CHAPTER 23

Measurements of Wave Breaking in the UK Coastal Research Facility

Howard N Southgate[1] and Stuart Stripling[1]

Abstract

Many experiments have been carried out on wave breaking in the past, but these have mainly been for regular, normally-incident waves. This paper describes experiments in the UK Coastal Research Facility in which over a hundred separate tests were carried out, covering regular, random, normally-incident, angled and multidirectional waves. Measurements were made of wave parameters as the waves underwent breaking in shallow water on a 1:20 slope. Analysis of the data to determine the wave breaking criterion, γ, for three random wave categories is presented.

Introduction

The criteria for values of wave height and water depth at which waves start to break in shallow water are an essential part of most computational models of nearshore wave propagation, and hence of many types of coastal engineering projects. A recent review (Southgate, 1995) has collated a large number of theoretical studies, laboratory experiments and field data sets which provide information for determining these criteria. Despite the large amount of work carried out, there remain important gaps in our understanding of the factors that influence breaker height criteria, with consequent uncertainties in the expressions used in wave prediction models. In particular, more information is required on breaker height criteria for random, angled and multidirectional waves.

This paper describes experiments carried out in the UK Coastal Research Facility (hereafter referred to as the CRF) to provide data for this purpose and for other aspects of wave propagation in shallow water regions where waves are breaking. About 100 tests were done in total, and five categories of wave were

[1]HR Wallingford Ltd., Wallingford, Oxon, OX10 8BA, U.K..

investigated. These were:

1) Regular waves, normal incidence
2) Regular waves, 25 degrees to the normal
3) Random long-crested waves, normal incidence
4) Random long-crested waves, 25 degrees to the normal
5) Multi-directional waves, mean direction at normal incidence

These tests were designed so that, as far as possible, equivalent average input wave heights and periods were tested in each category. This has enabled a direct comparison of trends in wave behaviour across the different categories to be made.

In addition, this paper presents an initial evaluation of breaker height criteria for three categories of random waves (random at normal incidence, random at 25° incidence, and multidirectional waves).

Experimental Arrangement

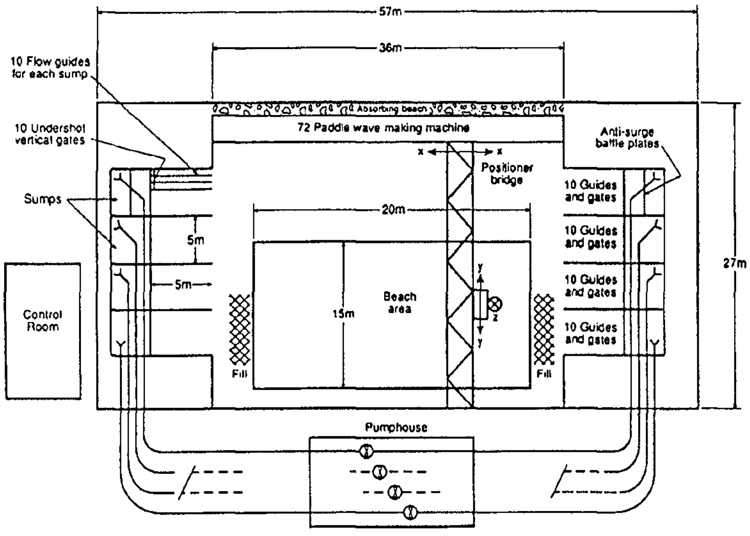

Figure 1. Layout of the CRF

The CRF is a state-of-the-art shallow-water wave basin constructed at HR Wallingford. The basin measures 36m by 27m and has a working area of about 20m by 15m. The wave-maker is 36m long and consists of 72 independent paddles capable of generating regular, random or multidirectional waves at normal or oblique incidence. In front of the wave-maker is a flat area followed by a 1:20 smooth concrete slope parallel to the wave-maker. The depth of water in the flat area is 0.5m. The overall layout is shown in Figure 1, and the main features of the CRF are described in more detail in Simons et al (1995).

For each test, wave conditions were measured at 14 locations along a line perpendicular to the coastline roughly midway between the two side boundaries of the basin. Measurements were made with twin-wire resistance probes. Most of the probes were clustered within and just offshore from the breaking region, giving a high spatial resolution in this region. Three probes were also positioned a short distance in front of the wave-maker in order to make measurements of the input wave conditions. These probes were positioned on a line parallel to the wave-maker, with the central probe on the same cross-shore line as the inshore cluster of probes.

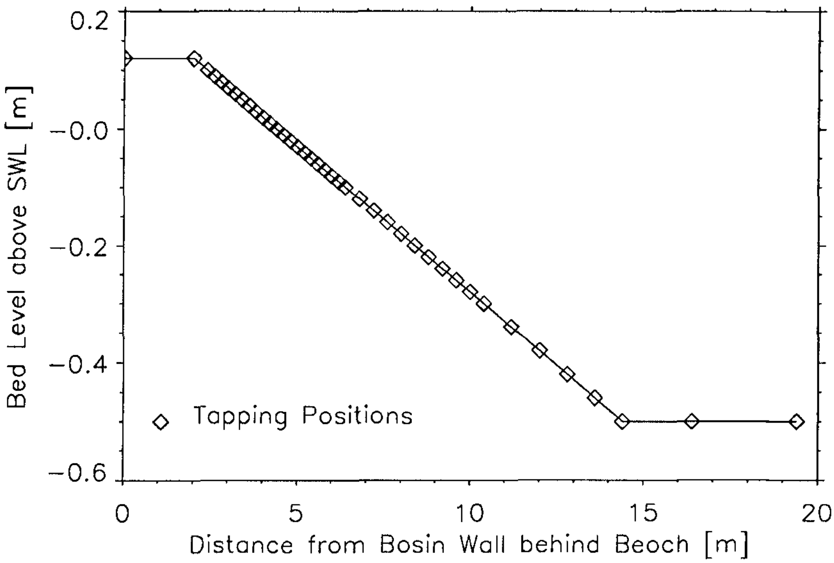

Figure 2. Cross-Shore Locations of Pressure Tappings

In addition to measurements of wave conditions, data was obtained on set-up of the water level caused by the breaking of waves. To measure the set-up, holes (known as pressure tappings) were drilled at spatial intervals into the basin floor along the cross-shore line (see Figure 2). These holes were connected via smooth nylon hydraulic tubes to individual stilling pots. Measurements of the water levels in each pot were made using the same type of twin-wire probes as for the wave measurements. This system of pressure tappings and stilling pots was installed specifically for this study and is now a permanent feature of the CRF. In all, 38 pressure tappings and stilling wells were installed, but only a subset of these were used in each test. For identification, each pressure tapping is given a number, with 1 closest inshore and 38 furthest offshore. Wave probe positions were selected to be coincident with a pressure tapping location so that corresponding values of wave parameters and water level set-up could be obtained.

A range of input wave heights from 0.03m to 0.1m was tested. Obviously, the higher waves broke further offshore and had a wider surf zone than the smaller waves. Therefore, in order to get the best spatial coverage and resolution, the locations of the probes needed to be changed according to the input wave height (the probes would need to be more spaced out for the higher waves). However, too much moving around of the probes would use up valuable experimental time, so a compromise was adopted in which there were two arrangements of probes. The first arrangement had the probes closely bunched near the waterline, and was used for low wave conditions (input wave height between 0.03m and 0.08m). The second arrangement had the probes more widely spaced, and was used for high wave conditions (input wave height of 0.09m and 0.1m). In each case every probe was located over a pressure tapping point. Figure 3 shows the relative locations of the probe positions for 'low' and 'high' wave conditions (the West Wall is the basin wall behind the beach, and the bed elevation is relative to the flat area in front of the wavemaker). Further details on the experimental arrangements can be found in CRF test report (Beresford and Channell, 1995)

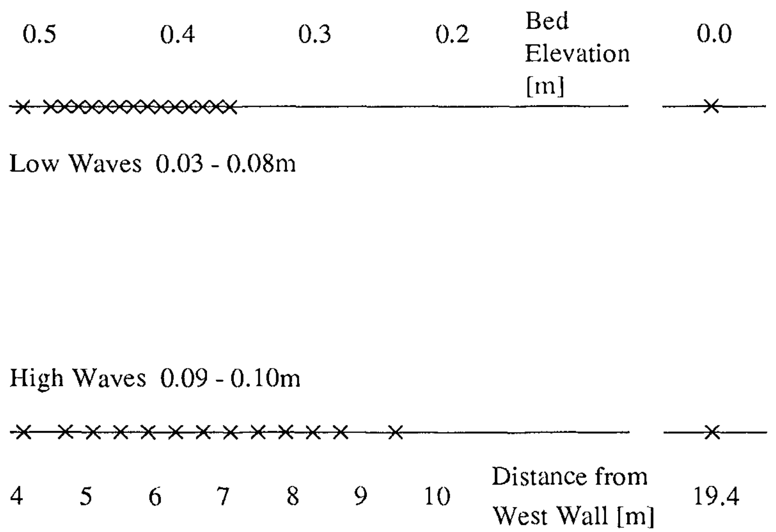

Figure 3. Locations of wave probes

Test Programme

A total of 125 tests was planned. Due to time constraints, only 108 tests were actually carried out. Of these, data from seven tests were found to be corrupted as a result of a hardware problem in the logging computer. Therefore, a total of 101 tests produced data successfully for subsequent analysis.

The following procedure was adopted in carrying out the test programme. Firstly, the water was allowed to settle to a quiescent state and then 'zero levels' (ie the digital readings corresponding to the still water level) for each probe were logged. The waves were started and run until transient effects had died away. This was checked by monitoring up to four of the probes online. After this, data collection for the first test started, and tests continued in sequence for about two hours. The wave-maker was then switched off, and the water allowed to settle. New zero readings were taken and testing was restarted.

The regular wave tests were performed first. The duration of these tests was the equivalent of 100 wave periods or 180 seconds, whichever was the longer. The two wave directions tested were at 0 degrees and 25 degrees to the normal to the shoreline. At the end of each test, the data quality was assessed. The data from the three offshore probes was analysed (by a wave counting method) and the average wave height over the three probes was calculated. The test was accepted if this wave height was within 10% of the target wave height. If not, the test was discarded and then repeated.

The random and multidirectional wave tests were then performed. For all the tests, the frequency spectrum was based on the JONSWAP formulation (Hasselman et al., 1976), with a peak enhancement factor equal to 3.3. As with the regular wave tests, the directions tested were 0 degrees and 25 degrees. For the multidirectional wave tests, the directional spectrum used a standard Cos-squared spreading function centred on 0 degrees. The length of each random wave test needed to be considerably longer than the regular wave tests to ensure that there were a sufficient number of the longest period waves in the spectrum for reliable statistical analyses to be carried out. Accordingly the length of each random wave test was set at 1200 seconds. The procedure for carrying out the random wave tests was the same as the regular wave tests, but a more stringent data quality criterion was applied. One of the main purposes of the experiment was to compare results of different wave categories for equivalent wave input (ie waves with the same average wave height and period). A random test was repeated if its input root-mean-square wave height differed by more than 5% from the input wave height in the equivalent regular wave test.

For all the tests, signals from all the 30 probes were sampled at a rate of 30 Hz. This is sufficient to determine maximum wave heights by wave counting analysis to an accuracy of better than 0.5% (Tayfun, 1993). This rate is more than is necessary for spectral analysis, but does not adversely affect the analysis.

Table 1 below summarises the numbers of tests carried out for each wave category.

Wave Run Category	Wave Height Range (cm)	Steepness Range	Wave Period Range (sec)	Number of Performed Runs	Number of Successful Runs
Regular Waves. Normal Incidence	3 - 10	0.005 - 0.055	1 - 3	25	23
Regular Waves. 25 Degrees Incidence	3 - 10	0.005 - 0.055	1 - 3	25	25
Random Waves. Normal Incidence	6 - 10	0.015 - 0.055	1 - 3	20	20
Random Waves. 25 Degrees Incidence	6 - 10	0.015 - 0.055	1 - 3	18	15
Multi-Dir Waves. Normal Incidence	6 - 10	0.015 - 0.055	1 - 3	20	18
Totals	-	-	-	108	101

Table 1. Summary of Tests Performed for each Wave Category

Within each category, input wave height and steepness values were chosen systematically within the ranges 0.03m to 0.1m for wave height, and 0.005 to 0.055 for wave steepness. Pairs of values were chosen to give wave periods between 1s and 3s. These ranges of wave height and period represented the allowed operating ranges of the wave-maker. The random wave parameters that are designed to be matched to the equivalent regular waves are the *root-mean-square* wave height, and the *peak* period.

A feature of the wave-maker software for random and multidirectional waves normal to the shoreline is set-down compensation. Set-down is a natural feature in random (but not regular) seas that refers to the raising of the water level under groups of lower waves and lowering of the water level under groups of higher waves. The software allows the movement of the paddles to be modified to ensure that the set-down propagates correctly without unwanted second-order wave effects. For the normal-incidence random and the multidirectional wave tests, the set-down compensation was switched on. However, for both wave categories an extra test was done with the set-down compensation switched off, in order to assess the differences in the final results. In both cases the differences turned out to be very minor, and substantially less than differences between equivalent runs for different wave categories. The random wave tests at 25 degree incidence were done without set-down compensation (the software at the time was only applicable to normally incident waves). Further details of the design input conditions for each test are given in Southgate et al (1996).

Spectral Analysis of Data

The CRF data has been analysed spectrally, and all the results in this paper are based on this analysis. The software uses a fast Fourier transform (FFT) algorithm, which requires the data to consist of exactly 2^n values, where n is a positive integer. Accordingly the data series for each probe in each run were truncated to 2^{12} (=4096) for the regular wave tests, and 2^{15} (=32768) for the random and multidirectional wave tests. One potential problem was the presence of a number of spikes in the time series data of water surface elevations. However, the spikes were narrow (usually consisting of only one data point) and few in number. Tests showed that they had a negligible effect on the statistical quantities of the whole time series, and therefore no action was taken to remove them.

The results of the spectral analysis are in two forms: a) frequency spectra (in 32 bands each of width 0.434Hz) for each of the wave probes, and b) statistical data derived from the frequency spectrum for each wave probe and corresponding stilling well probe. These latter data are:

1) The root-mean square wave height (H_{rms}), defined as $2\sqrt{2}.m_0^{1/2}$, where m_0 is the zero spectral moment.

2) The spectral period (T_m), defined as $(m_0/m_2)^{1/2}$, where m_2 is the second spectral moment.

3) The mean water level, derived from the stilling well probe data (the still water level is 0.5m).

Tabulated examples are shown in Southgate et al (1996). In deriving the data for b), the spectrum was truncated at high frequencies and only the first 16 frequency bands were considered (covering wave frequencies between 0Hz and about 7Hz). Wave energy at higher frequencies appeared to be 'noise' and represented only a small contribution to the total. Low-frequency wave energy is included in the analysis. A separate investigation of the low-frequency part of the spectrum would require a reanalysis with smaller band widths.

The spectral analysis has provided results in the form of wave frequency spectra, rms wave heights, spectral wave periods and wave setup at each probe location for each run. An example of the wave height results has been plotted in Figure 4 (diamonds) along with a computational model prediction with a best-fit breaker criterion, γ_{min} (full line). A full set of results for wave height decay and wave setup is shown in Southgate et al (1996).

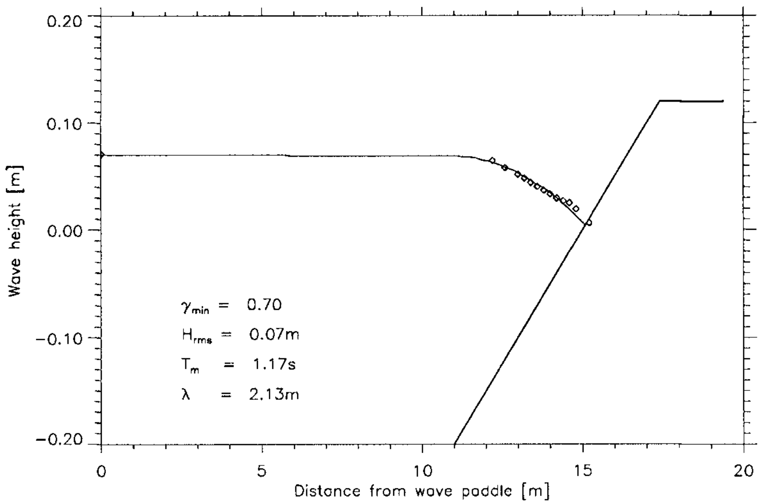

Figure 4. Random waves, Normal Incidence

From the full set of results some initial observations can be made:

a) Angled waves are generally slightly lower than normally incident waves. This can be explained by the angled waves undergoing refraction.

b) Regular waves are generally higher than random waves immediately before breaking and decay to lower values immediately after breaking. This is explained by regular waves breaking over a much narrower zone than random waves. Also the increase in wave height due to non-linear effects immediately before breaking is noticeable.

c) Multidirectional waves and random normally incident waves show very similar heights and patterns of decay

d) There is substantial spreading of wave energy to both lower and higher frequencies, and a reduction in the spectral period values as one travels inshore. The effect is particularly strong for regular waves.

e) Setup caused by regular normal waves starts further landward and reaches higher values than that caused by random normal waves or multidirectional waves.

f) Setup caused by random normal waves tends to be higher than that caused by random oblique waves or multidirectional waves.

Other plots of this data are possible, for example spectral period vs cross-shore distance, or spectral density vs wave frequency (at each location). Other modes of analysis are also possible, for example wave counting analysis, or spectral analysis using different frequency bands.

Determination of Breaker Height Criterion for Random Wave Categories

This data set has been used to illustrate how to derive an expression for the breaker height criterion, γ, for three categories of random wave (normal incidence, 25 degrees incidence, and multidirectional waves). γ is defined as the ratio of wave height to water depth when waves initially break in shallow water, and is a key input parameter in most computational models of shallow water wave processes. Many experiments have been carried out in the past to derive values of γ, but these have mainly been flume experiments, most commonly with regular waves. The present experiments provide the opportunity to derive expressions for γ for the three types of random wave categories with equivalent input wave conditions. For random waves the wave height in the definition of γ is the rms value.

For random waves, γ has a different interpretation than for regular waves. In the case of regular waves, γ refers to the wave height to depth ratio at initial breaking *for individual waves*. For random waves, γ is a single value representing an average value of wave height to depth ratio at initial breaking for a range of waves of different heights and wavelengths. In parametric surf zone wave models, it needs to be regarded as a parameter in the representation of the average rate of wave decay through the surf zone.

The most extensive previous study of breaker height criteria for random waves was done by Battjes and Stive (1985) who analysed twenty results from three separate laboratory exercises and two field exercises. Their analysis showed no systematic dependence of γ on bed slope, but a dependence on deep-water wave steepness. They used a hyperbolic tangent function to give a best fit to the data:

$$\gamma = 0.5 + 0.4 \tanh(33H_0/L_0)$$

The method of determining γ from the present experiments follows that used by Battjes and Stive. The idea is to use a parametric model of wave decay through the surf zone and repeat the runs for many different trial values of γ. For each run, the rms error of predicted wave height vs measured wave height at all points across the profile for which there are measurements is calculated. The value of γ which gives the minimum error is selected. The model used for this purpose was the wave part of the morphodynamic profile model, COSMOS-2D (Southgate and Nairn, 1993).

Model runs were performed for each experiment in each of the three random wave categories, stepping through a range of values of γ from 0.4 to 1.0 with

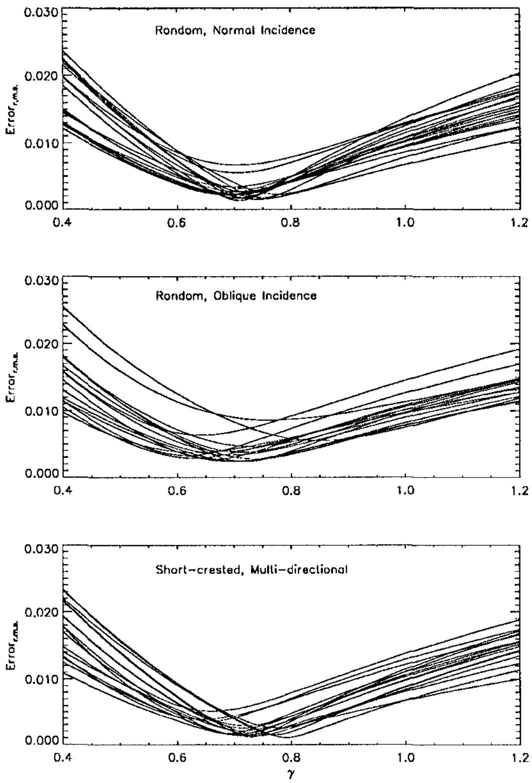

Figure 5. rms Error in Wave Height vs γ

increments of 0.01. At each value of γ, the root-mean-square (rms) error between the wave height measurements and the wave height profile predicted by the model at each measurement point was calculated. Figure 5 shows the range of γ values plotted against the rms error between the measured and the predicted wave height profiles. It can be seen that each wave has an optimum value of γ which provides a minimum rms error. This was taken to be the wave breaking coefficient for that wave.

Results

Figure 6 shows a plot of the deep water wave steepness against the optimum γ value, γ_{min}. To calculate the deep water wave steepness, the average rms wave height and wavelength (calculated by the linear dispersion relation from the peak period) at the three probes in front of the wavemaker were refracted out to deep water using Snel's law. In this plot, r is the correlation coefficient and sd is the standard deviation of the data from the linear regression line obtained using the method of least squares. It can be seen that the normally incident random waves

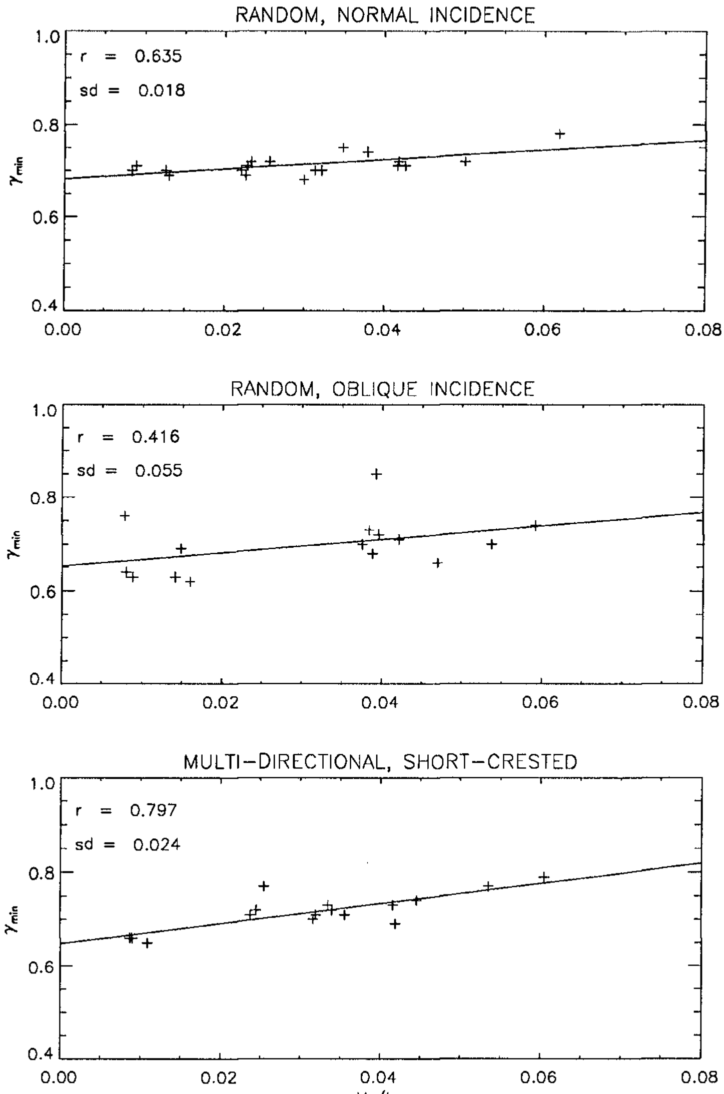

Figure 6. γ_{min} vs Deep Water Wave Steepness

and the multidirectional waves have quite high values of the correlation coefficient, but that random oblique incident waves have a lower value.

Figure 7 shows a plot of the deep water Irribarren number, I_d, where I_d is the beach slope divided by the square root of the deep water wave steepness. It can be seen here that the correlation coefficients are lower for the random normal and oblique incident waves than for the deep water steepness plotted in Figure 6. The

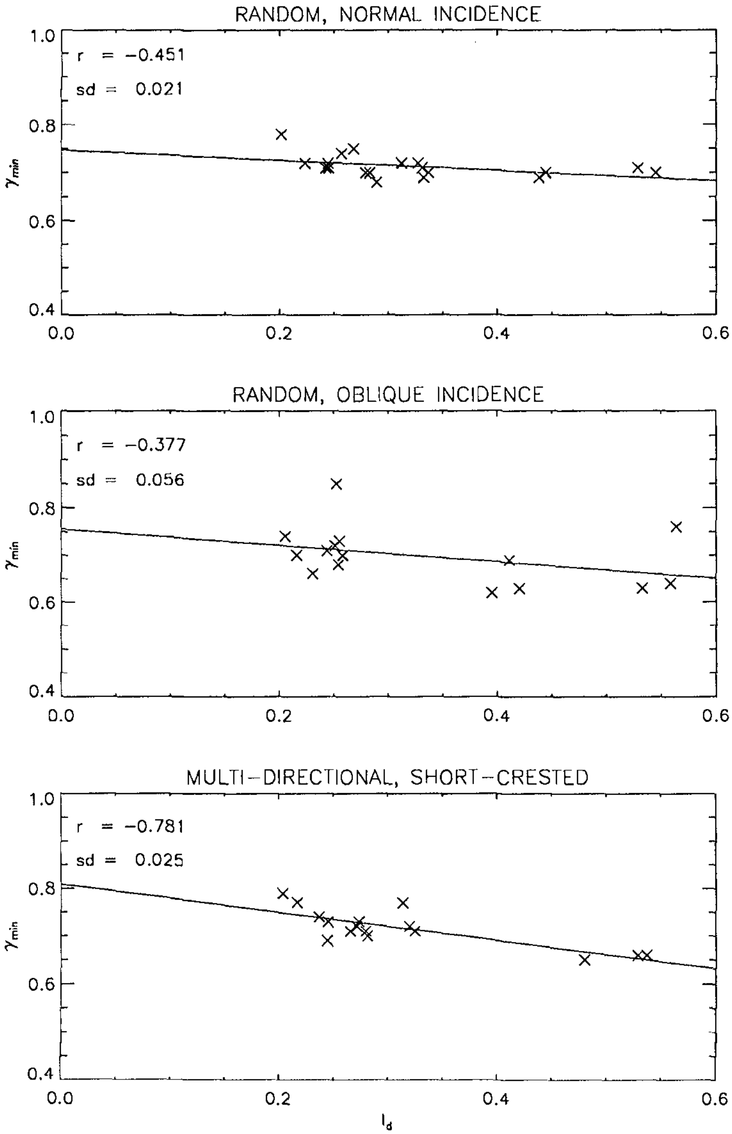

Figure 7. γ_{min} vs Deep Water Irribarren Number

multidirectional waves, however, still have a high correlation coefficient. This suggests that the deep water wave steepness is a more appropriate parameter than deep water Irribarren number to predict γ.

Figure 8 shows the deep water wave steepness regression lines and the trend line of Battjes and Stive (1985). The differences with Battjes and Stive appear

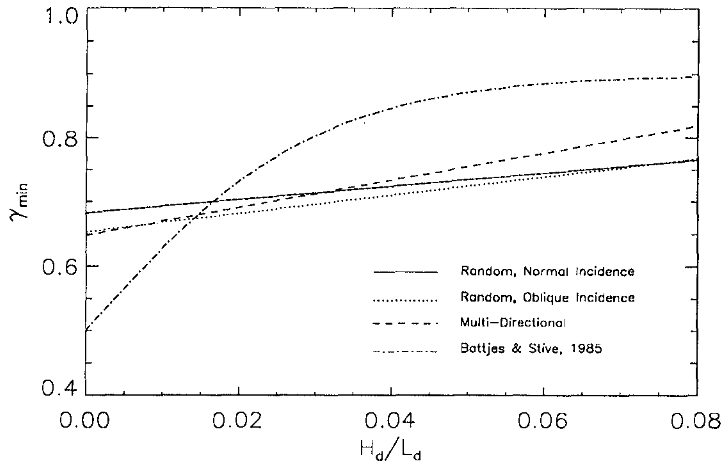

Figure 8. γ_{min} vs Deep Water Wave Steepness (trend lines)

quite large, but almost all the wave steepness values in Battjes and Stive's data lay between 0.01 and 0.03.

Conclusions

A series of experiments in the UK Coastal Research Facility have been performed to provide data on wave transformation and decay in the nearshore breaking region in a systematic manner using five different categories of input waves. This data has been processed by spectral analysis to provide information suitable for investigating nearshore wave processes and evaluating wave models. An initial, visual comparison of the results across the different wave categories is summarised in the section on spectral analysis. If necessary the data could also be reanalysed using alternative methods. Typical examples of applications of this data set would be:

a) Criteria for initial breaking of waves
b) Wave height transformation and decay
c) Wave setup and the 'transition zone' length (the distance between where waves start to break and where radiation-stress-driven phenomena start to appear, as revealed by wave setup)
d) Wave energy transfer between frequency spectral components
e) The fraction of waves breaking at any location (for random and multidirectional runs) determined from analysis of video records.

An analysis of the data for three categories of random wave (normal incidence, oblique incidence and multidirectional) has been carried out to determine breaker height criteria and their functional dependence on deep water wave steepness. However, to establish the most reliable expressions for breaker height criteria, it is recommended that this data set is combined with others, such as those used in Battjes and Stive (1985), so that the overall data set is as large as possible and covers as wide a range as possible of laboratory and field conditions.

Acknowledgements

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