Journal of Coastal Research	SI 50	307 - 311	ICS2007 (Proceedings)	Australia	ISSN 0749.0208

Correlation of Breaking Wave Characteristics with Energy Dissipation

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ABSTRACT

LEKSHMI G.R. and SANNASIRAJ S.A., 2007. Correlation of Breaking Wave Characteristics with Energy Dissipation. Journal of Coastal Research, SI 50 (Proceedings of the 9th International Coastal Symposium), 307 – 311. Gold Coast, Australia, ISSN 0749.0208

It is well accepted that wave breaking has a dominant role on the dynamics of upper layers of the ocean. While a lot has been learnt about wave breaking including the kinematics and dynamics of mixing, wave energy losses and ambient noise, there are many issues that are yet to be resolved These include the issue relating the energy dissipation with the wave spectral characteristics. In the present paper, the dependence of intensity of wave breaking on the energy dissipation has been studied. The simulation of wave breaking has been carried using constructive wave-wave interaction approach. The various intensities of breaking ranging from plunging to spilling have been generated in the controlled laboratory wave flume. The energy dissipation has been measured by tracing the water surface from pre-breaking to post-breaking zone. The results showed a noted difference in the amount of energy dissipation with the intensity of breaking. The study also reveals that wave breaking results in redistribution of spectral energy. Energy loss is found to be more towards the high frequency end.

ADDITIONAL INDEX WORDS: *Plunging, spilling, spectral redistribution*

INTRODUCTION

Breaking of waves is a dominant force dictating several complex oceanic processes. It results in various phenomena like air entrainment, generation of sound, energy dissipation etc. This has attained a lot of attention over the past years due to the impact of the resulting phenomena on various coastal engineering problems. Numerous works have been done to clearly understand the dynamics and kinematics of wave breaking. This includes both numerical studies and experimental work.

Wave breaking plays an important role in air-sea interaction. Air is entrapped during wave breaking resulting in the formation of a bubbly layer which significantly influences the exchange of mass, energy and momentum between atmosphere and ocean (LAMERRE, 1993).

The turbulence associated with wave breaking is considered to play a major role in mixing and dispersion processes. It also aids sediment transportation. Yet another important phenomena associated with wave breaking is the generation of sound. Laboratory studies conducted by SANNASIRAJ AND CHAN (2001) shows that the acoustic energy radiated during wave breaking is proportional to the energy dissipation and the square of the maximum wave slope parameter.

Waves lose considerable amount of their energy during breaking. Several laboratory works have been carried out in recent years to clearly understand the mechanism of energy loss during wave breaking. The amount of energy lost varies with the type of breaking. Plunging waves have been found to lose up to 25% of their initial energy whereas less than 10% of the initial energy is lost during a spilling breaker (RAPP AND MELVILLE, 1990). KWAY et al. (1997) reported 14-22% energy loss for plunging breakers.

Wave breaking also results in redistribution of spectral energy. During wave breaking, the energy spectrum undergoes significant changes under the combined effects on non-linear energy transfer and dissipation (PRINOS et al., 2004). It has been found that the energy loss is predominantly from the higher frequency end (ZHANG AND YUAN, 2005; SANNASIRAJ et al., 2000). STANSBERG (1992) noted a slight increase in energy towards the low frequency end. MEZA et al. (2000) reported that wave components of frequencies less than the spectral peak gain a small portion of (about 12%) energy lost by the high frequency components.

Several numerical studies have also been carried out to understand wave breaking. BANNER AND TIAN (1996) studied the growth rates of energy and momentum in breaking waves.

Despite numerous research works carried out in this field, the wave breaking characteristics has not been fully understood. This can be attributed to the very complex nature of wave breaking and the resulting phenomena. The highly unpredictable nature of the occurrence of wave breaking in the field adds to the problem. MELVILLE AND MATUSOV (2002) studied the distribution of wave breaking using aerial imaging and found that the number of breaking fronts per unit area of ocean surface is proportional to the cube of the wind speed.

The present work focusses on the energy dissipated during breaking and its dependence on the various spectral parameters. Study has been carried out on different kinds of breakers. These were generated from the same wave packet but with different intensities of breaking ranging from spilling to strongest plunging. The energy dissipation for various kinds of breaking has been compared. It attempts to throw light on the spectral redistribution of energy after wave breaking. The study also aims at correlating the steepness parameter with the energy dissipation.

EXPERIMENTAL STUDY

The experiments were carried out at the 2m wave flume of the Dept. of Ocean Engineering, IIT Madras, India. The wave flume is 30m long and 2m wide. It is attached with a piston type wave maker. The water depth in the flume was maintained at 0.8m through out the experiments. The schematic diagram of the experimental set up is shown in Figure 1.

Simulation of breaking waves

Breaking waves can be simulated in laboratory using different methods like wind shear, shoaling, wave focussing or using external stimulants. In the present study, the breaking wave simulation has been achieved through constructive interference of sinusoidal wave components. The wave packet consisted of 28 sinusoidal wave components of different frequencies. The phases of each component are chosen such that it results in constructive interference at the desired location.

The free surface displacement as per linear theory is given by the equation,

$$\eta(x,t) = \sum_{n=1}^{N} a_n \cos(k_n x - \omega_n t - \phi_n) \qquad (1)$$

where x is the distance from the wave maker, N is the total number of wave components, a_n is the amplitude of the nth component, ϕ_n is the phase of the nth component and ω_n is its radial frequency. k_n is the corresponding wave number. The phase of each component can be computed by the setting,

$$\cos(k_n x_b - 2\pi f_n t_b - \phi_n) = 1 \qquad (2)$$

where x_b is the location of wave breaking and t_b is the time of breaking. This implies,

$$\phi_n = k_n x_b - 2\pi f_n t_b + 2\pi m \quad (m = 0, \pm 1, \pm 2 \ldots..) \qquad (3)$$

Constant steepness spectrum was generated. The centre frequency and the band width of the spectrum are 0.76Hz and 0.68Hz respectively.

The time of breaking was set to 20s. By carefully varying the overall gain factor (G), five different kinds of waves namely the incipient breaking, spilling, weak plunging, good plunging and strong plunging were generated. All the four breakers were tuned to break at the same point. Waves were breaking at t = 18s. The point of breaking was noted to be 8.3m away from the wave maker. For the strongest plunging the gain factor was observed to be 0.748. The waves become weakly plunging for a gain factor of 0.649. The spilling breaker was tuned to a gain factor of 0.637. Gain factor of 0.72 gave a good plunging.

Measurement of energy dissipation

The energy dissipation (E_d) at a point is determined as the ratio of total energy density at that point (E_i) and the incident wave energy measured at a distance of about one wavelength before the location of wave breaking.

$$E_d = \frac{E_i}{E_o} \qquad (4)$$

A set of six conductance based wave probes were used for this purpose. They work on the principle of change in the total impedance value with the fluctuating water level. Out of the six wave probes, wave probes 1 & 6 were fixed at a distance of 4m and 12m respectively from the wave maker. The wave probes 2, 3, 4 and 5 were arranged 30cm apart. These four probes were then used for tracking the water surface profiles at various locations along the flume length before and after breaking. The time histories of water surface profiles at different points at 5-10cm intervals along the flume length starting from 7m to 10m from the wave maker were recorded. The rate of sampling was maintained at 0.005s at all locations. The points nearer to the breaking point were tracked at a closer interval of 5cm in order to capture the exact point of breaking.

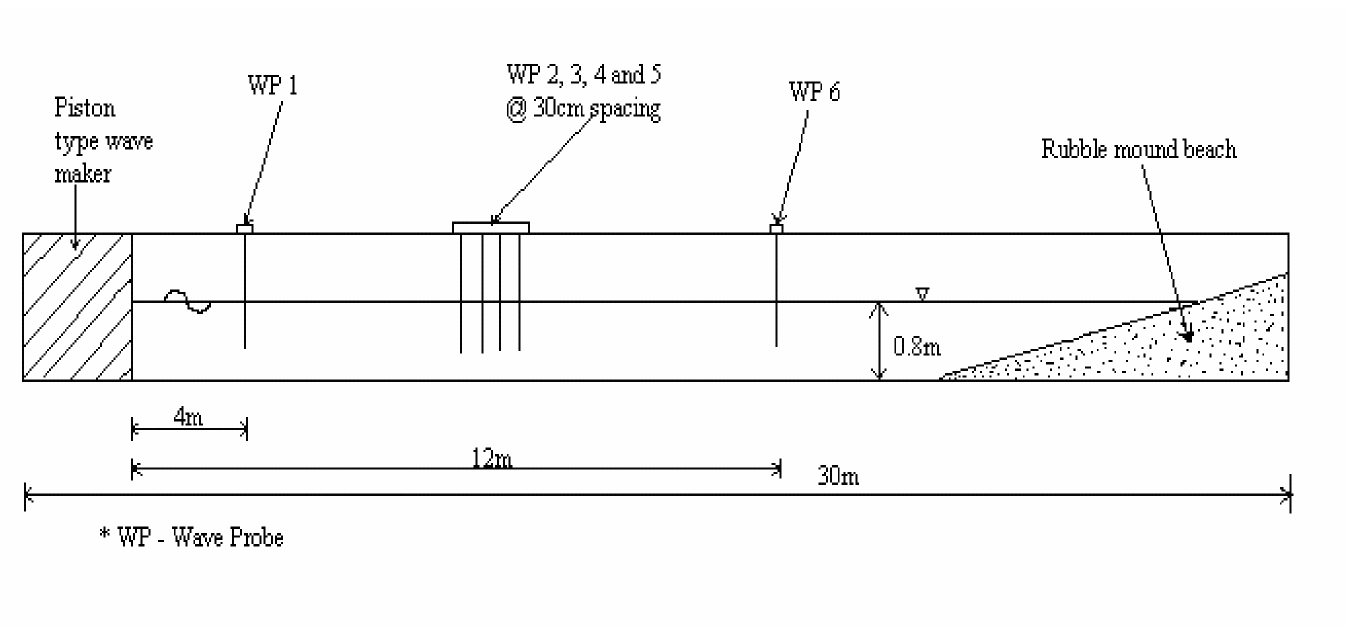

Figure 1. Sectional view of the experimental set-up

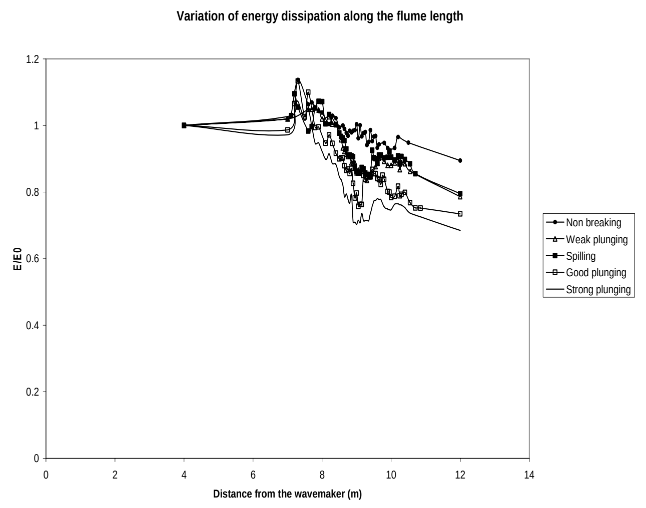

Figure 2. Normalised energy versus the distance from the wave maker

RESULTS AND DISCUSSION

The time histories of water surface profile at various locations along the wave flume were recorded using the wave probes. Results showed that there is a good agreement between repeated measurements of water surface profiles recorded by different probes at any location. Data were collected for 30s at a sampling frequency of 200Hz.

The time series were subjected to FFT to obtain the frequency spectrum and the total energy at each point was then computed. The readings recorded by the wave probe 1 were taken as reference and the energy at all other points were then normalised with the incident energy.

Energy dissipation

The variation of normalised energy density along the length of the flume for all the five stages of wave breaking is shown in Figure 2.

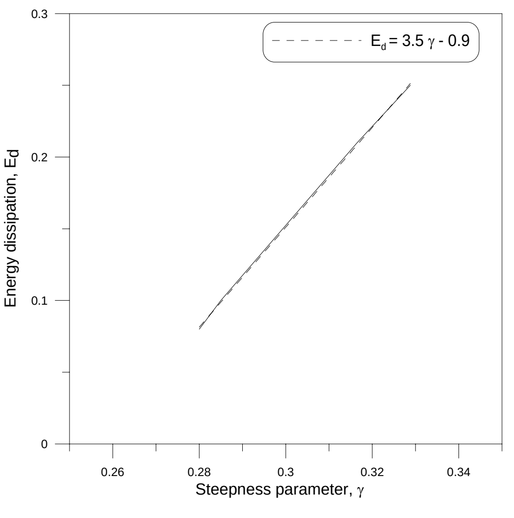

Figure 3. Variation of energy dissipation with the wave steepness parameter

The spectral analysis of the results showed that there is a net energy loss of about 3.5% in a non breaking wave propagating over the defined length of the flume. This is accounted to the frictional loss. Deducting this amount from the total energy lost in the other kinds of breakers, it is found that the strongest plunging breaker loses about 25% of its energy, whereas a spilling breaker dissipates about 8% of its energy during breaking. The weak plunging breaker which was tuned very close to the spilling breaker dissipates about 9% of its initial energy during the process of breaking. Energy loss of about 21% is found to occur in a good plunging breaker.

An attempt has been made to correlate the dissipation rate with one of the commonly used wave breaking characteristics, i.e., wave steepness. The steepness parameter (γ) was computed using,

$$\gamma = G\,a\,k_c \tag{5}$$

where G is the gain factor, a is the amplitude corresponding to the centre frequency and, k_c is the corresponding wave number. Figure 3 presents the variation of the energy dissipation rate with the steepness parameter γ.

It is interestingly noted that the variation of rate of dissipation of energy is proportional to the steepness parameter. Hence, the energy dissipation rate of a wave breaking event can be estimated from the steepness parameter using,

$$E_d = 3.5\gamma - 0.9 \tag{6}$$

The correlation coefficient and the root mean square error obtained by using Eq. (6) are 0.99 and 0.45%, respectively. The slope of the curve might dictate the frequency distribution of incident wave energy. Further studies are underway to estimate the slope of the curve from other wave spectral parameters. In third-generation wind-wave models, the wave breaking dissipation is accounted to be proportional to the overall steepness parameter (THE WAMDI GROUP, 1988). However, the steepness parameter is defined in terms of tunable dissipation coefficient and the proportionality power has also been adopted as a tunable parameter to arrive at better wave prediction. The results from the present study would lead to address these tunable coefficients in the dissipation source term of a wind-wave model.

Frequency redistribution

Figure 4 shows the variation of wave frequency spectrum before and after spilling type of breaking. The energy spectra at locations 4m, 8.3m, 8.9m and 12m away from the wave maker are plotted for each case. The point of breaking is noted to be at 8.3m. It can be seen that the energy loss had occurred from the frequency band above the peak frequency. However, a relatively significant amount of energy loss is observed near the peak frequency. Figures 5 to 7 show variation of energy spectrum during plunging (weak, good and strong plungers) type of breaking, respectively. The loss of energy is mainly from the high frequency tail of the spectrum above the peak frequency. Except for weak plunging case, there is no loss of energy near the peak frequency for good and strong plunging cases. This may be due to the frequency shifting during severe plunging type of breaking. The loss of energy is predominantly from a frequency range of 0.8Hz to 1.1Hz.

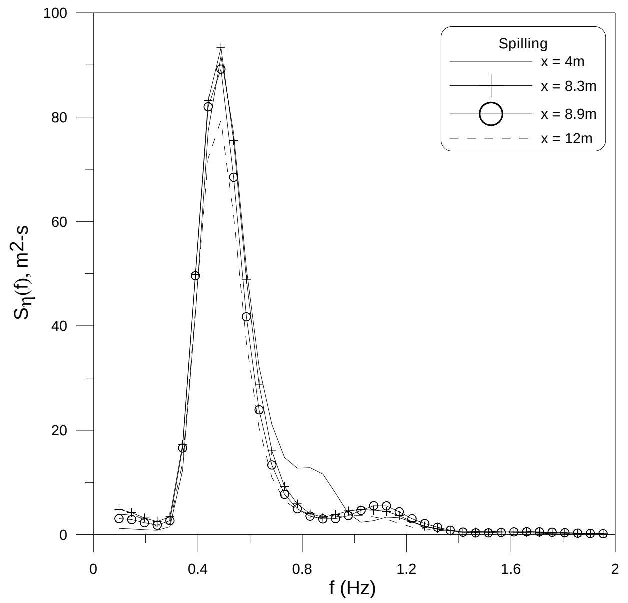

Figure 4. Variation of wave frequency spectrum for spilling breaker before and after breaking.

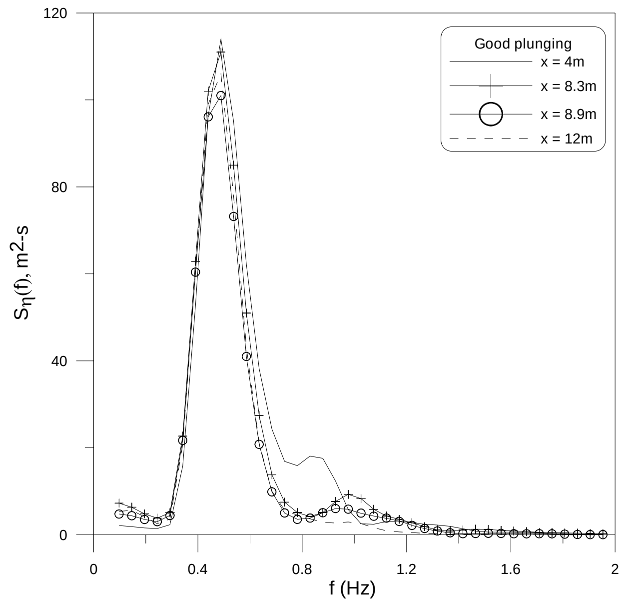

Figure 6. Variation of wave frequency spectrum for good plunging breaker before and after breaking.

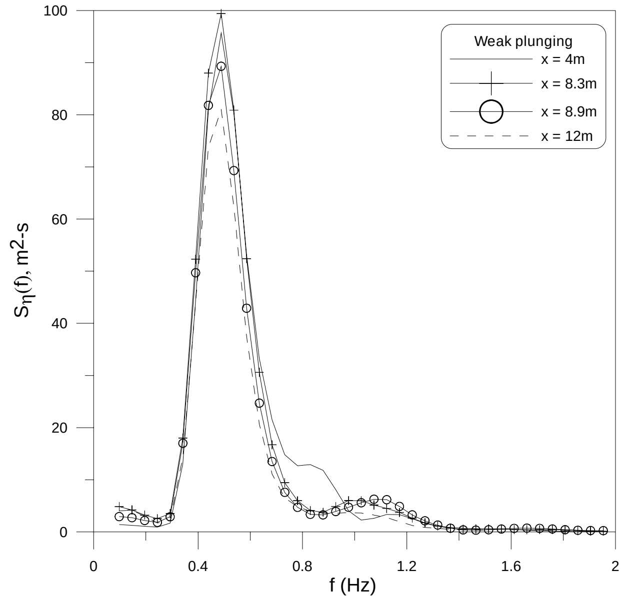

Figure 5. Variation of wave frequency spectrum for weak plunging breaker before and after breaking.

CONCLUSION

In this paper, the dependence of the rate of energy dissipation during wave breaking with other characteristics of wave breaking has been examined. An experimental study was carried out to simulate different intensities of wave breaking ranging from spilling to plunging. The amount of energy dissipation during breaking showed a notable change with the intensity of breaking. There is about 8% loss due to spilling breaker and a maximum of 25% energy loss due to strong plunger. Hence, the interdependence of the energy dissipation with the steepness parameter was studied. It has been found that the dissipation rate is proportional to the steepness parameter. However, further studies are required to estimate the proportionality constant. The frequency variation of energy density during the process of wave breaking shows significant features. The net energy loss is found to be mainly from the high frequency spectral components.

ACKNOWLEDGEMENTS

This work is supported from the research project sponsored by Naval Research Board, India.

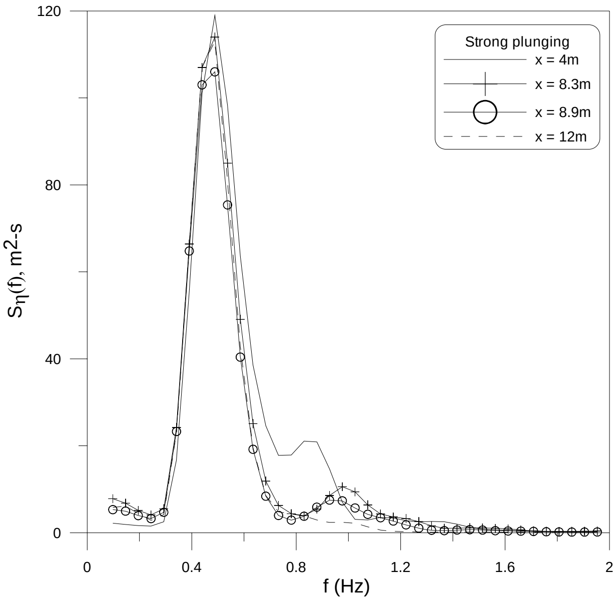

Figure 7. Variation of wave frequency spectrum for strong plunging breaker before and after breaking.

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