

CHAPTER 76

PROBABILITY OF WAVE BREAKING IN THREE-DIMENSIONAL SEAS.

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Introduction

Current guidance notes for the design of offshore or coastal structures to withstand breaking waves are based on the behaviour of long-crested, monochromatic waves. It has been acknowledged for some time that although useful for first approximations and in some cases conservative load estimation, the adoption of long-crested wave theories and design principles for a short-crested sea environment may be inappropriate.

Halliwell & Machen (1981) have shown that in shallow water, isolated breaking waves under short-crested conditions can occur with greater elevations and hence potentially greater destructive power than existing design codes predict. Similarly work by Easson & Greated (1984) has highlighted deficiencies in wave theories to predict particle velocities and accelerations within waves by direct non-contact measurement of these properties, the implications being that such theories may significantly underestimate the total wave loading encountered under breaking waves. These observations call into question our ability to predict accurately and so design to withstand wave breaking effects in short-crested environments.

This paper reviews some of the present approaches to the prediction of wave breaking or whitecapping occurrences and compares data

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collected offshore with simulations conducted in wave basin facilities in Edinburgh, which illustrate that wave breaking can occur at wave steepnesses significantly below those which are commonly assumed to represent the onset of breaking implying that design procedures must recognise and allow for this.

Survey of Reported Studies

Several authors have investigated the statistical properties of wave breaking by the visual observation of sea or model sea conditions to characterise properties of breaking or whitecapping wave crests.

Holthuijsen & Herbers (1986) observed the occurrence of whitecaps at a wave recording buoy in open sea conditions off the Dutch coast, the situation being such as to effectively represent a deep sea environment. Concurrent with the wave data, a visual identification time history technique for identifying the occurrence of whitecaps at the buoy permitted their correlation with wave elevation. By this method, each wave crest between zero-downcrossings could be individually distinguished as a whitecap or an undisturbed, plain wave. Their work compared the marginal and joint probability distributions of a number of wave characteristics (height, period, steepness, etc.) for both wave types together with a brief look into breaking occurrences within wave groups and as a function of wind speed. Unfortunately, although directional measurements were made at the site by the buoy, the nature of the resulting wave spectra were not presented.

Certain of the present authors recently pursued a similar series of investigations under model conditions using a video time logging technique (Mather et.al. 1988) to identify the occurrence of whitecaps on the resulting time history and other wave crest instabilities which were judged to be breaking waves. Under these idealised conditions - free of the effects of wind input, non-stationary wave conditions and currents - it was shown that no single geometric property of directionally spread waves recorded by a conventional omni-directional probe, could be used to distinguish breaking from plain waves.

These appear to be the only experiments reported which visually identify the breaking of waves and correlate them to elevation time histories in a three-dimensional environment, that is to say other than in a wave flume.

Papers by Kjeldsen & Myrhaug (1980) and Kjeldsen et.al. (1981) have established a number of wave geometry properties determined from single point measurements which are useful first descriptions of individual waves. In addition to the conventional definition of Wave Steepness (see Appendix), they also define Crest Front and Rear Steepnesses, Horizontal and Vertical Crest Assymetries. They established the advantages to be gained from using an analysis based on the Zero-Downcrossings rather than Crest or Zero-Upcrossing Period, from the standpoint of physically representative parameters and visual interpretation. They justify their opinion that the joint probability density function of Crest Front Steepness and Wave Height (evaluated between zero-downcrossings i.e. Crest to Preceding Trough) provides the most relevant characteristic for the useful forecasting of breaking waves (at high values of each property) but no guidance is given as to the quantitative regression line useful for this purpose.

Snyder and Kennedy (1983) investigated the probability of occurrence of whitecapping over an area at a fixed instant of time as distinct from other authors who considered temporal characteristics at discrete points. They argue the virtues of a variety of plausible wave and sea-surface characteristics which may potentially influence the occurrence of wave breaking. They assume that a single property may be adopted to form the basis of their theory and suggest on heuristic grounds that this must be a scalar quantity and exhibit relative maximum values only at wave crests. This leads to the identification of wave elevation, vertical surface acceleration and surface curvature as candidate properties. The use of elevation as an identifier is readily dismissed since breaking can be observed over a range of wave heights, just as some of the largest waves do not necessarily break. The argument used to dismiss the adoption of surface curvature is that of the practical difficulties to be encountered in quantitative description, analytical treatment and especially its measurement. Such problems of description and analysis stages are not insurmountable as work by Longuet-Higgins (1962) and Glazman (1985) demonstrates, whilst those of measurement do not seem to have been addressed in recent years in the context of water waves, despite the advances in topographic and remote-sensing methods.

X-Band microwave backscatter experiments by Kwoh & Lake (1984) operating with wavelengths of approximately 3cm, reported that backscattering events occurred in discrete bursts which were highly correlated with wave breaking events, contributions to these signals coming from the "background waveform" (the dominant source) and parasitic capillaries. Experimenting with a scanning laser-slope gauge they point out that scattering begins slightly before breaking under relatively smooth surface conditions, whereas conventional microwave backscatter detection relies on Bragg-Wave size surface roughness and that at peak response time the only high frequency feature in their tests are small radii wave crests implying that this small scale curvature may be a causal property of wave breaking. Srokosz (1988) however has pointed out that turbulence behind a breaking wave also leads to locally high curvatures and thus cannot reliably be applied as a characteristic, prerequisite to breaking.

The remaining identifier, that of vertical component surface acceleration, has so far seemed to yield the most promising identification results both in experiments (Snyder et.al. 1986) and theoretically [Longuet-Higgins 1969, Ochi & Tsai 1983, Srokosz 1984, Tung & Huang 1987, Huang et.al. 1986).

Huang et.al. (1986) developed an analytical description of whitecap coverage using the acceleration threshold criterion applied to probabilistic expressions of wave crest amplitude. As with other theories, they apply the restriction that wave breaking only occurs at wave crests in their model and so do not generalise the total coverage to include the effect of entrained foaming water which can be distinguished visually. The model is based on the Wallops spectrum (Huang et.al. 1981), containing the influence of the wind frictional velocity u_* , but the method could easily be applied to the more widely adopted Pierson-Moskowitz or JONSWAP system. In the work of Snyder et.al. the probabilistic description was obtained without adopting the (empirical) u_* and so is to be preferred as an analytic predictive tool although the empirical relationship in the Huang & Long model is probably no less valid and indeed may be preferred for its relative simplicity.

The work of Ochi & Tsai (1983) was one of the earliest to develop a probabilistic function for wave breaking occurrences, basing their efforts on the need to establish a more reliable statistical relationship between wave height and wave period, of those waves which would break. Their Figure 3 illustrates the difficulty in applying a single numerical relationship between these properties either as an average or an upper limiting criteria.

Model Simulation of Sea States

The Fluid Dynamics Unit at Edinburgh University has obtained wave data in the form of elevation plus two subsurface particle velocity components from a Southern North Sea platform site.

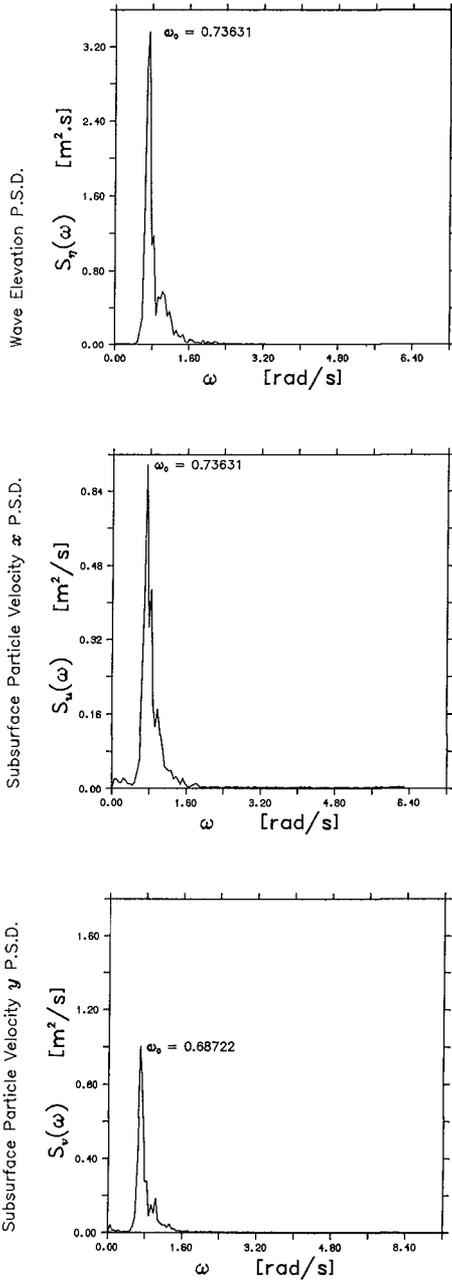
To extract the requisite spectral information from these records, the "Extended" Maximum Likelihood Method, due to Isobe et.al. (1984) was implemented. Sample resulting omni-directional point spectra of wave elevation and particle velocities together with the directionally spread variation of elevation spectra are shown in Figure 1. The growth in the spectral peak and its spread to lower frequencies as the storm developed was clearly visible when comparing successive sample spectra.

To investigate the probabilistic properties of wave breaking in the sea states computed from the site data, wave basin reproduction of these results was undertaken in the Edinburgh University Wide Wave Basin. This facility is described elsewhere [Salter, 1981] but briefly occupies a working area of 23m x 5m with 1.2m depth and with eighty, 0.3m width wavemakers occupying one long side. The wave generation system currently implemented is the "mixed frequency snake" summation of wavefronts permitting specification of the reproduced seas' RMS amplitude and discrete spectral form together with a discrete comb type directional spreading function.

The task of evaluating the directional wave spectrum in the wave basin poses the same problems of the same task at full size. In our experiments, the same analysis technique (the EMLM) was used as for determining the site directional spectrum, except that rather than elevation / velocity component combinations of data being analysed, it was decided to construct and use an array of conventional fixed wave probes. Seven probes were used and arranged as two regular, common-axis Mercedes-Benz style stars each of differing arm radius. This arrangement is more valuable in situations where the principal wave direction is unknown rather than for our application in a wave basin of known direction but the experience gained will, we feel, be of value when more fully assessing the analysis procedure at a later date.

Based upon visual inspection of the site spectra, we chose to attempt our simulations with the peak enhanced JONSWAP spectral form combined with the Cosine-power directional spreading function over a restricted range of angular values considered appropriate for modelling purposes ($\pm 45^\circ$) and beyond which the site data fell off to less than three percent of the peak value. The success of the simulations hinges on finding suitable parameters of the existing formulations, to match in a least squares way, the model form to the site results (Figures 2,3).

For the purposes of simulation this approach is not ideal, and the



British Gas / HGB Offshore Data
 η, u, v Frequency Spectra ... Data Set #9

FIGURE 1

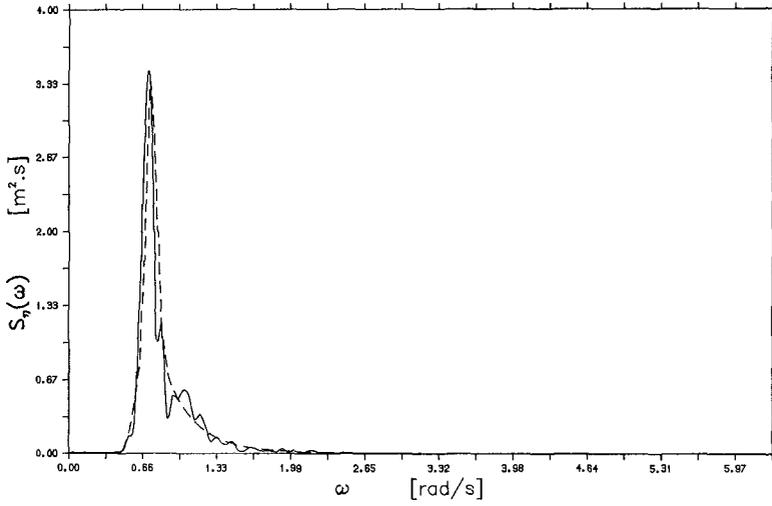


FIGURE 2

Wave Elevation Parameterised Spectra

British Gas / HGB Data Set #9

Site Data Full Line

Parameterised JONSWAP ($\gamma = 3.75$) Dashed

Peak Frequency $\omega_p = 0.73631$ rad/s

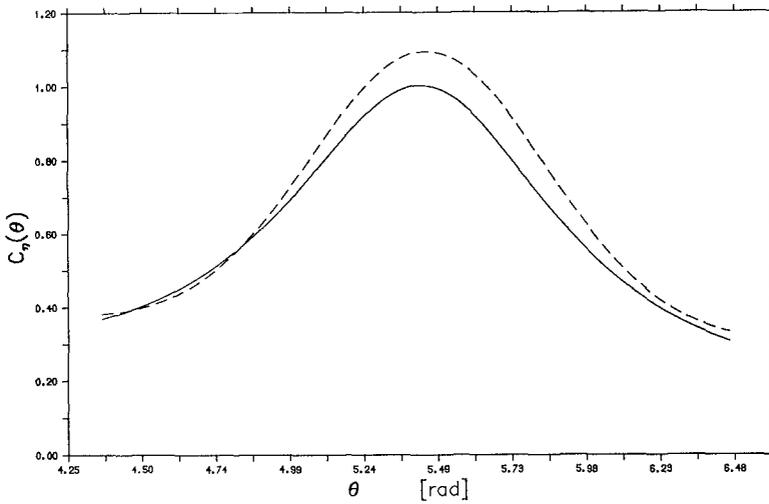


FIGURE 3

Wave Elevation Parameterised Spectral Spreading

method proposed by Bryden & Greated (1984) in which white noise is passed through a digital filter offers realistic advantages. The filter used for wavemaker control can be formed to directly match the measured spectral output of the site data and so overcome the effects of mis-match between the real data and parameterised form. In so doing the greater influence of high-frequency components on wave breaking effects can be more reliably investigated below the upper limits of frequency reproduction possible with flexible-fronted wavemakers. The parameterised spectral forms invariably concentrate their modelling accuracy at the spectral peak and over the average rate of decay beyond that, without accounting for subtle variations which may occur - and were readily distinguishable in the spectra we evaluated throughout the storm - in the tail of the spectrum. This method is implemented in the Heriot-Watt University wave basin facility, but unfortunately this task was committed to other work at the scheduled time for testing. The Edinburgh Wide Wave Tank was however available and although not geared to White Noise Filtering wave generation, the reproduction of the parameterised spectra was well within its' capabilities.

The JONSWAP spectral form may represent a developing and developed sea-state by virtue of the peak enhancement factor (γ). In order to match the parameterisation to the measured spectra, the following justifications were adopted.....

- Peak frequencies will be the same $\omega_{0J} = \omega_0$
- Range of frequencies must match $\omega_{maxJ} = \omega_{max}$
- Total power in the spectrum must match $\int S_J(\omega)d\omega = \int S(\omega)d\omega$
- Peak spectral energies must be the same $S_J(\omega_0) = S(\omega_0)$

The parameterised spreading function was based solely on the measured spreading at the peak frequency (ω_0) and was not evaluated as a function of frequency so reducing the amount of computation necessary,

Least squares fitting of each parameterisation (frequency and direction) was adopted to optimise the spreading parameter (s) about the principal direction and for matching the third and fourth of the above frequency spectra constraints.

The original scope of the experimentation was to investigate the probability of wave breaking at an early stage of storm development (swell conditions) and then at the height of the same storm for which data was available, together with the effect of introducing or ignoring any directionality. As our experiments progressed it became clear that the record selected to represent the swell condition was not going to yield any significant breaking wave results as the physical size of the model sea was too small for reliable visual breaker identification in addition to the more implicit reason that wave breaking is generally to be associated with local rather than distant sea state generation. The number of breaking waves which did occur - even in an extended length test - were so few that there was too low a level of confidence in the results to yield an adequate statistic. As a consequence of the tests were re-defined to examine the effect on the breaking wave statistic of an increase in the energy content of the evaluated spectral form at the peak of the storm.

Four situations were reproduced from the parameterisations of available offshore wave spectral data. The first reproduced the omni-directional spectrum in a uni-directional (monochromatic) form, as is common practise, whilst the second introduced spreading according to the Cosine-power function suitably scaled to maintain the constant total power of the spectrum. The third and fourth tests used the same spectral form, peak frequency and frequency range but with an increase in the area under the spectral curve corresponding to a rise in the RMS waveheight of 40% based on a Rayleigh distribution. The technique adopted for identifying the geometric properties of the individual breaking waves is described elsewhere [Mather et.al. (1988)] and briefly, relates the time locations of visually identified breaking waves (from a video replay), to the wave record obtained from the reference wave probe. In this way each breaking crest is "flagged" to allow further investigation of whatever geometric or temporal property may be of interest (e.g. steepness, crest asymmetry, etc.)

Test Results

Probability density function histograms of geometry properties for each of the lower energy sea-states are shown in Figures 4,5, overlaying in each case the probability density histograms of breaking waves and all waves (plain and breaking). The properties illustrated were chosen from consideration of the results of Kjeldsen et.al. (1981), which were those most promising readily computed geometric characteristics likely to distinguish breaking from non-breaking waves. Review of our results led us to conclude that for each of the properties evaluated, breaking waves could occur over their whole range of realisable values.

In many instances the low number of samples of breaking waves lead to seemingly spurious results detached from the main body of the probability distribution, for example in all instances of elevation. Also clear is that the highest waveheight, longest periods, highest elevations or greatest steepnesses that do occur do not always break. This characteristic is particularly unsettling in each case of wave steepness, where the steepest identified breaking waves only exist up to about 75% of the values attained by plain waves. This may be a consequence of the fact that a visually identified breaker has to possess some whitecap which may have formed some relatively long time (at model scales) before passing the wave elevation probe. As a result the elevation will have diminished and the corresponding steepness reduced. Plain waves may on the other hand retain their form all the way up to breaking and inspection of the scales for each wave steepness shows that no waves occurred above values of between 0.055, 0.060 in each seastate of differing average wave height and director spreading. The values obtained for wave steepness on an individual wave basin were all significantly below the maximum value limited by breaking proposed by Hallam et.al. (1978) of 0.142. Small numbers of plain (i.e. non-breaking) waves did approach this value but with so many waves, this number became sufficiently insignificant as not to be apparent on the histograms.

The same problem is encountered when plotting the joint probability distribution (contour plots, Figures 6,7) in that as a wave breaks, its elevation and thus waveheight is reduced so that identified individual wave breaking occurrences on these figures are shifted away from their values at the point of breaking to that noted in each case,

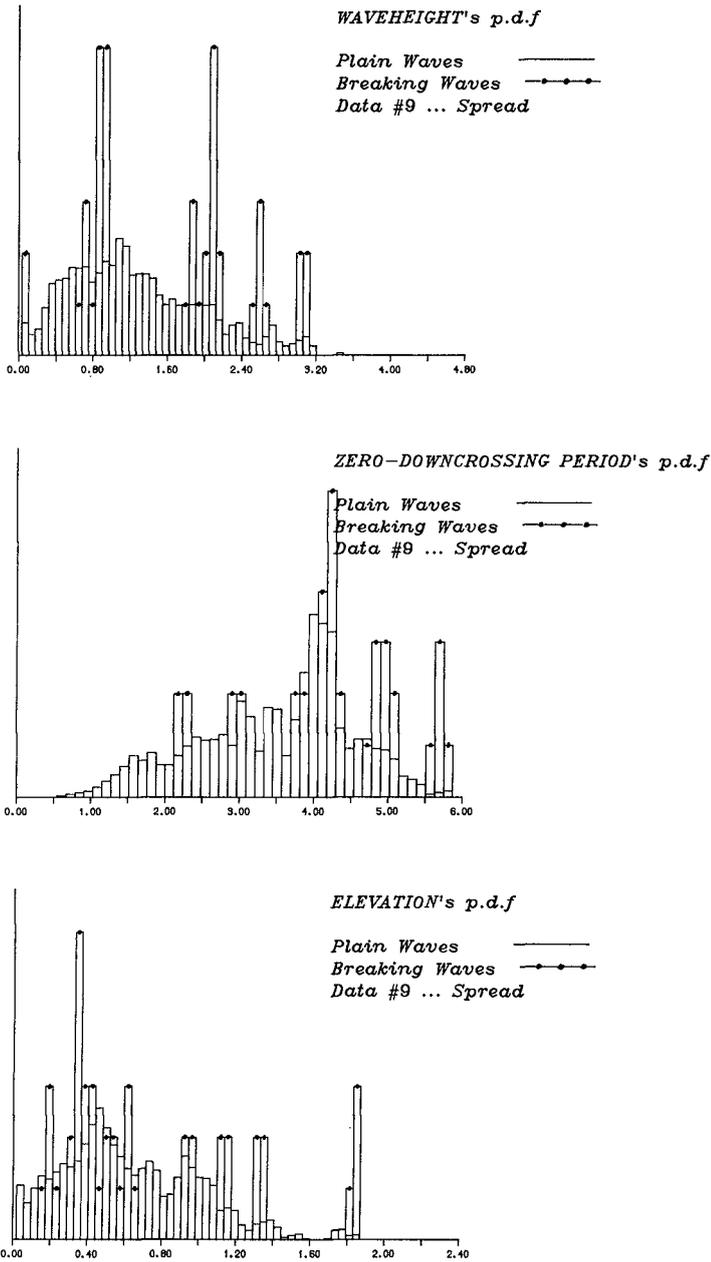


FIGURE 4 abc

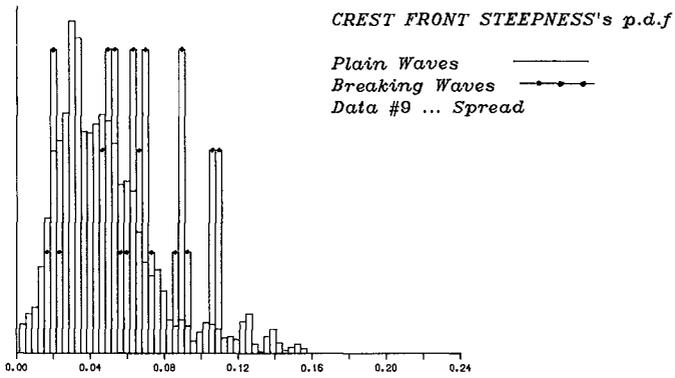
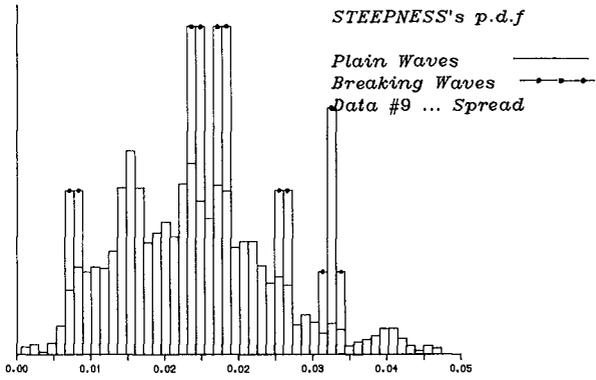


FIGURE 4 de

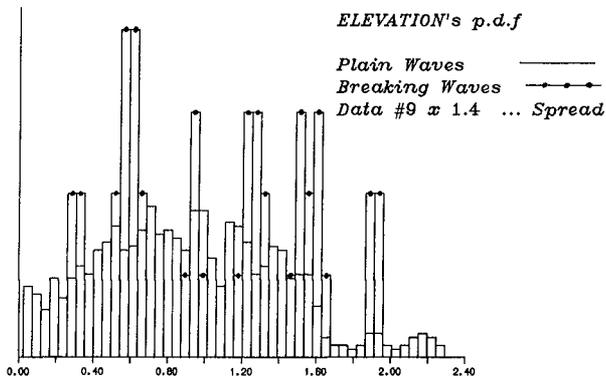
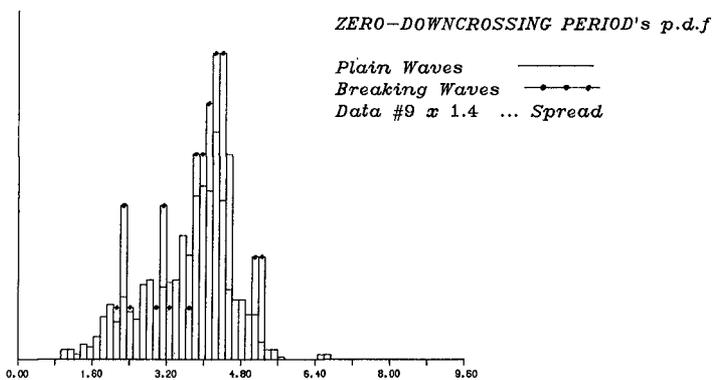
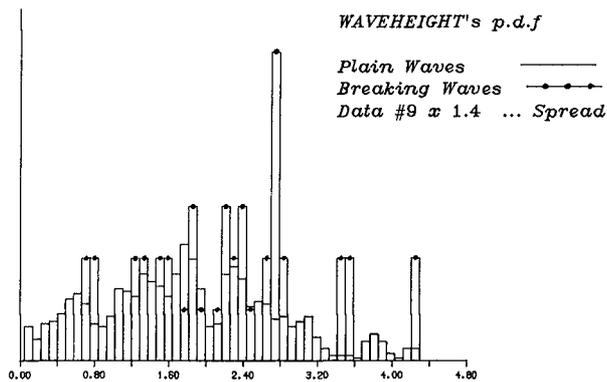


FIGURE 5 abc

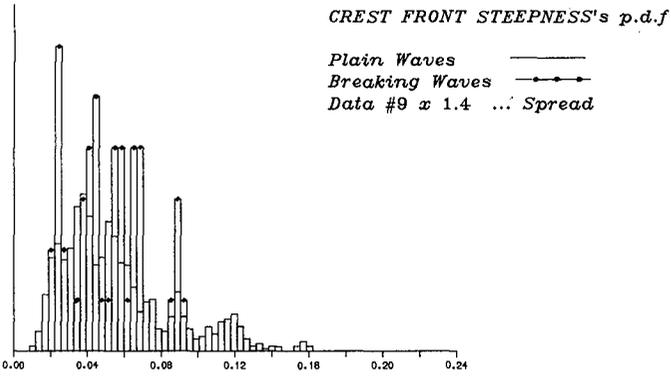
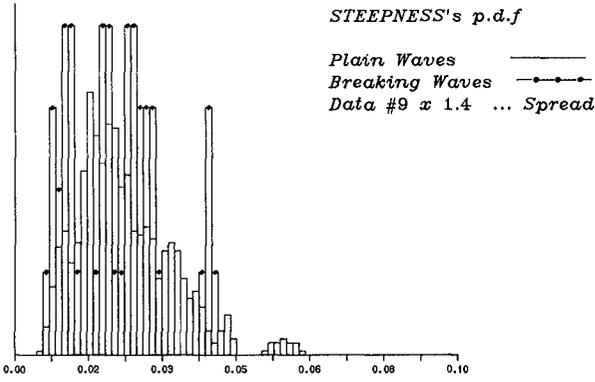


FIGURE 5 de

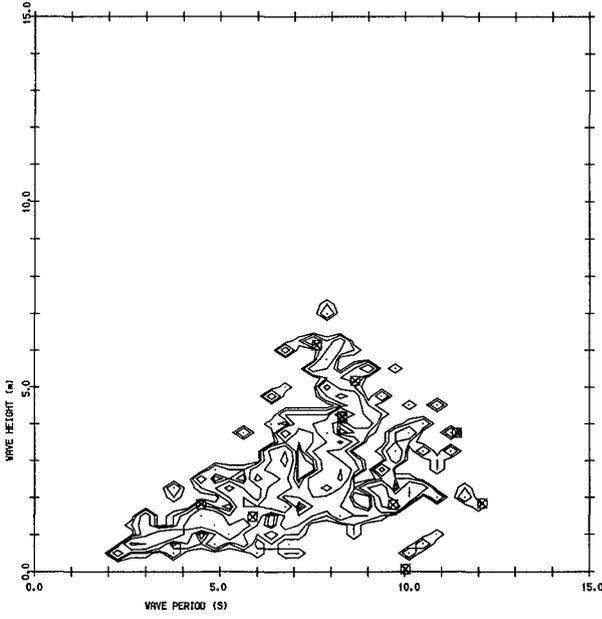


FIGURE 6

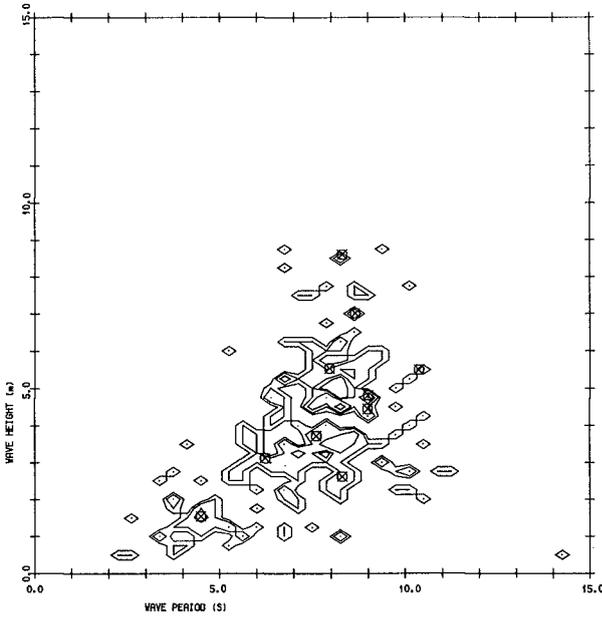


FIGURE 7

these being the values observed at the elevation probe.

Two interesting points of note arise when comparing the monochromatic and directionally spread plots in each case of RMS waveheight. The introduction of a directional spread eliminates the occurrences of outlying, extreme value combinations of waveheight and period over the observed test periods though this observation cannot necessarily be assumed to be true when considering extreme value occurrences. This appears to be accompanied in each case by a drift of values towards the regression line equivalent to the maximum wave steepness.

Conclusions

These tests lend support to earlier work by Holthuijsen & Herbers (1986) and Mather et.al. (1988) that in directional seas there seems to be no obvious relationship between the occurrence of visually identifiable breaking events and any of the geometrically defined wave characteristics in current use. Future work in this field at the University of Edinburgh is to concentrate on attempts to relate the probability of wave breaking to sea-state spectral characteristics and simulations of directionally spread sea surfaces.

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