closely at the peak frequency region whereas the Scott spectra is found to give comparatively a better overall fit to the measured spectra.

4.5 Inter-comparison of Results By Different Methods

In order to examine and compare the results of analyses by the Tucker's, Zero upcrossing and spectral methods used in this study, computed values of significant wave heights and zero crossing wave periods by the three methods for a selected 200 records were taken. A linear regression line was fitted to the various pairs of data by the method of least squares. The best-fit line giving the lowest value to the sum of squares of the deviations was drawn as shown in Figures 8, 9, 10 and 11. The regression coefficient r^2 was computed for evaluating the degree of correlation between the values under comparison using the usual equation. A regression coefficient close to 1.0 would indicate that there is a good correlation between the two sets of values being used for comparison.

4.5.1 Relationship between wave heights H_{sT} and H_{4rms}

Significant wave heights computed by the Tucker's method (H_{sT}) and that computed by the spectral method (H_{4rms}) were plotted as shown in Figure 8 and a regression line is drawn based on the method of least squares. A good correlation with a regression coefficient of 0.922 is observed. The linear relationship is found to be in the form $H_{sT} = 0.025 + 1.045\ H_{4rms}$ indicating that the significant wave heights obtained by the Tucker's method give 5 to 7 per cent higher values than those obtained by the spectral method.

4.5.2 Relationship between wave heights H_{ss} and H_{4rms}

Significant wave heights computed by the zero upcrossing or statistical method (H_{ss}) were plotted against those computed by the spectral method (H_{4rms}) and a regression line is drawn as shown in Figure 9. A very good correlation between H_{ss} and H_{4rms} can be noted with the regression coefficient equal to 0.957. The corresponding equation of the linear line of best fit is $H_{ss} = 0.005 + 1.015\ H_{4rms}$ which indicates that the significant wave heights computed by the zero upcrossing method give somewhat higher values in the order of 1.5 to 2 per cent when compared to those obtained by the spectral method.

From this, it may be concluded that the significant wave heights

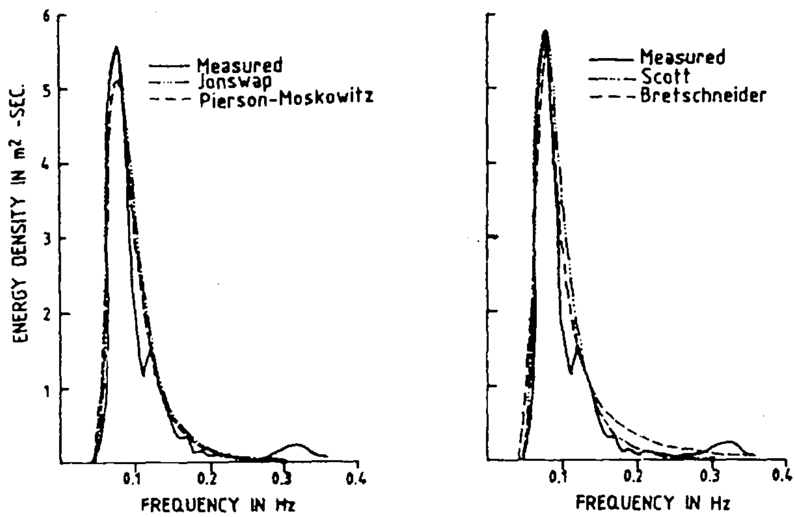

FIG. 6. COMPARISON BETWEEN MEASURED AND THEORETICAL SPECTRA (Hs=2.23m)

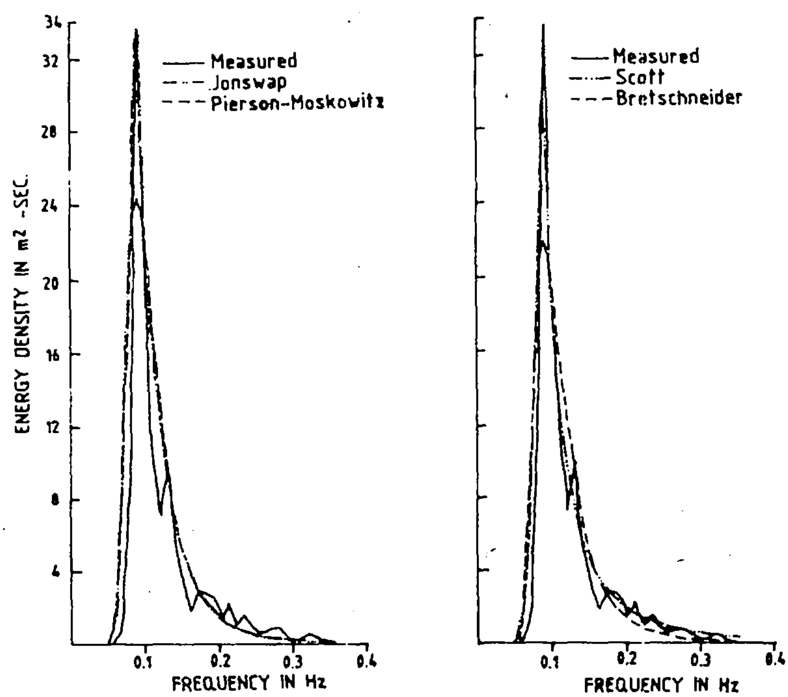

FIG. 7. COMPARISON BETWEEN MEASURED AND THEORETICAL SPECTRA (Hs=4.67m)

estimated by the Tucker's method are generally higher than those estimated by the other two methods, namely the zero upcrossing and the spectral methods. Whereas the spectral method has a tendency to give the lowest values for the significant wave heights when compared to those obtained by the other two methods.

4.5.3 Comparison between wave periods T_{ZS} versus T_{mo2}

Figure 10 presents a plot of zero crossing wave period (T_{ZS}) computed by the zero upcrossing method against that estimated by the spectral method (T_{mo2}). There is a considerable scatter of the data on either side of the line of best fit. The regression coefficient of the straight line fitted by the method of least squares is 0.748 and the equation of the linear relationship is $T_{ZS} = 0.396 + 1.007\ T_{mo2}$ indicating zero crossing wave periods obtained by the zero upcrossing method are generally higher than those computed by the spectral method.

4.5.4 Comparison between wave periods T_{ZT} versus T_{mo2}

As shown in Figure 11, the plot of the zero crossing wave period estimated by the Tucker's method (T_{ZT}) against those estimated by the Tucker's method (T_{ZT}) against those estimated by the spectral method (T_{mo2}) gives considerable scatter on either side of the line of best fit. This is indicated by the low value of the regression coefficient (= 0.391). The equation of the straight line of best fit derived by the method of least squares is $T_{ZT} = 1.781 + 0.798\ T_{mo2}$ indicating that the wave periods estimated by the spectral method are generally lower when compared to those obtained by the Tucker's method.

5. CONCLUSIONS

This paper presents the results of analysis of wave data measured off Daman on the west coast of India using three different methods: namely, the Tucker's, the zero upcrossing and the spectral methods. The wave climate off Daman is dominated by the south-west monsoon which gives rise to higher waves with shorter periods. During the non-monsoon period excluding the cyclone-affected days, the waves are comparatively smaller with longer periods. The cyclone generated waves which may occur in October or November are higher and steeper than those occurring during the rest of the year.

The maximum significant wave height of the south-west monsoon measured was 3.22 m with the associated zero crossing wave period being 7.5 sec. This occurred in July 82. The corresponding highest maximum wave height with associated wave period were 5.15 m and 8.5 sec. respectively. During the severe cyclone of 8 November 82, the maximum significant wave height and the highest wave height measured off Daman were 5.97 m and 8.40 m respectively.

Occurrence of most severe sea state at the measurement station coincided with the shoreward movement of the cyclone and hitting the land-fall point on the coast. The spectral peak periods as well as the zero crossing wave periods showed a tendency to be lower in values during the wave decaying stage when compared to those values in the growing stage of the sea state.

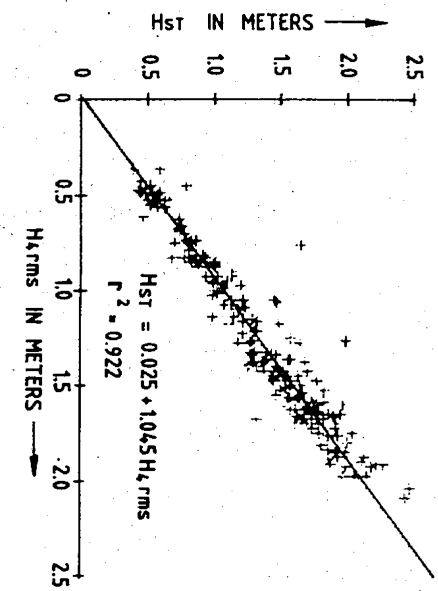

FIG. 8 PLOT OF H₄rms Vs Hst

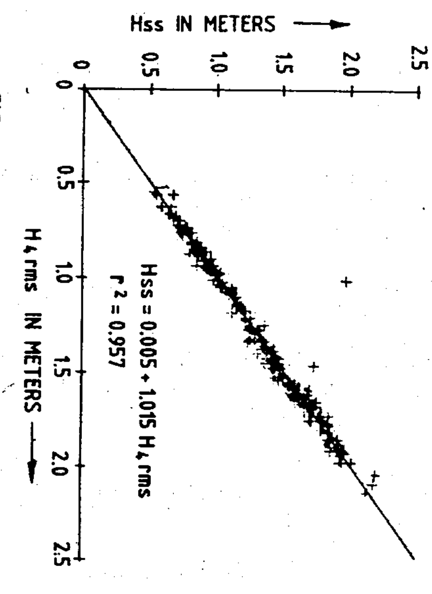

FIG. 9 PLOT OF H₄rms Vs Hss

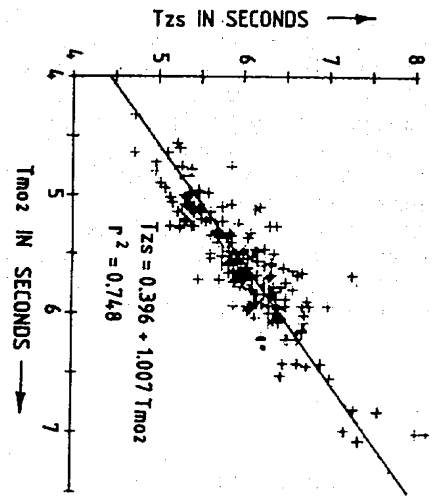

FIG. 10 PLOT OF Tmo2 Vs Tzs

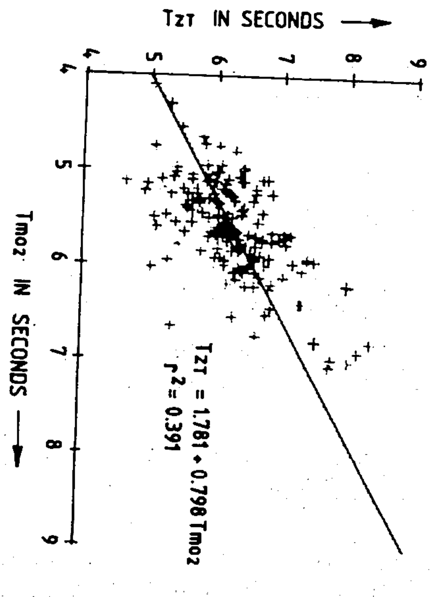

FIG. 11 PLOT OF Tmo2 Vs Tzt

A comparison between the measured and the theoretical spectra indicated that the two-parameter Scott spectrum gives comparatively better over-all fit whereas the five-parameter JONSWAP spectral formulation gives good fit in the peak frequency region of the measured wave energy spectrum.

Inter-comparison of the significant wave heights as well as the zero crossing wave periods estimated by the Tucker's, the zero upcrossing and the spectral methods indicates that there is a very good correlation between wave heights computed by different methods. However, the relationship between wave periods computed by different methods is not very good. Significant wave heights estimated by the Tucker's method are found to be generally higher than those estimated by the other two methods. The spectral method is found to give lower significant wave heights than those given by the zero upcrossing and Tucker's methods. Zero crossing wave periods estimated by the spectral method are lower than the average wave periods obtained by the zero upcrossing method.

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