China Ocean Engineering, Vol.14, No.2, pp.229－242.
China Ocean Press, 2000. Printed in P.R. China.

Experimental Study on the Effects of A Breakwater on Wave Field Characteristics

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Abstract — Studies on the possible effects of a detached breakwater on the characteristics of the wave field are carried out experimentally. A serpentine wave generator is used to generate both uni- and multi- directional waves. Characteristics of the wave fields analyzed here include the wave field directionality, and the probability distributions of surface elevations and of the wave heights. Owing to the presence of the breakwater, waves outside the harbour are found to be reflected with, however, concentrated energy within the harbour entrance. In general, wave heights can be approximated with a Rayleigh distribution, with occasional deviations from the theory. This occurs more frequently for waves with higher peak frequency values than for those with lower values both for uni- and multi-directional waves. Surface elevations can be approximated with the Gaussian model, although the Edgeworth's form of the type A Gram-Charlier series expansions would yield better fits. Wave directionality is found to have no discernible effects on the statistical characteristics of the wave field.

Key words: *wave directionality; statistical distributions; surface elevations; wave heights*

1. Introduction

It is well known that, as a first approximation, the probability distributions of the sea surface fluctuations can be treated as Gaussian. Together with the assumption of a narrow-banded wave field, it can then be shown that the wave heights are Rayleigh distributed (Longuet-Higgins, 1952). When the nonlinearity can no longer be neglected, the distribution of the water surface fluctuations will deviate from normality. This was first demonstrated by Longuet-Higgins (1964), and later by Huang and Long (1980). On the other hand, it seems that the distribution of wave heights will not seriously be affected by wave nonlinearity (Chakrabarti and Cooley, 1977). However, researchers did point out the fact that the Weibull distribution fits the high wave tails more satisfactorily than does the Rayleigh distribution (Forristall, 1978; Mase, 1989). The effects of spectral width on wave height distributions were shown to be more effective than does nonlinearity (Longuet-Higgins, 1980; Larsen, 1981). Possible influences of wave directionality on the wave height statistics were inferred (Nerzoc and Prevosto, 1998). However, as far as the authors are aware, there seems to have no theoretical and experimental justification for this conjecture.

As waves propagate into coastal regions, they will experience the shoaling effects caused by the underlying topographical conditions. When waves shoal, nonlinear wave-wave interactions become effective already at the third order of wave steepness. With a planned coastal construction, the wave field is even more affected. There seems to have no existing theory that could predict the wave field characteristics under such complicated circumstances.

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It is therefore customary to perform physical model tests to study the possible interactions between a future coastal structure and its surrounding wave field. With the advances of both computer algorithms and control techniques, experimentalists can nowadays generate waves that have more resemblance to those found on the ocean surface. The waves thus generated in a wave flume can have not only the prescribed spectral densities, the grouping characteristics, but also profiles with desired asymmetries (Mansard and Funke, 1988). It should be noted that the waves generated in a two-dimensional flume, regular or random, are always long-crested. In other words, all the waves can have only one direction of travel.

Oceanic waves are in reality of short-crested nature. One would need a multi-elements, or serpentine, wave generator and a wave basin to generate short-crested random waves. Owing to the enormous costs associated with multi-elements wave-generators, only a limited number of institutions around the world are equipped with the kind of facilities (Mansard *et al*, 1997).

The Ocean Engineering Laboratory started to use multi-dimensional waves to study the interactions between waves and structures a few years ago. This article reports experimental results using a fishing harbour for the physical model tests. Both uni- and multi-directional waves are used to study the possible dependence of the wave field characteristics on wave directionality, as well as on the presence of a detached breakwater. The Maximum Likelihood Method (MLM) is used to analyze wave directionality. Distributions of wave heights and surface fluctuations are fitted with models found in the literature. It is hoped that more insights concerning the characteristics of the wave field could be obtained this way.

2. Experimental Setups

2.1 The Wave Basin

Experiments were conducted in the wave basin of the Ocean Engineering Laboratory of the Department of Harbour and River Engineering, National Taiwan Ocean University. The wave basin has a dimension of $50 \times 50 \times 1.0$ (width × length × depth, in meters). A serpentine wave generator is installed on one side of the basin. This wave generator is composed of 7 units each with 8 paddle elements. The width of each paddle elements is 50 cm. The total length of the wave generator is therefore 28 meters. A 1:6 gravel beach is located at the opposite of the basin that ensured good dissipation of incident wave energy. The optimum water depth for the experiments is 60 cm. Waves with periods ranging from 0.5 to 5 seconds, and up to 20 cm of wave height, with incidence angles varying from 0° to 180°, can be generated. A detailed description of the characteristics of the wave basin, accompanied with experimental results can be found in Huang (1998).

2.2 Model Harbour Ba-Dou-Ze

Fishing harbour Ba-Dou-Ze (hereafter abbreviated as BDZ) is located in the northeastern part of Taiwan, in Keelung City. Relative stringent requirements must be fulfilled in order to minimize collision risks for small fishing boats. The water surface fluctuations should not exceed, respectively, 30 cm and 50 cm during monsoon seasons and typhoon invasions. To fulfill this purpose, a detached breakwater of a total length of 150 meters was proposed. The location of the breakwater has a relatively large depth, −25 meters. During the experiments, a model of the fishing harbour BDZ to a scale of 1 / 81 was placed inside the basin. The objective of the model tests was to determine the efficiency of the detached breakwater in satisfying the tranquility requirements under severe wave conditions. The orientation of the detached breakwater was varied to determine the optimal layouts of it. Fig. 1 shows the experimental setups schematically.

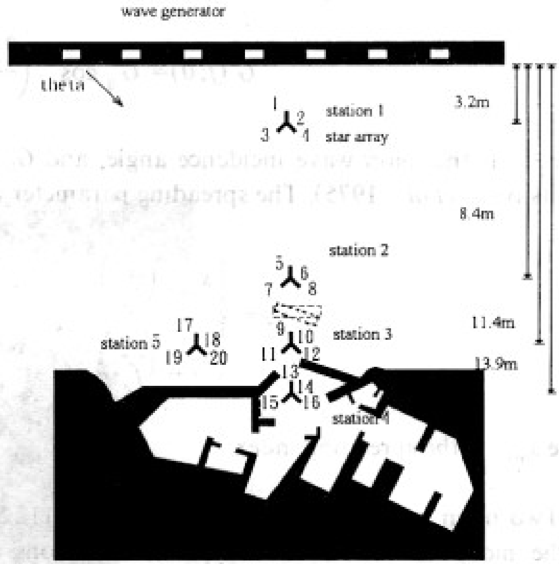

Fig. 1. Schematic representation of the experimental setups for the fishery harbour Ba–Dou–Ze.

2.3 Experimental Conditions

The target spectra used for the experiments are of the JONSWAP type. The modified version of the JONSWAP spectrum can be expressed as (Goda, 1985):

$$S(f)=\alpha_{Ph}\frac{H_{1/3}^2}{T_p^4 f^5}\exp\left\{-\frac{1.25}{(T_p f)^4}\right\}\gamma^{\exp\left[-\frac{(T_p f-1)^2}{2\sigma^2}\right]} \tag{1}$$

where α_{Ph} is the so-called Phillips constant, $\alpha_{Ph}\approx 0.0081$. It was derived by Philips (1958) by arguing that the high-frequency tail of a wind-generated wave spectrum is governed only by wave-breaking, and

$$\sigma=\begin{cases}\sigma_a & f\leqslant f_p\\ \sigma_b & f\geqslant f_p\end{cases} \tag{2}$$

the mean values of γ = 3.3 together with σ_a = 0.07 and σ_b = 0.09 were used during the experiments. The peak frequency, $f_p = 1/T_p$, is related to the significant wave period, $T_{1/3}$, through:

$$f_p=\frac{1}{CT_{1/3}} \tag{3}$$

where the constant C is given by Goda (1985) as C = 1.05.

The directional spectrum, $D(f, \theta)$, can be expressed as:

$$D(f,\theta)=S(f)\,G(f;\theta) \tag{4}$$

where $G(f;\theta)$ is the spreading function. In generating multi-directional waves, the spreading function of Mitsuyasu-type (Mitsuyasu *et al.*, 1975) is used:

$$G(f;\theta)=G_0\cos^{2s}\left(\frac{\theta-\theta_0}{2}\right) \tag{5}$$

where θ_0 is the main wave incidence angle, and G_0 is a function of the spreading parameter s (Mitsuyasu *et al.*, 1975). The spreading parameter is related to the frequency through:

$$s=\begin{cases} s_{max}\left(\dfrac{f}{f_p}\right)^{5} & f\leqslant f_p \\ s_{max}\left(\dfrac{f}{f_p}\right)^{-2.5} & f\geqslant f_p \end{cases} \tag{6}$$

where s_{max} is the spreading index.

Two main wave directions, $\theta_0 = 90°$ and $112.5°$ are chosen to simulate wave incidence for the monsoon seasons and typhoon invasions respectively. The significant wave height $H_{1/3}$ is 9 cm ($\approx$ 7.3 meters in prototype) for a predicted return period of 50 years. Three peak frequencies are chosen for the experiments. Table 1 summarizes the experimental conditions used in this study.

Table 1 Experimental conditions. An infinite spreading index denotes unidirectional waves. The incidence angle of the waves is measured counterclockwise, whereas the inclination of the breakwater is measured clockwise, with respect to the wave generator

Peak frequency (f_p) (Hz)	0.7, 0.9, 1.1
Significant wave height ($H_{1/3}$) (cm)	9.0 6.0
Main incidence angle (θ_0) (°)	90, 112.5
Breakwater length (cm)	185.2
Breakwater inclination (°)	0, 22.5
Spreading index (s_{max}) (–)	∞, 10, 25, 50

Surface elevations are measured with capacitance wave gauges. Limited by the available A/D channels, only five measuring stations, hereafter called No. 1 to No. 5, can be placed in the basin to measure the directionality of the wave field. Each measuring station has four wave gauges, forming a so-called star array. As can be seen from Fig. 1, while station No. 4 is within the harbour entrance, all other stations are located outside the harbour. Since the water depth is relatively shallow at station No. 4, the outer radius of the star arrays is 10 cm for this station, and 15 cm for all other stations. During the experiments, a constant sampling rate of 50 Hz was selected. There are therefore approximately 9000 recorded data points from each wave gauge to be used for the analysis.

Measured data are first mean- and trend-removed according to the usual procedure. Wave heights and periods are determined from wave record through zero-upcrossing. To increase the degrees of freedom (DOF) in the spectral estimate, wave records are separated into several non-overlapping segments. A partial cosine taper function is added to every segment to avoid the effect of side lobe leakage. Ensemble averaging of the Fast Fourier Transformed (FFT) rough spectral densities is first performed, followed by smoothing with a Hanning window in the frequency domain (Bendat and Piersol, 1986). The final smoothed spectra have 16 degrees of freedom and a frequency resolution of $\Delta f \approx 0.1$ Hz.

3. Models Used for Analysis

3.1 Models for the Distribution of Wave Heights

In this paper, three probability models have been used for the study of the possible distribution of the wave heights around the harbour area. The three models are the normal (Gaussian), the Rayleigh, and the Weibull distribution. They can be expressed as follows.

a) The normal distribution

The Gaussian distribution has been used in many fields where the phenomenon is the cumulative result of many independent influential factors (Thiébaux, 1994). Seldom has it been applied to the description of the distribution of wave heights. However, there are evidences that, at least for laboratory wind-wave flume results, the Gaussian model can be used to model the distribution of wave heights (Piroth, 1994; Yim, 1997).

b) The Rayleigh distribution (Chakrabarti and Cooley, 1977)

c) The two-parameter Weibull distribution (Forristall, 1978; Mase, 1989; Sundar *et al.*, 1993):

$$p\,(H', \alpha, \beta) = \alpha\beta H'^{\alpha-1} \exp\left(-\beta H'^{\alpha}\right) \qquad \alpha, \beta \geqslant 0, \quad H' > 0 \tag{7}$$

where H' is the normalized wave height, $H' = H/H_{\text{mean}}$. α and β are, respectively, the shape and scaling parameters of the distribution. With its two adjustable parameters, the Weibull distribution is more flexible in fitting the data than the other two statistical models applied here. It becomes the Rayleigh distribution with $\alpha = 2$ (Hahn and Shapiro, 1967). On the other hand, with $\alpha \rightarrow 3$ or 4, the Weibull distribution has an appearance which resembles that of the normal distribution (Chen and Ma, 1991).

3.2 Models for the Distributions of Surface Elevations

a) The Gaussian distribution

This model has the similar appearance as that used for wave height distributions. The only difference is that, since the mean values of the wave records are set to zero, instead of η_{mean}, η_{rms} is used as the normalization factor.

b) The Gram-Charlier series expansion (Longuet–Higgins, 1964; Huang and Long, 1980):

$$p(\eta') = \frac{1}{\sqrt{2\pi K_2}} \exp\left[-\frac{t^2}{2}\right]\left[1 + \frac{1}{6}\lambda_3 H_3 + \frac{1}{24}\lambda_4 H_4 + \frac{\lambda_5 H_5}{120}\right] \tag{8}$$

where $\eta' = \eta / \eta_{rms}$ is the dimensionless surface elevation, k_n the n-th cumulant, and $t = \eta' / \sqrt{k_2}$ and $\lambda_n = k_n / \sqrt{k_2^n}$ with H_n being the n-th Hermit polynomial. As far as possible, all the statistical fits are checked for the goodness-of-fit with the χ^2-tests.

3.3 Estimate of the Directional Spectrum

Almost all the estimating methods of directional spectrum are based on the properties of measured cross-spectral densities. A review of the state of the art of presently available analytical methods can be found in Benoit *et al.* (1997).

Four analytical methods have been tried. Among the four methods, the Direct Fourier Expansion method (DFE; Borgman, 1969) has the widest spread of the estimated spreading function, and sometimes even unrealistic negative side lobes may result. It is believed that the Maximum Entropy Method (MEM; Hashimoto *et al.*, 1988; Nwogu, 1989) yields the most reliable results. This method was first developed for point measurements, and was later adopted for wave staff arrays by Nwogu (1989). However, this method can easily be affected by the presence of noise, and the iteration algorithm may sometimes not converge. The cross-spectra reconstructed from directional spectrum estimated by the Maximum Likelihood Method (MLM, Brissette, 1992) are often found to be inconsistent with those computed from measurements, and the Iterative Maximum Likelihood Method has been used to correct this (IMLM, Oltman–Shay and Guza, 1984). Occasionally, however, the results of the IMLM may become irregular. In the following, we will therefore only present our results obtained from MLM. The relevant equations can be easily found in the literature (Chadwick *et al.*, 1995).

4. Results and Discussion

4.1 Distribution of Wave Heights

Figs. 2~4 show the distributions of wave heights fitted to the three models mentioned in Section 3. These three figures are shown here to demonstrate the possible differences between uni- and multi-directional wave fields (Figs. 2 and 3), as well as the effect of different spreading indexes on the distribution of wave heights (Figs. 3 and 4). Sundar *et al.* (1993) studied wave kinematics in a groin field, and they found that the wave heights are Weibull distributed. Our results here indicate that, all the three models applied here can be used to describe the possible distribution of wave heights. However, as can be seen from these figures, the degrees of satisfaction for the three models are rather different. While the curve of the Weibull distribution almost coalesces with that of the Rayleigh in Fig. 2, it has now moved toward that of the Gaussian in Fig. 3.

Nearly all of the existing random wave synthesis algorithms are based on equations satisfying the assumption of linear, small amplitude waves. The phases of these waves are randomly and uniformly distributed (Miles and Funke, 1989). It should be noted that these are also the underlying assumptions, which lead to the Rayleigh distribution of wave heights. Kimura (1981)

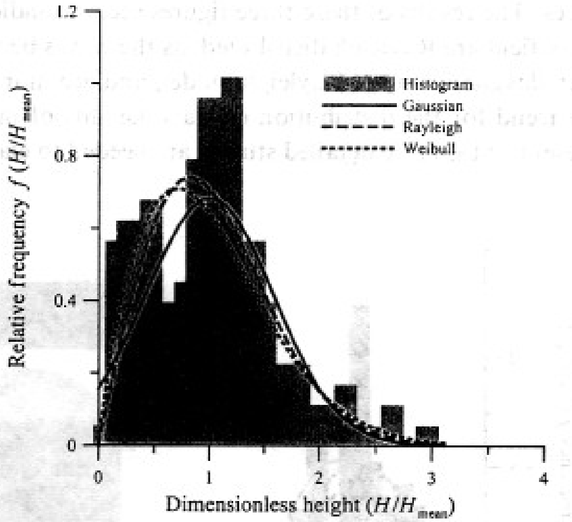

Fig. 2. Wave height distribution fitted to Normal (solid line), Rayleigh (dashed line), and Weibull (dotted line) distributions. Case studied: uni-directional waves with $f_p = 0.7$ Hz, $\theta_0 = 90°$, $H_{1/3} = 9$ cm. Waves recorded by the second wave staff of station No. 2, i. e., wave gauge No. 6.

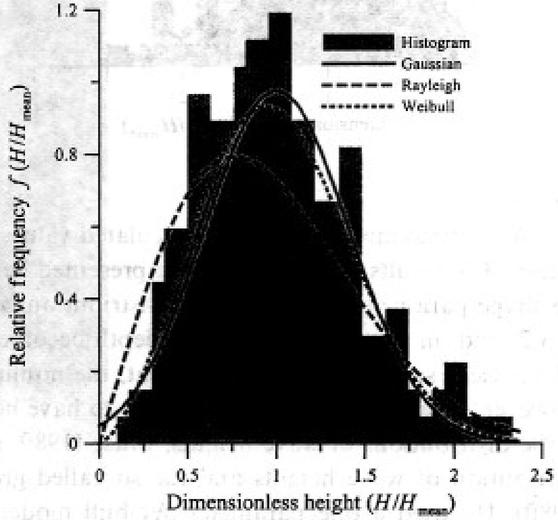

Fig. 3. Wave height distribution fitted to Normal (solid line), Rayleigh (dashed line), and Weibull (dotted line) distributions. Case studied: multi-directional waves with $f_p = 0.9$ Hz, $s_{max} = 50$, $\theta_0 = 90°$, $H_{1/3} = 9$ cm. Waves recorded by wave gauge No. 6.

studied the joint distribution of wave heights and periods of random waves in a wave flume. Although a two-dimensional Weibull model is used, the shape parameter for the marginal distribution of wave heights is found to have a mean value of 2.0. It should be noted that this implies that the wave heights are Rayleigh distributed. The experiments of Kimura were conducted in a two-dimensional wave flume. They are therefore similar to the uni-directional cases of the present experiments. The result presented in Fig. 2 is therefore consistent with that of Kimura.

Fig. 3 shows the distribution of wave heights for the case of a relatively high spreading index, $s_{max} = 50$. It can be seen that the wave heights are better described as to have a Gaussian distribution. When the wave energy becomes more scattered, $s_{max} = 10$. Fig. 4 shows that all the three models can be used to describe the distribution of wave heights with no appreciable differences. The results of these three figures seem to indicate that, wave heights of an uni-directional wave field are Rayleigh distributed; as the waves become scattered in all directions, wave heights then deviate from the Rayleigh model, and are more Gausisan distributed. The exact cause and the trend for the distribution of wave heights of multi-directional wave fields are not clear at present, thus, more detailed studies are needed to clarify this.

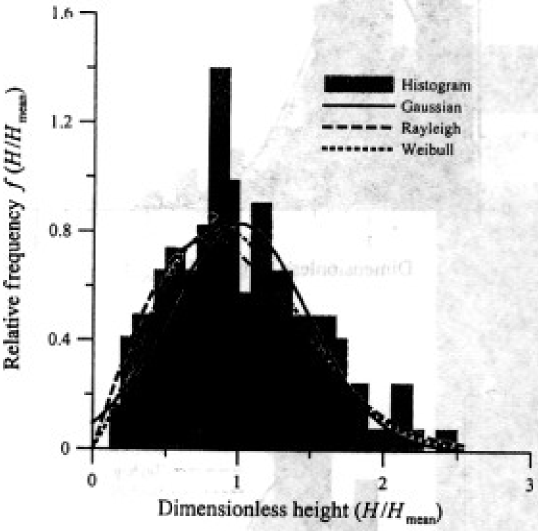

Fig. 4. Wave height distribution fitted to Normal (solid line), Rayleigh (dashed line), and Weibull (dotted line) distributions. Case studied: multi-dimensional JONSWAP Spectrum with $f_p = 0.7$ Hz, $s_{max} = 10, \theta_0 = 90°$, $H_{1/3} = 9$ cm. Waves recorded by wave gauge No. 6.

We have summarized all the calculated values of the two parameters for the Weibull distribution. The results are too long to be presented here. It can be shown that most of the values of the shape parameter of the Weibull distribution, α, are distributed within the range of $2.1 \leqslant \alpha \leqslant 3.2$, and, in general, as the water depth becomes shallower, the larger will be the value of α. This is clear since it is well known that, the nonlinear effect will be enhanced during shoaling. However, it can be said that there seems to have no appreciable systematic order for the change of the distributions of wave heights. Mase (1989) studied the possible relationship between the distribution of wave heights and the so-called groupiness factor due to Funke and Mansard (1980). He used a one-parameter Weibull model for the distribution of wave heights. Mase found that there is weak correlation between the shape parameter of the Weibull distribution and the groupiness factor. The shape parameter is found to become larger for decreasing groupiness factor. Since groupiness factors are not calculated in this study, no comparisons of our results with Mase's (1989) can be made at present.

4.2 The Distribution of Surface Elevations

The distributions of surface elevations are modeled with both the Gaussian and the Gram-Charlier series expansion. Fig. 5 shows the distribution of surface elevations for the case of uni-directional waves with a peak frequency $f_p = 0.9$ Hz, and an angle of incidence $\theta_0 = 90°$, The data are taken from wave gauge No. 2, where the water is relatively deep, $h \approx 47.5$ cm. As can be seen from this figure, both these models can be used to fit the distribution of surface elevations satisfactorily. The curve of the Gram-Charlier series expansion is a little skewed toward the negative x-axis, indicating that the waves are only weakly nonlinear. However, even within the harbour entrance, where the water depth is relatively shallow, $h \approx 29.0$ cm, the distribution of surface elevations for the case of multi-directional waves is still similar to that shown in Fig. 5. The results are therefore not presented here.

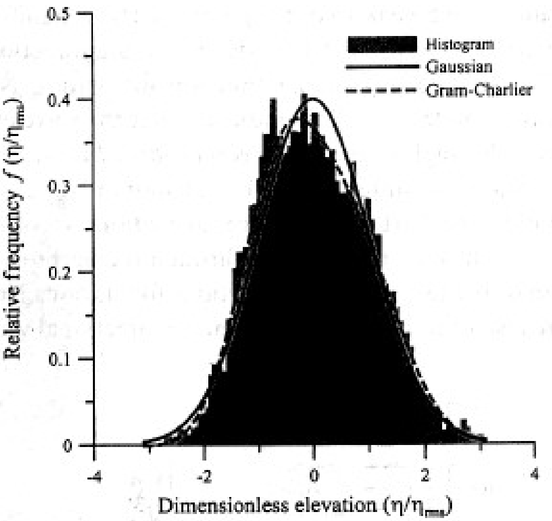

Fig. 5. Distribution of surface elevations modeled with (a) the Gaussian (solid line), and (b) the Gram-Charlier series expansions (dashed line). Case studied: uni-directional waves with $f_p =$ = 0.9 Hz, $H_{1/3} =$ 9 cm, $\theta_0 =$ 90° . Waves recorded by wave gauge No. 2.

Another way to study the asymmetry of surface elevations is through the parameters of skewness and kurtosis. These two parameters are defined as (Hahn and Shapiro, 1967):

$$\beta_1 = \frac{\frac{1}{N}\sum_{i=1}^{N}(\eta_i - \eta_{\text{rms}})^3}{\left[\frac{1}{N}\sum_{i=1}^{N}(\eta_i - \eta_{\text{rms}})^2\right]^{\frac{3}{2}}} \tag{9}$$

$$\beta_2 = \frac{\frac{1}{N}\sum_{i=1}^{N}(\eta_i - \eta_{\text{rms}})^4}{\left[\frac{1}{N}\sum_{i=1}^{N}(\eta_i - \eta_{\text{rms}})^2\right]^{2}} \tag{10}$$

where η_i is the measured surface fluctuation, with η_{rms} the associated root mean square value. It is well known that for a Gaussian distribution one would have $\beta_1 = 0$ and $\beta_2 = 3$. These two parameters were also tabulated but are not shown in this paper. It suffices to mention that the results indicate that, the waves around the fishing harbour BDZ are only weakly nonlinear, and the Gaussian model provides a good first order approximation.

4.3 The Effect of A Detached Breakwater on Wave Energy Concentration

Distributions of energies for the wave field around the fishing harbour BDZ have been estimated by use of MLM. Experiments were first conducted for the cases without the planned breakwater. After measurements were carried out for all the cases, the basin was drained and the breakwater installed. The effect of the detached breakwater was then studied under the same experimental conditions.

Fig. 6 shows the estimated spreading functions for the four stations in the absence of the breakwater. Generated uni-directional random waves should have a JONSWAP type target spectrum, with a peak frequency $f_p = 1.1$ Hz, a significant wave height $H_{1/3} = 9$ cm, and an incident angle of $\theta_0 = 90°$. Theoretically, an uni-directional wave field has a spreading index $s_{max} \to \infty$. The estimated spreading function for station No. 1 has a finite width with a peak value of approximately 0.8. This indicates that the wave energy is not as concentrated as expected. However, the angle of incidence is reproduced correctly by the wave generator. The main direction of the waves is shifted from 81° at station No. 2 to 72° at station No. 3, due to bottom effects. Within the harbour entrance, at station No. 4, the waves show a pronounced peak again at 81°. The channeling effect through the harbour entrance can be clearly seen through comparison of the two spreading functions for stations No. 3 and No. 4. Similar results, not shown here, are also obtained for cases of multi-directional waves.

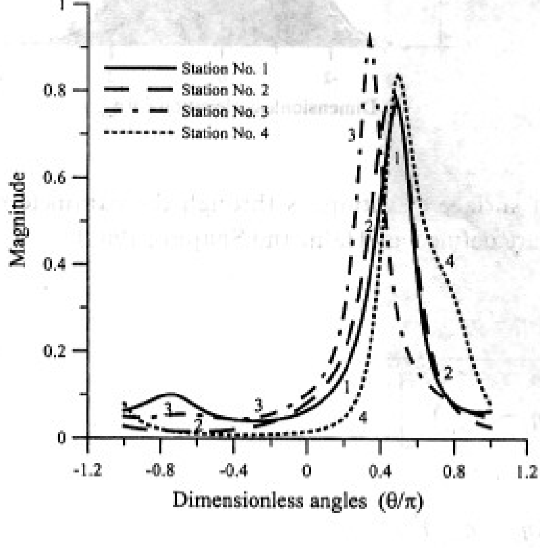

Fig. 6. Estimated spreading functions $G(f_p, \theta)$. Case studied: uni-directional waves with $f_p = 1.1$ Hz, $\theta_0 = 90°$, $H_{1/3} = 9$ cm, in the absence of breakwater.

With the construction of the detached breakwater, waves become even more scattered. The results of multidirectional waves are shown in Fig. 7. In this figure, the waves have a spreading index of $s_{max} = 50$. The bimodal feature of the spreading function can be clearly seen for waves at station No. 2. Since this station is located just in front of the breakwater, it is therefore conjectured that this second peak is caused by waves reflected from the breakwater. It is believed that the bimodality of the spreading function for station No. 3 is caused by re-reflected waves. However, a rigorous check of the reflected wave energies as was done by Davidson *et al.* (1998) is not carried out at the moment. During preparation of this paper, the question of phase locking in front of the breakwater has been raised by one of the referees. Huntley and Davidson (1998) have demonstrated that due to phase locking estimated spreading functions will have spurious peaks. It is argued that, as shown by Dickson *et al.* (1995, see also Huntley and Davidson, 1998), phase locking may result in nodes and antinodes in front of the breakwater. These effects manifest themselves through pronounced peaks and valleys in the estimated spectral densities. Since the pronounced peaks and valleys are absent in our spectral densities (not shown here), it is conjectured here that the effects of phase locking is not important in the present study.

Notice also that the estimated spreading function at station No. 4 has a peak value that is by approximately a factor 3 larger than that at station No. 1. This feature of the spreading function may lead one to suspect that the wave energy at this station is higher than that at station No. 1. It should be pointed out that, since the spreading function only gives an indication of the degree of energy concentration at the measuring site, this high-energy impression is fictitious. We have plotted the spectra of these stations (not shown here), and the results confirm the above argument.

Although the breakwater can detain most of the energy from entering the harbour, it is clear by the comparison of Figs. 6 and 7 that, within the harbour, the waves still have concentrated energy at approximately 90° , as the curve for station No. 4 in Fig. 7 shows. With lower values of the peak frequency, the waves become even more concentrated, the results are, however, all similar to those shown in Fig. 7 and is therefore not be repeated here.

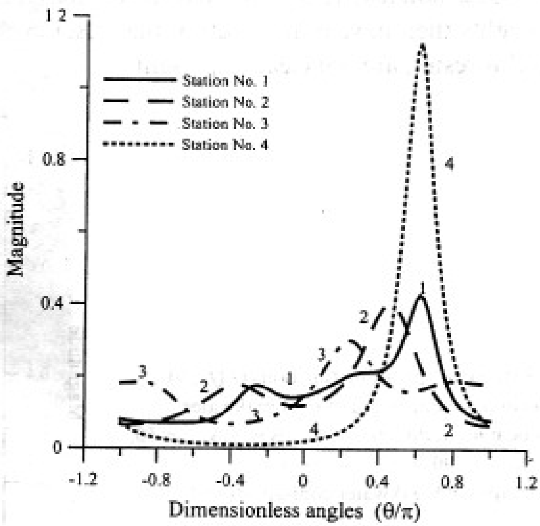

Fig. 7. Estimated spreading functions $G(f_p, \theta)$. Case studied: multi-directional waves with $s_{max} = 50$, $f_p = 1.1$ Hz, $\theta_0 = 90°$, $H_{1/3} = 9$ cm, with the proposed breakwater configuration 1.

With its present configuration, the proposed breakwater is thus shown to be not efficient in detaining wave energy from entering the harbour. An alternative arrangement is therefore chosen and the efficiency is again tested.

The new breakwater should have the same length of 150 meters (in prototype) as in the first proposal, with however, an angle of 22.5° against the wave generator. In prototype, the new breakwater is now in the direction of SEE−NWW as opposed to the orientation of SE−NW of the first proposal. The second configuration of the breakwater is drawn with dashed lines in Fig. 1. Fig. 8 shows the estimated spreading functions for multi-directional waves with a peak frequency of $f_p = 0.7$ Hz. All other conditions are the same as in Fig. 7 to facilitate comparison. It is seen that waves within the harbour entrance are not as concentrated as those in Figs. 6 and 7. Concentrated wave energies in the directions of 0° and 180° behind the breakwater for station No. 3 can still be seen. The cause of this result is not clear at present. From Fig. 8, it seems that the new configuration of the breakwater can effectively detain and scatter waves from being concentrated within the harbour entrance. However, for waves with a peak frequency $f_p = 0.9$ Hz (not shown here), it is found that the waves still have a dominant direction within the harbour entrance. The wave energy in the harbor is, nevertheless, markedly reduced.

5. Conclusions

The characteristics of the wave fields before and after the planned construction of the detached breakwater have been studied experimentally. It is found that:

— The distributions of wave heights can be modeled with a Gaussian, a Rayleigh, and a Weibull distribution. Most of the values of the shape parameter of the Weibull distribution, α, are between 2.3 and 2.4. When this parameter is used as a criterion for the actual shape of wave height distribution, it is safe to say that, wave heights in a laboratory basin have a Rayleigh distribution.

— Occasionally, this shape parameter may have a value equal to 3, or even larger, and wave heights then have a distribution that resembles the Gaussian. The possible factors, which lead to this result, are not clear at present.

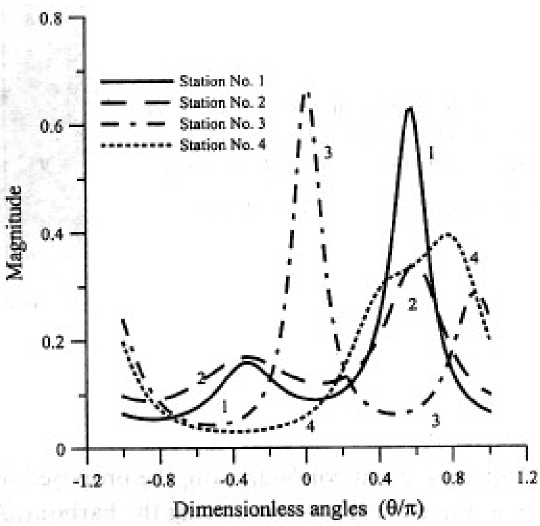

Fig. 8. Estimated spreading functions $G(f_p, \theta)$ for the second configuration of the breakwater. Case studied: multi-directional waves with $s_{max} = 50$, $f_p = 0.7$ Hz, $\theta_0 = 90°$, $H_{1/3} = 9$ cm, with the proposed breakwater configuration 2.

— Albeit weakly nonlinear surface elevations in the basin can be described by the normal distribution. The use of the Gram-Charlier series expansion yields results only marginally better than the Gaussian model does.

— The above three conclusions apply irrespective of the existence of detached breakwater of Harbour Ba-Dou-Ze.

— The Maximum Likelihood Method (MLM) can be used to estimate the distribution of energy of a multi-dimensional wave field satisfactorily. After the construction of the breakwater, secondary peaks appear for the estimated spreading functions in front of the breakwater. Since these secondary peaks appear at locations opposite to the main peaks of incident waves, it is therefore conjectured that they are caused by waves reflected by the breakwater.

— It is found that when the breakwater has an orientation of SEE−NWW, it can detain waves more effectively than the originally proposed orientation of SE−NW.

Acknowledgements — This project is partially supported by the National Science Council, contract No. NSC−88−2611−E−019−030, and partially by the Agriculture Committee, Executive Yuan, contract No. 88−AST−1.4−FID−01(3). The experiments used for this article were conducted by Mrs. N.−W. Huang and W.−S. Chen. The authors wish to express their sincere gratitude.

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