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Characteristics of a Breaking Wind-Wave Field in the Light of the Individual Wind-Wave Concept*

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Abstract: The relation between the intensity of breaking of individual wind-wave crests and parameters of wave size and wave form (*e.g.*, height, period, steepness and skewness) is examined, and the process of change of these parameters is studied in a wind-wave tank (reference wind speed $15\,\mathrm{m\,sec^{-1}}$, fetch 16 m). Distributions of the wave form parameters are different for breaking and nonbreaking waves. Fully breaking waves seem to hold the relation $H \propto T^2$, where H is the individual wave height and T is the period. The condition of breaking is not simply determined by the simple criterion of Stokes' limit. Wave height and steepness of a breaking wave are not always larger than those of a nonbreaking wave. This suggests the existence of an overshooting phenomenon in the breaking wave. The wave form parameters are found to change cyclically in a statistical sense during the wave propagation. The period of the cycle in the present case is estimated to be longer than four wave periods. An intermittency of wave breaking is associated with this cyclic process. Roughly speaking, two or three succeeding breaking-waves sporadically exist among a series of nonbreaking waves along the fetch.

1. Introduction

Breaking of wind waves occurs intermittently and sporadically, and it results in unsteady and nonuniform distributions of whitecaps including bubbles and spray droplets (Donelan *et al.*, 1972; Thorpe and Humphries, 1980). As a result, the effects of whitecaps on air-sea interaction processes, such as exchange of momentum and heat and scattering of light and microwaves, cannot be precisely estimated without taking account of this unsteady and nonuniform nature of whitecaps. However, in most cases, only an overall percentage of whitecap coverage or wave breaking has been the subject of measurement.

Since the whitecapping itself is a phenomenon which is associated with individual wave crests, the above unsteady and nonuniform nature should be investigated in relation to the characteristics of individual waves. As for breaking phenomena of individual waves, such as bubble entrainment and direct splashing of droplets, a few measurements have been made (*e. g.*, Toba, 1961; Toba *et al.*, 1975; Koga, 1981, 1982). The lifetime of individual whitecaps has also been measured by some investigators (*e. g.*, Monahan, 1969, 1971; Kondo *et al.*, 1973; Thorpe and Humphries, 1980), and mean characteristics of individual wind waves were studied by Toba (1978) and Tokuda and Toba (1981). The internal flow pattern of individual waves under nonbreaking conditions was investigated by Okuda (1982a, b, 1983). However, the relation between the individual whitecap and the characteristics of the individual wave, including its unsteady nature, is still not clear.

The present paper introduces wave form parameters, which describe the size and shape of an individual wave. The relation between the parameters and whitecapping phenomena was investigated in a wind-wave tank. Emphasis was placed on the unsteady and sporadic nature of whitecapping phenomena.

2. Experiment and analysis

The experimental set-up is shown schematically in Fig. 1. The intensity of breaking of an individual wind wave is classified on the basis

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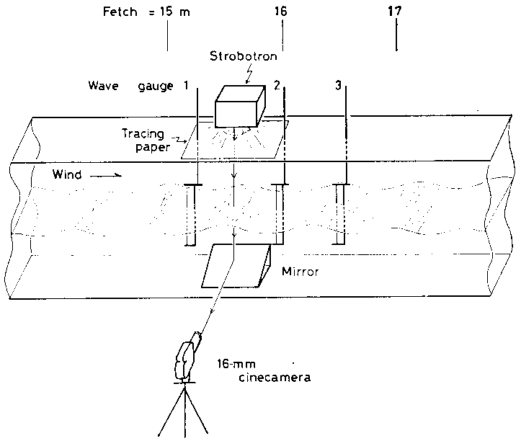

Fig. 1. Schematic picture of the experimental set-up.

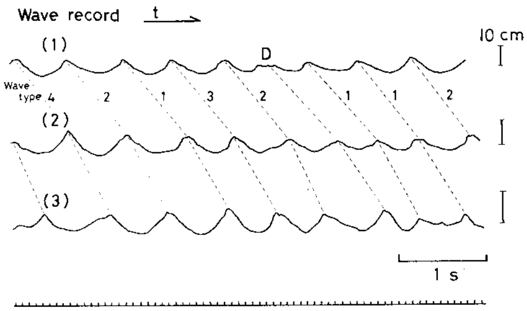

Fig. 2. Example of the wave records. The scale with vertical marks indicates the time of photographing. Individual wave crests clearly identified in the three wave records 1, 2 and 3 (measured by wave gauges 1, 2 and 3, respectively) are connected by dashed lines. Wave type of each individual wave is indicated by the numbers 1 to 4 as defined in section 2. *D* indicates a wave excluded from analysis because of its distorted form in the wave record.

of the amount of entrained bubbles. For the precise measurement of the amount, the wave surface was photographed from below by the use of a 16-mm cinecamera through a mirror placed on the bottom of the tank. A strobotron illuminates the tank from the top through a sheet of tracing paper, and distinct outlines of entrained bubbles and the characteristic pattern of the water surface were obtained as shadowgraphs. The elevation of the wave surface was simultaneously measured by three wave gauges installed at three fetches before and behind the photographed area (40 cm × 30 cm). The fetches for wave gauges 1, 2 and 3 are 15.16 m, 15.92 and 16.45, respectively. Examples of the wave record are shown in Fig. 2. The time of photographing was also recorded simultaneously with the wave record, as seen in the bottom of the figure. The wind-wave tank used was 20 m long, 0.6 m wide and 1.2 m high and contained fresh water 0.6 m in depth.

For wind-wave conditions at various fetches F and reference wind speeds at the center of the flume U_r, the reader should refer to the detailed description in Koga (1981). The present experiment was conducted under high-wind conditions $U_r = 15\,\mathrm{m\,sec^{-1}}$ (friction velocity $u_* = 148\,\mathrm{cm\,sec^{-1}}$). The significant wave height and period were 8.2 cm and 0.68 sec, respectively, and occasional breaking of wind waves with bubble entrainment was seen at a fetch of 16 m.

2.1. *Wave form parameters*

The definition of an individual wind wave was made in wave records as illustrated in Fig. 3a (Zero-crossing trough to trough method after Tokuda and Toda, 1981), and wave form parameters were determined, according to Tokuda and Toba (1981), by the use of the wave records as follows:

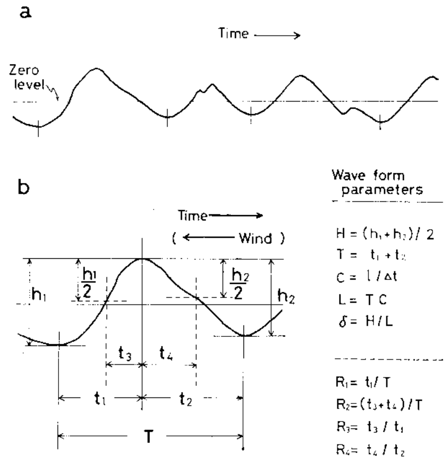

Fig. 3. Definition of individual waves and wave form parameters in a wave record. (a) The wave crest between adjacent vertical segments is the unit of the present analysis and is called an individual wave (zero-crossing trough-to-trough method of definition). (b) Definition of the wave form parameters.

$$\left.\begin{array}{ll}\text{wave height} & H=(h_1+h_2)/2 \\ \text{wave period} & T=t_1+t_2 \\ \text{phase speed of wave} & C=l/\Delta t \\ \text{wave length} & L=TC \\ \text{steepness} & \delta=H/L,\end{array}\right\} \quad (1)$$

where h_1 is the vertical distance between the crest and the downwind trough and h_2 the vertical distance between the crest and the upwind trough. t_1 indicates the time interval between the downwind trough and the crest and t_2 the time interval between the crest and the upwind trough on a wave record, while Δt indicates the time lag between the passing of a wave peak between two wave records measured at different fetches with a separation l. These parameters are illustrated in Fig. 3b.

In addition, the present study introduces the following nondimensional quantities,

$$\left.\begin{array}{ll} R_1=t_1/T, & R_2=(t_3+t_4)/T, \\ R_3=t_3/t_1, & R_4=t_4/t_2,\end{array}\right\} \quad (2)$$

where t_3 is the time interval between the surface point with height $h_1/2$ on the downwind trough and the crest, and t_4 the time interval between the crest and the surface point with height $h_2/2$ on the upwind trough on a wave record. These parameters are also illustrated in Fig. 3b. R_1 indicates the asymmetry or the skewness of wave shape in the horizontal direction and R_2 indicates kurtosis. R_3 and R_4 indicate the inclinations of downwind slope and upwind slope, respectively.

2.2. *Wave types classified according to intensity of breaking*

Waves were classified into four types based on the amount of entrained bubbles as follows:

Type 1: fully breaking,
Type 2: partly breaking,
Type 3: nonbreaking (1), and
Type 4: nonbreaking (2).

The amount of entrained bubbles was continuously photographed by a 16-mm cinecamera and examples of photographs ("view from below") for Types 1 and 4 are shown in Fig. 4. Type 1 is a wave in which bubble entrainment is seen in the whole width of the tank during in the whole time interval when the wave is passing the photographed area (Figs. 4a–4d). Type 2 is a wave in which bubble entrainment is seen over part of the width of the tank or over part of the time interval. Types 3 and 4 are waves without bubble entrainment, but they are distinguished on the basis of whether or not they have a clear convergent line on the downwind slope of the wave (*e.g.*, Koga, 1982) (Figures from 4e to 4h show Type 4). Type 1 and Type 4 are the two extreme stages with and without breaking, respectively. Type 2 and Type 3 represent intermediate states.

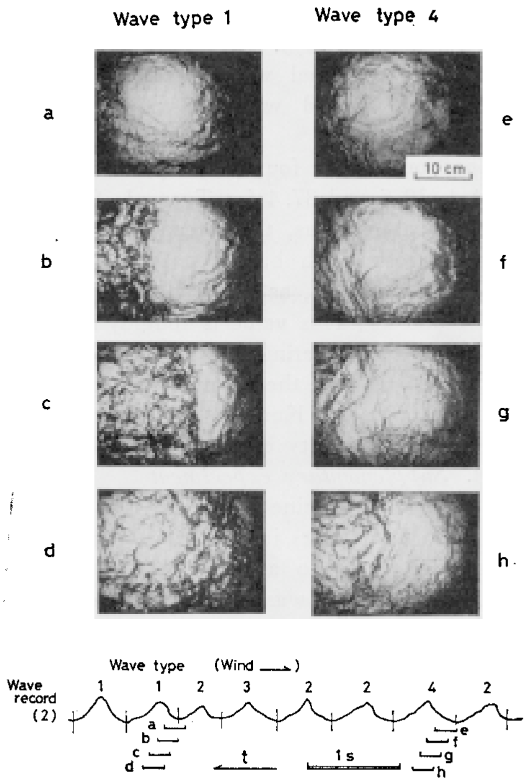

Fig. 4. Examples of successive photographs of the "view from below" for wave Types 1 and 4. Each short horizontal segment marked *a* to *h* under the wave record (2) measured by the 2nd wave gauge indicates the horizontal extent of each photograph.

In the case when an individual wave crest recorded by the 1st wave gauge cannot be identified in the record obtained by the 2nd wave gauge, or, even if the same crest is identified, when at least one of the two crests of the records is so distorted that the form parameters may not be clearly measured, the individual waves were excluded from the analysis. The percentage of excluded waves to the total (164 waves) was about 25%. Examples of the classification of individual waves including an excluded one (marked with D) are shown in Fig. 2.

Proportions of the four wave types are 27.6 %, 24.4, 10.6 and 37.4 for Types 1, 2, 3 and 4, respectively. Thus, the percentage of breaking wave crests with bubble entrainment at a fixed fetch is 52.0%, as given by the sum of Types 1 and 2. This value is roughly in agreement with the experimental relation between the percentage and the parameter u_*L/υ obtained by Toba and Kunishi (1970), where υ is the kinematic viscosity of air.

2.3. Supplementary experiment

In order to examine characteristics of the wave form parameters in the above experiment (hereafter referred to as "case 1"), a supplementary experiment was performed under low-wind conditions without wave breaking (hereafter referred to as "case 2"). The wind-wave tank used was 8.0 m long, 0.15 m wide and 0.70 m high and contained fresh water 0.53 m in depth. The wave record was obtained at a fetch of 3.7 m in wind conditions with a friction velocity $u_*=56\,\mathrm{cm\,sec^{-1}}$. In this condition, the significant wave height and period were 2.0 cm and 0.30 sec, respectively. A wave record which consists of 550 consecutive individual waves was analysed. As the wave record was obtained by one wave gauge, only H, T, R_1, R_2, R_3 and R_4 were determined in case 2. These wave form parameters were examined in the two cases.

3. Results

3.1. Relation between wave types and wave form parameters

Figure 5 shows the dependence of values of wave form parameters on the four wave types. Parameters with the mark Δ indicate the difference between the values at the 1st and 2nd wave gauges. Parameters without the mark Δ indicate the mean of the two values. Phase speed of wave C was calculated from the phase lag between the two wave records at the 1st and the 2nd wave gauges, and $\Delta C=C'-C$, where C' was calculated from the phase lag between the two wave records at the 2nd and the

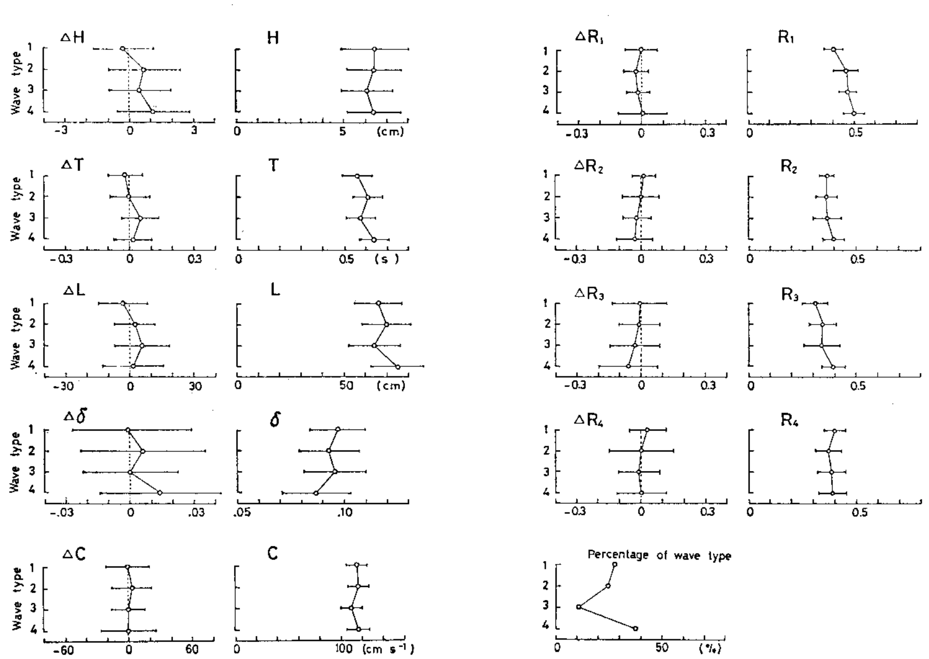

Fig. 5. Dependence of wave form parameters on the four wave types. Parameters with and without the mark Δ indicate the difference between the values at the two wave gauges (subtracting the value at the 1st wave gauge from the value at the 2nd wave gauge) and the mean of the two values, respectively.

3rd wave gauges. For the parameter R_1, dependency on the two extreme types (Type 1 and Type 4) is distinctive. For the other parameters, though the standard deviations for the values for the different wave types overlap, the mean value of some parameters (*e.g.*, T, L, δ) is significantly different between the two extreme wave types (*i.e.*, Types 1 and 4).

Differences in these values indicate that the form of individual waves differ between the two extreme wave types as follows. For Type 1, H is the same as that for Type 4, while T and L are a little smaller than those for Type 4. This results in δ being larger for Type 1 by about 0.01. R_1 for Type 1 is 0.4 which is smaller than the corresponding value for Type 4, and R_2 and R_3 are also a little smaller. These values indicate that individual waves of Type 1 are skewed forward and have a relatively sharp crest. On the other hand, for Type 4, the wave shape is not skewed forward as $R_1 \approx 0.5$.

The phase speed of individual waves is not so different between the two wave types and it shows negligible change along the fetch for both wave types. However, if we note the fact that L and T for Type 1 are smaller than those for Type 4, we can say that waves of Type 1 have a relatively large phase speed for their smaller L and T compared with those of Type 4.

Figure 6a shows the correlation of H and T. Individual waves of Type 1 (solid circles) are distributed approximately within the area enclosed by the two dashed lines which hold to the relation $H \propto T^2$. Individual waves of Type 4 (open circles) are distributed within an area that lies generally outside these two lines but some parts of these two areas overlap. Waves of Types 2 and 3 (solid and open triangles, respectively) plot between these two extreme types. Figure 6b shows the correlation of δ and R_1. The parameter R_1 most clearly distinguishes breaking waves from nonbreaking waves as seen in Fig. 5. Detailed inspection indicates a positive correlation between δ and R_1 for waves of Type 1. These figures show that wave types defined by the degree of breaking are related to the distribution pattern of the wave form parameters, and indicate that each wave type has a characteristic form in a statistical sense.

3.2. Change of wave form parameters during propagation and relation between wave types

Let us first examine the change of the wave form parameters using the data shown in Fig. 5

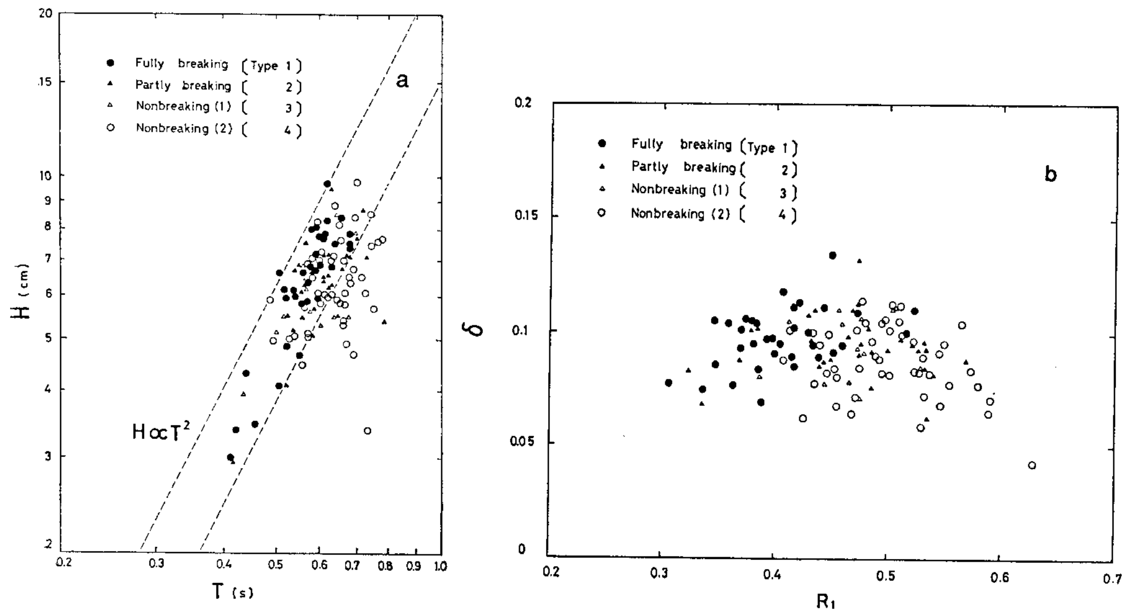

Fig. 6. Correlations between the wave form parameters. (a) H–T correlation. The dashed lines indicate the relation $H \propto T^2$. The four wave types are indicated by four symbols as indicated in the figure. (b) δ–R_1 correlation.

(parameters with the mark Δ), which were obtained from the 1st and the 2nd wave gauges. For Type 1, H, T and L decrease on average, while δ, R_1, R_2 and R_3 remain nearly constant. For Type 4, on the other hand, H, T and L increase, on average, as they propagate. The increase of H is especially distinctive, and is the main cause of the distinct increase in δ. At the same time, the decrease of R_2 and R_3 indicates a sharpening of the crest. However, waves of Type 4 do not seem to be skewed forward and have no clear tendency to be skewed, since R_1 is about 0.5 and changes little.

Figure 7 shows the change of mean values of the parameters H, T, δ and R_1 along the fetch including data from the 3rd wave gauge for waves of Type 1 and Type 4, where the wave type was determined from photographs taken between the 1st and 2nd wave gauges. For waves of Type 4, both T and R_1 barely change along the fetch, and remain at high levels, while H and δ increase along the fetch. On the other hand, for waves of Type 1, H and δ decrease along the fetch, but T and R_1 remain at low levels. These changes in the mean values of the parameters indicate that the form of an individual wave changes cyclically in a statistical sense and Type 1 and Type 4 represent the two extreme stages in this cycle.

Judging from the changes in H or δ in Fig. 7, the period of the cyclic process will be longer than two times the time interval t_{13} in which a mean individual wave passes from the 1st wave gauge to the 3rd wave gauge since less than half a cycle of change is observed in this interval. t_{13} can be roughly estimated using l_{13} (distance between the 1st and the 3rd wave gauges) and C (the mean phase speed) as follows:

$$t_{13} \approx l_{13}/C = 129\,\text{cm}/115\,\text{cm sec}^{-1} = 1.1\,\text{sec}.$$

Therefore, the period of the cyclic process will be longer than 2.2 sec in the present case. This corresponds to a time interval longer than four wave periods.

3.3. *Arrangement of wave types along fetch*

The temporal arrangement of wave types was observed in the present study using a 16-mm cinecamera that photographed an area covering about half wavelength. The transition from one wave type to another probably does not occur within one wave period, since, as discussed above, the period of the cyclic process is longer than four wave periods. Therefore, the spatial arrangement of wave types for two consecutive individual waves will not be different from their temporal arrangement in the wave record as they pass a fixed point. We can examine the spatial arrangement of wave types along fetch using the present experimental data.

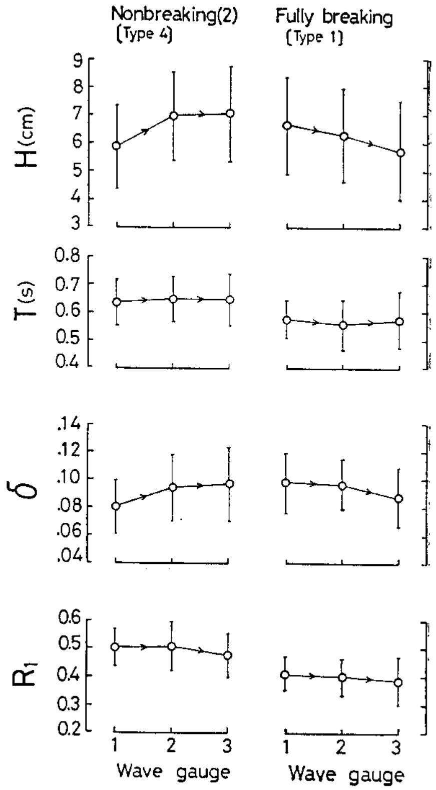

Fig. 7. Change of wave form parameters during wave propagation. Mean values of the parameters H, T, δ and R_1 are shown along fetch (from wave gauges 1 to 3) for the waves of Types 1 and 4. Vertical bars indicate the standard deviations.

Table 1 shows the percentage of a given wave type occurring just before (downwind side) or just after (upwind side) wave of Type 1 or 4. In some cases, a wave before or after belonged to the excluded ones, because of its strongly distorted wave form in the wave record. In such cases, if the same distorted crest could be identified in the records at the 1st, 2nd and 3rd wave gauges, the wave was also classified into one of the four types in order to prevent a decrease in the number of data. These additional

Table 1. Percentage occurrence of a given wave type occurring before or after waves of Type 1 or 4.

		Percentage occurrence of a wave type (%)			
		1	2	3	4
Overall mean		27.6	24.4	10.6	37.4
Wave type 1	down-wind wave type	36.1	30.6	11.1	22.2
	up-wind wave type	36.1	22.2	11.1	30.6
Wave type 4	down-wind wave type	17.5	28.1	10.5	43.9
	up-wind wave type	14.0	31.6	14.0	40.4

Table 2. Comparison of wave form parameters between the two cases

Case	Reference wind speed U_r (m sec^{-1})	Fetch F(m)	Friction velocity of air u_* (cm sec^{-1})	Significant wave Height $H_{1/3}$(cm)	Significant wave Period $T_{1/3}$(sec)
1	15	16	148	8.2	0.68
2	—	3.7	56	2.0	0.30

Case	H	T	Mean of wave form parameters R_1	R_2	R_3	R_4
1	6.4±1.3	0.61±0.08	0.463±0.064	0.376±0.051	0.354±0.072	0.388±0.061
2	1.4±0.5	0.27±0.05	0.446±0.074	0.432±0.059	0.421±0.079	0.440±0.076

data were only used for analysing the arrangement of wave types in consecutive waves. As a result, three series of wave record data consisting of 81, 54 and 29 consecutive waves were available for analysis. Waves of Type 1 (36 samples) were most frequently preceded by waves of Type 1 (36.1% occurrence) and less frequently (22.2% occurrence) by waves of Type 4. The same tendency is seen for the wave type on the upwind side. Thus, waves of Type 1 have a wave of the same type before or after them more frequently than would be expected if the arrangement were random. Similarly, waves of Type 4 (58 samples) have a wave of Type 4 before or after them more frequently than other types.

These results suggest that consecutive breaking waves (as represented characteristically by Type 1) sporadically exist among a series of nonbreaking ones (as represented characteristically by Type 4). Intermediate wave types, Types 2 and 3, modulate the above arrangement. At the same time, it should be remembered that each individual wave in the arrangement will change its wave type with time according to the above described cyclic process. Therefore, the actual arrangement of wave types will shift relative to the propagating waves, thereby maintaining the sporadic occurrence of breaking waves.

3.4. *Wave form parameters in low-wind conditions*

In Table 2, mean values of wave form parameters in low-wind conditions (case 2: wave field without breaking) are compared to those in the high-wind condition (case 1: wave field with occasional breaking). R_1 does not differ much between the two cases. But, R_2, R_3 and R_4 for case 2 are larger than those for case 1 by about 0.06. This indicates that the degree of asymmetry of the wave shape in the horizontal direction as indicated by R_1 does not differ much between the two cases. However, the sharpness of wave crest indicated by R_2, R_3 and R_4 for case 2 is not more pronounced than that for case 1.

4. Discussion

The present study indicates that the wave form parameters of individual waves change cyclically and Types 1 and 4 represent the two extreme stages of the cycle while Types 2 and 3 are intermediate stages between these two extremes. Okuda (1982b) has pointed out the existence of such a process of cyclical change for individual wind waves under low-wind con-

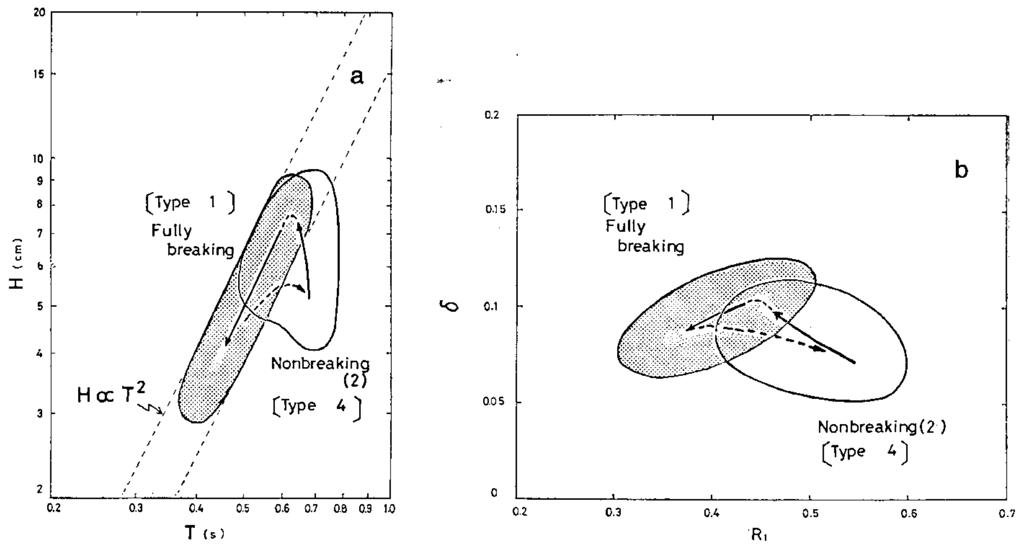

Fig. 8. Schematic representation of the cyclical process of change of an individual wave in the correlation diagrams. Arrows indicate the direction of the cycle. (a) Process of change in the H-T correlation. Dashed lines indicate the relation $H \propto T^2$. (b) Process of change in the δ-R_1 correlation.

ditions without breaking in a wind-wave tank. The present study indicates that this cyclic process of change also occurs under high-wind conditions with occasional breaking. Figure 8 shows schematically the process of change in the H-T and δ-R_1 correlation diagrams. Actually, since waves in a wind-wave tank develop along the fetch on average, the cyclic process may not be a closed one. In addition, each individual wave does not necessarily undergo the whole process of change without disappearing because of the intrinsic irregularity of the waves. The cycle shown in Fig. 8 is a statistical one. Intermittent breaking and the sporadic occurrence of breaking waves will be associated with the cyclical process of change of the waves.

The cyclical process of change is expected to occur when waves proceed through a wave packet consisting of high and low amplitude waves. The packet may be a result of an instability of a wave train, such as a side-band instability of gravity waves, as discussed by Benjamin and Feir (1967). Donelan *et al.*, (1972) observed whitecaps being formed sporadically in the ocean. They related the sporadic formation of whitecaps to the dynamics of the wave packet. They supposed that individual wave breaking (whitecap) occurs if the wave attains a Stokes' limit of wave steepness during its passage through a wave packet, and that the whitecap persists until the steepness falls below the limit. Their supposition for the sporadic formation of whitecaps seems reasonable.

The present results, however, show that the conditions for breaking are more complicated than the simple supposition of Donelan *et al.* (1972). H and δ of the breaking wave are not always larger than those of the nonbreaking wave, and the distributions of these parameters for both the breaking waves and the nonbreaking waves overlap each other. This suggests the existence of overshooting in the breaking process or in the process of recover of an individual wave.

The above complexity is caused partly by a direct coupling of the individual waves with the air flow over them. Okuda (1982a, b) has shown that a vorticity layer caused by the shearing stress is concentrated near the crest and that growth and decay of the layer are closely related to the cyclical process of change of individual waves. The coupling is very effective in strong wind conditions such as in the present study ($u_* = 148\,\mathrm{cm\,sec^{-1}}$). It is a result of the coupling of the waves with the air flow that individual waves are skewed forward even in the case of their overall mean, as seen in the present experiment. The steepness of the fully breaking waves ranges rather widely from 0.07 to 0.13 and the mean value (about 0.1) is much smaller than the Stokes' limit of 0.142, as seen in Fig. 6b. This can be attributed to the fact that the conditions for breaking (especially the formation of bubbles) are strongly controlled by the wind-induced local surface current as pointed out by Koga (1982). For short wind waves such as in the present case, most bubbles are formed by entrainment caused by convergence of the surface current on the downwind slope near the crest.

In this paper, we have treated individual waves as a unit of a wave field. The similarity structure of these waves will be a result of their direct coupling with the air flow over them as discussed by Toba (1978) and Tokuda and Toba (1981). The present results have shown that each of the wave types (especially Types 1 and 4) have characteristic distributions of wave form parameters. This suggests that the similarity structure of the different wave types varies slightly in relation to the cyclical process of change of individual waves. In fact, in Fig. 6a, only the waves of Type 1 (solid circles) are approximately distributed within the area enclosed by two dashed lines indicating $H \propto T^2$.

The similarity relation $H \propto T^2$ for fully breaking (Type 1) waves can be derived dimensionally, if H is not dependent on the friction velocity u_*, but is dependent on g (acceleration of gravity) and T only. Namely,

$$H = AgT^2, \qquad (3)$$

where A is a nondimensional universal constant. A is about 2.0×10^{-2} for the mean of the two dashed lines in Fig. 6a. The gross distribution of all the points is along the 3/2-power law, $H = B(gu_*)^{1/2} T^{3/2}$, which was presented by Toba (1978) and is supported experimentally by Tokuda and Toba (1981), where B is a nondimensional universal constant. The H-T relation which is independent of u_*, for fully breaking waves may be interpreted as indicating that the influence of surface drift (specified by u_*) is not explicitly important in realizing the limiting form of breaking waves.

The present experiment has shown that wave form parameters are good indicators for describing unsteadiness of individual waves in a wave field with frequent breaking. The supplementary experiment suggests that the simple wave form parameters R_2, R_3 and R_4 are useful indicators for the investigation of the mean characteristics of individual waves under different wind conditions including cases without breaking. However, the main part of the present experiment was conducted under only one wind condition. Further measurement is necessary for clarifying the dependence of wave form parameters on wind and wave conditions including the cases for a wave field without breaking.

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個々波の概念から見た崩れを伴う風波場の特性

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要旨: 風洞水槽において，個々波の崩れの程度と個々波の大きさや形状を示す波形パラメーター（たとえば，波高，周期，スティープネス，スキューネスなど）の関係を調べ，崩れ波の非定常性や散在性を論じた（代表風速 15 m sec^{-1}，フェッチ 16 m）．波形パラメーターの値には，崩れ波と非崩れ波とで差が見られる．そのうち，十分崩れている個々波の波高 H と周期 T のあいだには，$H \propto T^2$ の関係があることが推察できた．崩れの条件は単純なストークス限界より複雑である．崩れ波の波高やスティープネスは非崩れ波の場合に比べ必ずしも大きいとはかぎらない．これは崩れ波のオーバーシュートの性質を示唆している．波形パラメーターは，平均像として個々波が伝播するにつれ周期的に変化することが推定できた．その周期は個々波の平均的周期の 4 倍以上と見積られ，崩れの間欠性はこの周期的変化と関連している．また，崩れ波は，大まかに言って，フェッチ方向に 2，3 個つらなって存在することがわかった．

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