

CHARACTERISTICS OF WAVE GROUPS IN THE ARABIAN SEA ASSOCIATED WITH  
CYCLONIC ACTIVITY

P. VETHAMONY      J.S. SASTRY  
Scientist            Head

Physical Oceanography Division  
National Institute of Oceanography  
Dona Paula, Goa - 403004, India.

ABSTRACT

A few deep water wave records collected during the cyclone and active monsoon phase were analysed to obtain wave group characteristics. The mean wave height is considered as the "reference level" to define a wave group instead of significant wave height. Based on narrow and sharply peaked spectra during the wave growth stage and energy transfer from lower to higher wave numbers, it has been surmised that wave group formation is more prevalent during this stage than during wave decay conditions. The study shows that waves of relatively large heights and short periods with steepness exceeding the theoretical limit ( $= 0.143$ ) can exist in a group in the neighbourhood of relatively low waves with longer periods. It is inferred that "jumps" may form only from a wave group after strong modulation in wave height and it need not have large steepness.

INTRODUCTION

The disastrous effects of wave groups have been known to the ancient sailors. However, little attention has been paid by ocean engineers to this phenomenon till recently. The damage to the Sines Main Breakwater, Portugal (Baird et al, 1980) and the attack of a highly elevated wave on the production platform at the Ekofisk area, Norway (Kjeldsen, 1984) have underlined the necessity for a review of the design practices to include the wave group characteristics while designing coastal and offshore structures. Wave groups may be responsible for slow drift oscillations of moored objects, capsizing of ships, instability of rubble mound breakwaters, etc. The phenomenon of wave "jumps" is probably more severe than has hitherto been assumed. A wave group is a sequence of high waves (exceeding a certain wave height) which is often called a run. If the number of runs are more in a record, the spectra will be narrow and sharply peaked and the maximum energy concentration may occur around the average period of the individual waves in the group.

During May, June and July 1979, several wave records have been collected in the East Central Arabian Sea using shipborne wave recorder under different wind conditions. The wave records show the formation of wave groups associated with cyclonic and monsoon conditions. A few records selected for wave group analysis represent the highest energy conditions recorded during the period of observation. The transfer of energy between waves during growth stage is argued to be the main contributing factor for the formation of wave groups. The study supports the finding of Kjeldsen (1984) that waves with steepness greater than the theoretical limit ( $= 0.143$ ) can exist in a group.

#### DATA AND ANALYSIS

R.V. Gaveshani had conducted three cruises in the East Central Arabian Sea during May, June and July 1979 as a part of the monsoon research programme of the National Institute of Oceanography (India). The period covers (a) the premonsoon phase when the winds are relatively calm, (b) the onset phase which could be triggered by a monsoon depression or a cyclone, and (c) the active monsoon phase when the winds are strong and steady in speed and direction. On 15th June a low pressure system formed in the Laccadives Sea and deepened into a deep depression and later into a cyclone, moving north-northwest and later in the northwest direction. The track of the cyclone and the location of the stations where the wave data have been collected are shown in Figure 1.

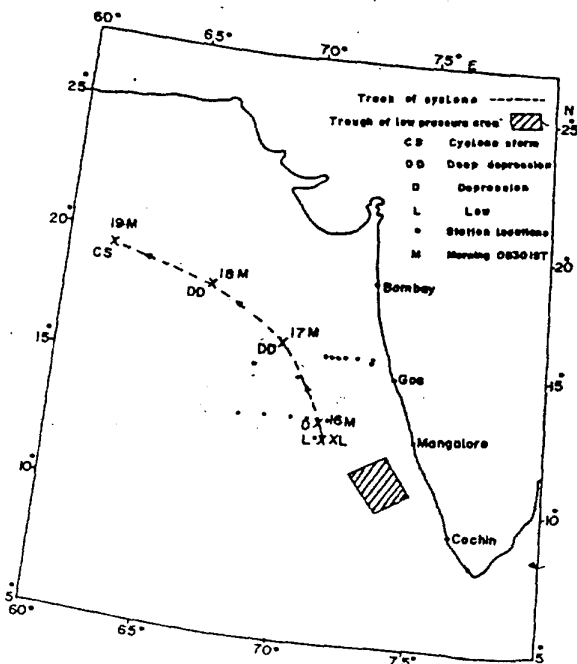
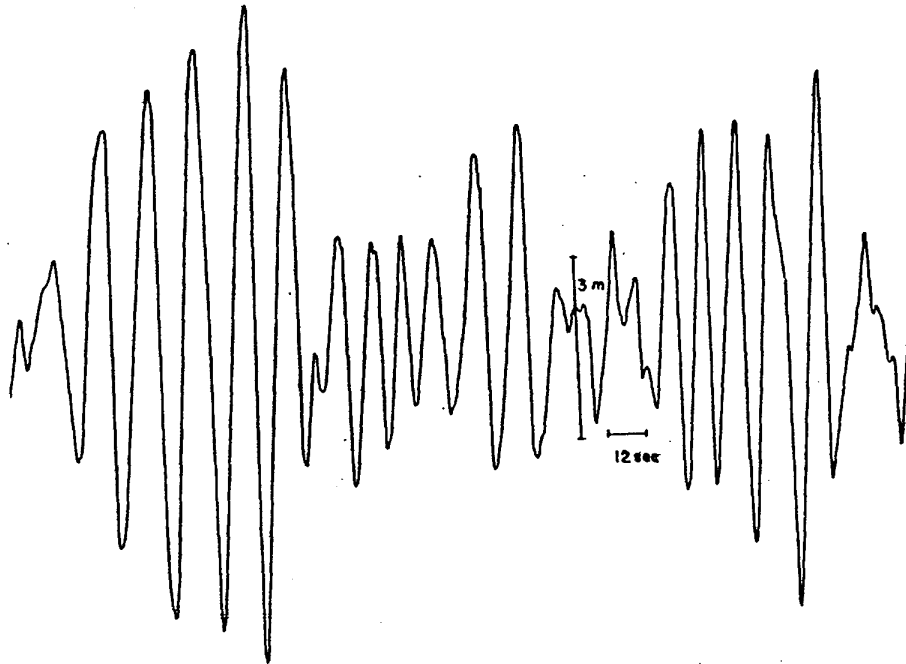


Fig. 1 Station locations and track of cyclonic disturbance.

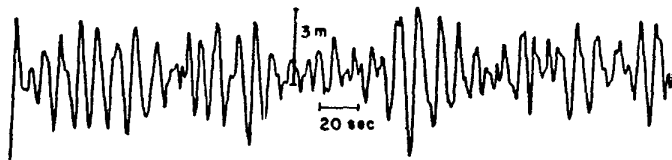
(A) Typical wave pattern  
(during calm weather)      Date : 26-5-79  
Time : 0015 hrs



(B) Typical wave groups  
(during cyclone)      Date : 18-6-79  
Time : 1330 hrs



(C) Typical wave groups  
(during active monsoon)      Date : 1-7-79  
Time : 1330hrs



Date : 17-6-79  
Time : 2305 hrs  
(D) A Typical Jump

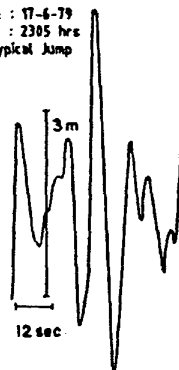


Fig. 2 Typical Wave Profiles

Figures 2 (A-C) show typical wave records pertaining to the three phases (Fig. 2A: low waves during calm weather; Fig. 2B: wave groups associated with cyclone; Fig. 2C: wave groups when monsoon was fairly well established and active; Fig. 2D: typical wave jump). The first 8 records were collected during the period when the depression intensified into a cyclone. The remaining records were collected during the active monsoon phase.

Wave spectra and statistics have been computed using the computer programs developed at the National Institute of Oceanography

TABLE I WAVE CHARACTERISTICS

Record No.	$T_p$ (Sec)	$Q_p$	Sk	Ku	E	$\bar{H}$ (m)	$\bar{T}$ (sec)	$H_s$ (m)	$T_s$ (sec)	$H_{max}$ (m)
1	09.0	2.25	0.24	3.14	0.57	1.74	08.9	2.55	08.6	3.59
2	10.3	2.23	0.06	2.73	0.52	1.87	09.8	2.62	10.2	3.57
3	11.1	2.96	-0.03	2.76	0.42	2.54	09.9	3.73	10.0	5.03
4	11.1	2.74	-0.10	3.26	0.42	1.80	09.1	2.58	09.6	4.24
5	10.3	2.35	-0.03	2.81	0.50	1.78	08.7	2.46	09.5	4.37
6	11.1	2.01	0.02	2.93	0.64	2.03	09.2	2.94	10.0	4.14
7	12.0	1.88	0.01	2.74	0.67	2.42	10.1	3.46	10.6	4.90
8	13.1	1.95	0.11	2.52	0.65	3.97	11.3	5.55	11.7	7.76
9	09.6	2.56	0.01	-	0.51	2.99	09.8	4.41	10.5	6.29
10	12.0	1.91	0.04	2.92	0.55	3.13	10.0	4.36	09.6	7.52
11	12.0	1.98	0.06	-	0.56	3.56	09.5	5.11	10.3	6.86
12	11.1	1.98	0.09	3.36	0.66	3.28	09.7	4.68	10.2	7.41
13	12.0	2.81	0.02	-	0.55	3.74	10.0	5.58	10.3	7.40
14	12.0	1.95	0.03	2.63	0.60	3.73	09.3	5.29	09.9	7.36
15	12.0	2.82	0.01	-	0.56	4.67	10.6	6.29	11.4	8.50
16	12.0	2.24	0.01	-	0.57	4.38	09.8	6.16	10.3	8.79
17	11.1	2.91	0.02	-	0.64	4.34	09.1	6.17	10.4	9.26

(Varkey and Gopinathan, 1980). Table I shows the wave statistics - spectral peak period ( $T_p$ ), spectral peakedness factor ( $Q_p$ ), skewness (Sk), kurtosis (Ku), spectral width parameter (E), mean wave height ( $\bar{H}$ ), mean wave period ( $\bar{T}$ ), significant wave height ( $H_s$ ), significant wave period ( $T_s$ ) and maximum wave height ( $H_{max}$ ). Percentage of waves exceeding  $\bar{T}$ ,  $\bar{H}$ ,  $T_s$  and  $H_s$  in each record were computed and are shown in Table II. The authors define a wave group to exist if there are two or more consecutive waves with heights or periods exceeding  $\bar{H}$  or  $\bar{T}$  rather than  $H_s$  (the reason for this criterion is given elsewhere). Hence for wave group analysis, the percentage of waves exceeding  $\bar{T}$ ,  $\bar{H}$ ,  $T_s$  and  $H_s$  in the groups were determined and are tabulated (Table II). From each group, wave group characteristics - group height ( $H_g$ ), group period (average period of the individual waves in the group,  $T_g$ ), maximum group height ( $H_{g,max}$ ) and maximum group period ( $T_{g,max}$ ) were computed and their averages over the whole record are tabulated (Table III).

TABLE II PERCENTAGE OF WAVE EXCEEDANCE

Record No.	$\bar{T}$	$\bar{H}$	Percentage of waves exceeding				$T_S$ group	$H_S$ group
			$T_S$	$H_S$	$\bar{T}$ group	$\bar{H}$ group		
1	47.7	43.1	53.8	12.3	33.8	23.1	44.6	03.1
2	47.8	39.1	39.1	14.5	37.9	27.5	24.6	04.3
3	57.9	47.4	56.6	11.8	43.4	28.9	42.1	10.5
4	58.1	45.3	47.7	14.0	47.7	27.9	36.0	03.5
5	58.4	52.8	43.8	13.5	42.7	38.2	22.5	04.4
6	56.3	40.0	43.8	16.3	53.8	29.5	36.3	05.0
7	53.8	50.0	48.8	15.0	41.3	37.5	36.3	00.0
8	47.2	49.1	41.5	09.4	28.3	45.3	18.9	03.8
9	56.8	45.5	42.0	13.6	45.5	27.3	26.1	00.0
10	46.5	53.5	53.5	11.3	32.4	39.4	39.4	02.8
11	55.0	48.8	37.5	15.0	36.3	35.0	18.8	05.0
12	54.2	43.1	48.6	18.1	44.4	25.0	40.3	09.7
13	52.4	41.5	48.8	15.9	39.0	20.7	34.1	02.3
14	53.5	44.2	39.5	14.0	38.4	31.4	26.7	07.0
15	60.0	37.8	40.0	15.6	46.7	20.0	26.7	08.9
16	52.6	46.2	39.7	11.5	38.5	34.6	25.6	07.7
17	55.6	42.0	29.6	13.6	40.7	28.4	16.0	00.0
Mean	53.8	45.3	41.5	13.8	40.6	30.6	28.2	04.6

TABLE III WAVE GROUP CHARACTERISTICS

Record No.	$\bar{T}_g$ (sec)	$\bar{H}_g$ (m)	$\bar{T}_{g \max}$ (sec)	$\bar{H}_{g \max}$ (m)	Average No. of waves per run in	
					$\bar{T}$ group	$\bar{H}$ group
1	10.2	2.37	11.4	2.95	3.7	3.0
2	12.2	2.48	13.7	2.84	3.1	3.8
3	11.4	3.75	12.5	4.48	2.8	3.1
4	10.9	2.55	11.9	3.08	3.2	3.0
5	10.1	2.28	10.8	2.66	3.2	2.8
6	11.0	2.89	11.9	3.32	3.3	2.4
7	12.4	3.08	14.0	3.65	3.7	3.0
8	13.9	5.22	15.2	6.07	2.5	3.0
9	11.6	4.04	13.3	5.25	3.3	3.4
10	12.2	4.29	13.3	5.01	3.3	2.3
11	11.4	4.87	12.7	5.89	3.6	3.5
12	11.9	4.65	13.2	5.64	3.2	3.0
13	12.2	5.14	13.3	5.96	3.0	3.0
*15	12.7	6.59	13.4	7.34	2.6	2.3
16	11.8	5.64	13.0	6.79	2.7	3.9
17	10.9	6.34	11.9	7.44	3.0	2.6
*14	11.0	4.93	11.9	5.48	3.7	2.7

## RESULTS AND DISCUSSION

As seen from Table I, fairly high waves existed due to the development of cyclonic and active monsoon conditions prevailing over the Arabian Sea during the period of observation. The maximum wave height is found to be higher ( $> 6.0$  m) during the active monsoon phase than during cyclonic conditions. During non-stormy and inactive monsoon periods waves in the Arabian Sea seldom exceed 2.0 m. Even though the number of occurrence of storms is very small in the Arabian Sea compared to that in the Bay of Bengal, the waves generated by the occasional storms and monsoon winds are severe enough to cause damage to coastal and offshore structures (most of India's offshore oil production activities are going on in the Arabian Sea).

### Wave - spectral characteristics and grouping

The spectra (Fig. 3) are single peaked and reveal the existence of single wave system. An analysis of wind data shows that the

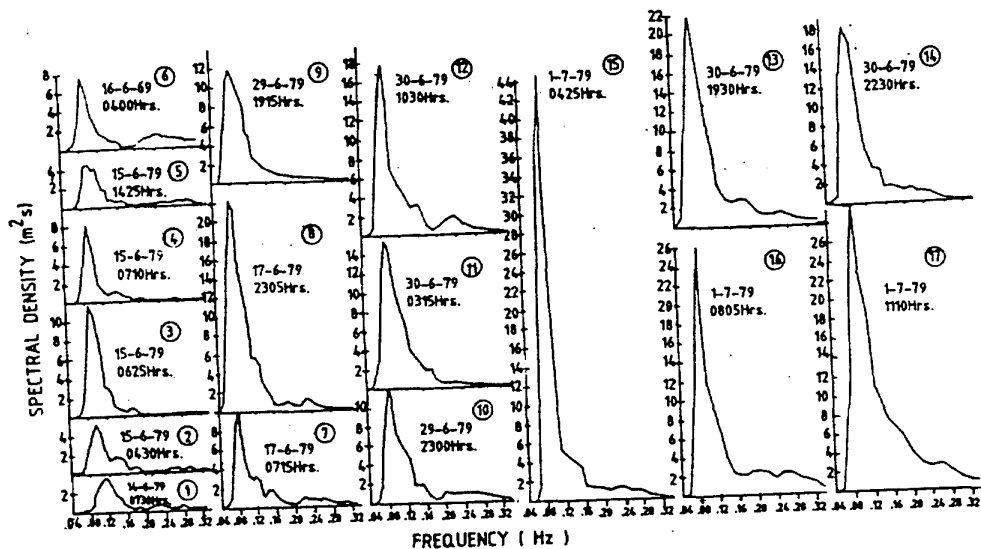


Fig.3. Wave Spectra.

wind speed gradually increases from 6-25 knots (approx.) between 14-18th June, 1979. Usually the winds are predominantly southwesterlies/westerlies over the Arabian Sea in the southwest monsoon season. Due to the formation of cyclone the winds have shifted to north-northeast direction. It is seen that as the wind speed increases spectral energy also increases gradually (spectra No. 1-8) and the spectral peak shifts towards low frequencies (0.111-0.076 Hz) depicting the generation of larger waves with longer periods.

Table I shows that skewness values (except three) are positive and relatively small. Kurtosis values are centered around 2.90. For an ideal Gaussian sea surface skewness and kurtosis would be zero and three respectively. The skewness and kurtosis values show that the sea surface is nearly Gaussian. Spectral width parameter values are relatively smaller, showing that the spectra are narrow-band. The authors do not find any relationship between the spectral peakedness factor and run length as was reported by Goda (1970). As the wave system travels away from the generating area, it gradually loses its higher frequency components and the spectrum becomes narrow with the major portion of the energy concentrated around its peak frequency (Refer the spectra). Also in the developing stage, the spectra are very steep as has been observed by Hasselmann et al (1973) during the JONSWAP Project. It is generally known that sharply peaked and narrow-band spectra indicate the presence of wave groups. Wave group formation is a non-linear phenomenon and the energy transfer from lower to higher wave numbers causes waves to travel in groups. The energy transfer mechanism is most efficient during wave growth stage. During the beginning of the decay stage swells exist in the wave field and these are only regular waves and not wave groups. Spectra of this regular wave system are also narrow and sharply peaked. Hence wave groups should not be confused with gentle swells. From the foregoing description, it may be surmised that wave group formation is more pronounced during wave growth stage than during wave decay conditions.

#### Wave - period, height and grouping

The values of  $T$  and  $\bar{T}$  show that if wave group formation is more pronounced, major part of the spectral energy will be concentrated around  $\bar{T}$  ( $\bar{T} \approx T_p$ ). It is known that wave groups in deep water are formed by the slow modulation of amplitude of nearly uniform wave trains. This wave sequence consists of a wave with a carrier wave number  $k_c$  and other waves with wave number around  $k_c$ . As the wave train travels, waves with higher wave numbers are superposed on waves with lower wave numbers and are overtaken by the longer waves. In this process, a "convergence" of the waves takes place and there is the possibility of waves growing in height before breaking. The energy content of the wave group after convergence will be much higher than that before interaction.

The percentage of waves exceeding  $\bar{T}$  and  $\bar{H}$  in period and height in the groups are 40.6 and 30.6 respectively (Table II); these are, of course, less than the percentage of waves above  $\bar{T}$  and  $\bar{H}$  (53.8 and 45.3 respectively) in the whole record (Table II). It is interesting to note that percentage of waves exceeding  $\bar{H}$  in the whole record (13.8) or in groups (4.6) is very small (Table II). It is noteworthy that in three cases, the number of waves exceeding  $\bar{H}$  in a group is zero, whereas the same wave records show well defined wave groups. This is the reason for not taking  $\bar{H}$  as the "reference level" to define the wave group, and considering instead  $\bar{H}$  or  $\bar{T}$ . The average number of waves per period group (= 3.2) or per height group (= 3.0) is found to be nearly the same. It need not be the same. Goda (1976) reports the number of waves exceeding  $\bar{H}$  on the average, as being close to 5. The maximum number of successive waves present in the period group (= 8) is greater than that in the height group (= 6). Considerable scatter in wave group statistics may be expected since wave group formation is purely non-linear in nature. Burcharth (1980) reports considerable scatter in the wave group statistics even for the very similar seas analysed.

Wave - steepness and grouping

Table IV shows a few identified waves with high steepness, some of them even exceeding the theoretical limit (= 0.143). It is

TABLE IV TYPICAL WAVE STEEPNESS (HIGHER VALUES)

Record No.	Wave height (m)	Wave period (sec)	Steepness	Preceding wave		Following wave	
				Height (m)	Period (sec)	Height (m)	Period (sec)
10	5.04	4.7	0.1451*	4.47	06.5	2.71	14.0
14	7.36	5.6	0.1455*	5.60	08.2	5.32	12.1
16	5.85	4.8	0.1629*	4.51	11.7	2.85	11.1
11	3.66	4.3	0.1224	3.60	08.2	5.67	09.9
12	2.85	3.6	0.1412	4.49	10.2	4.20	07.8
14	3.28	3.9	0.1370	6.24	09.8	3.17	11.5
14	4.39	4.6	0.1303	4.73	08.4	4.13	09.3
16	6.65	5.8	0.1266	5.95	10.0	5.70	10.0

\* Steepness exceeding the theoretical limit (= 0.143)

obvious from the tabulated values that such steep waves with short periods and relatively large heights can exist in a group in the neighbourhood of relatively low waves with longer periods (first 3 cases in Table IV only). The traditional concept that gravity waves break when they reach a steepness of 0.143 seems to be invalid where random gravity waves are concerned (Kjeldsen, 1984). The steepness value 0.143 (for wave breaking) is derived for a monochromatic wave train and for wave groups it should not be expected that the steepness limit for wave breaking to occur is 0.143 since the wave group formation is a non-linear phenomenon. In the present analysis the maximum steepness observed is 0.163. Kjeldsen (1984) after performing laboratory experiments reports that waves with steepness upto 0.21 could exist before breaking.

Jumps - dangerous waves

A "jump" is defined as a highly elevated wave whose height is greater than or equal to  $H_s$  and appears between small waves of heights less than or equal to  $\bar{H}$ . A few jumps identified from the analysis is shown in Table V. It is not necessary that  $H_s$  in a record should be a jump, unless it is followed and preceded by  $H_s^{\max}$  small waves. Referring to Table V, jumps are found to be larger waves with fairly low periods. The preceding and following waves may have longer or shorter periods, but heights should be less than  $\bar{H}$ . It seems that it is not necessary for the jumps to have large steepness (Table V). Melville (1982) suggests that large gradients occurring in the neighbourhood of local minima in wave amplitude may be due to the mechanism of crest pairing (one crest overtakes another and disappears). Kjeldsen (1984) indicates that these types of elevated waves are non-breaking, transient sea waves resulting



TABLE V TYPICAL JUMPS' CHARACTERISTICS

Record No.	Jumps			Preceding wave		Following wave	
	Height (m)	Period (sec)	Steepness	Height (m)	Period (sec)	Height (m)	Period (sec)
11	5.67	09.9	0.0370	3.66	04.4	1.86	07.5
12	5.23	10.7	0.0293	2.63	10.7	2.71	13.3
12	5.85	08.6	0.0508	0.94	10.9	2.05	09.6
13	6.25	11.0	0.0330	3.15	11.7	2.66	13.9
13	7.40	11.8	0.0339	1.10	04.1	2.84	08.9
13	6.69	12.0	0.0229	1.86	12.8	1.65	06.4
16	8.79	10.1	0.0557	2.74	12.5	2.41	10.9
17	6.32	10.7	0.0353	3.38	05.9	3.19	08.1

from superposition and phase locking of many individual waves upon each other. In the authors' view, a jump may form only from a wave group after strong modulation in wave height and after travelling further, it may grow in height or break depending upon the local conditions. In other words, a jump is a matured individual wave originating from a wave group.

#### CONCLUSIONS

An analysis of some wave records collected during the monsoon depression and active monsoon phase showed the presence of wave groups. A group consists of two or more consecutive waves with heights or periods above mean wave height or mean wave period and analysis has been carried out of height as well as period groups. All the spectra are single peaked and reveal the existence of single wave system. From the shape of the spectra and energy transfer process (mainly during wave growth stage) it has been surmised that wave group formation is more pronounced during wave growth stage than during wave decay conditions. If wave group formation is more pronounced, major part of the spectral energy will be concentrated around  $T_g$ . In some records, even two consecutive waves with heights above  $H_s$  is absent in spite of the fact that visual screening of the records show well defined wave groups. Hence instead of  $H_s$ , the mean wave height is considered as the "reference level" to define a wave group. The study shows that waves of relatively large heights and short periods with steepness exceeding the theoretical limit ( $= 0.143$ ) can exist in a group in the neighbourhood of relatively low waves with long periods. In the authors' view, a jump may form only from a wave group after strong modulation in wave height and after travelling further, it may grow in height or it may break depending upon the local conditions.

It is difficult to draw general conclusions regarding wave group characteristics with this limited data. For wave group analysis the usual 15 or 20 minute wave records pose the problem of extracting reliable wave group statistics since the number of wave groups present in this record length is very small. Continuous data during wave growth and

decay stages for different wind conditions are necessary to study the phenomenon of wave group formation.

#### ACKNOWLEDGMENTS

The authors are thankful to Dr. H.N. Siddiquie, Director, NIO, Goa for providing facilities to carry out this work. They are grateful to their colleagues onboard R.V. Gaveshani for the collection of data during the bad weather. They extend their sincere thanks to Dr. S.P. Kjeldsen, Chief Research Engineer, Norwegian Marine Technology Research Institute for going through the manuscript and giving comments.

#### REFERENCES

1. Baird. W.F. Caldwell. J.M. Edge. B.L. Magoon. O.T. and Treadwell. D.D. (1980): Report on the Damages to the Sines Breakwater, Portugal, Proc. 17th Coastal Engineering Conference, ASCE, Sydney, pp 3063-3077.
2. Burcharth. H.F. (1980): A Comparison of Nature Waves and Model Waves with Special Reference to Wave Grouping, Proc. 17th Coastal Engineering Conference, ASCE, Sydney, pp 2992-3009.
3. Goda. Y. (1970): Numerical Experiments on Wave Statistics with Spectral Simulation, Report of the Port and Harbour Res. Inst., Japan, Vol-9, No. 3, pp 3-75.
4. Goda. Y. (1976): On Wave Groups, Proc. BOSS Conference, Trondheim, pp 115-128.
5. Hasselmann. D.F. et al. (1973): Measurements of Wind Wave Growth and Swell Decay During the Joint North Sea Wave Project, Deutsches Hydrogr. Zeitschrift.
6. Kjeldsen. S.P. (1984): Dangerous Wave Groups, Norwegian Maritime Research, Vol-12, No. 2, pp 4-16.
7. Melville. W.K. (1982): The Instability and Breaking of Deep-water Waves, J. Fluid Mech., Vol-115, pp 165-185.
8. Varkey. M.J. and Gopinathan. C.K. (1980): Programs for Computing Energy Spectra and Other Related Statistics from Wave Records, Paper presented at the National Workshop on Energy from the Sea, Goa, Dec. 1980.