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On reflection and diffraction due to a detached breakwater

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Abstract

Wave reflection and diffraction due to the presence of a detached breakwater are studied with the aid of directional wave fields. At first, experiments were carried out for the case where a breakwater is the sole factor affecting the wave field. It is shown that, estimated directional spectra in front of a detached breakwater can be separated into two parts in the spatial domain. Denoting these as the incident and reflected part of the total energy, an estimate of the reflection coefficient can be obtained. An empirical equation is proposed. This equation relates the reflection coefficients with the distances of the measuring stations away from the breakwater, as well as directionality of the wave field. This equation was then applied to the experiments where the fishing harbour Ba-Do-Zhi (BDZ) was used as model. It is shown that favorable results are obtained. On the other hand, diffraction due to the detached breakwater was also studied in a similar way. It is shown that predictions based on the empirical equation are in quantitative agreements with measurements. It is proposed that these empirical equations can be used in engineering applications.

Keywords: Reflection; Diffraction; Directional spectrum

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1. Introduction

The main factors in evaluating various design alternatives are the effects that will be caused by the planned breakwater. These consist the reflection and diffraction of the wave fields due to its presence and both factors are essential in determining the efficiency of the breakwater. Now, since the wave field around a detached breakwater is composed of incident, reflected, scattered and diffracted waves, it is clear that the wave field is rather complicated. In the past, the influence of wave directionality was neglected; both experiments and numerical analyses were often carried out where the wave field is assumed to be uni-directional implicitly. However, the dominant wave direction of a wave field is rather hard to determine. This is true even for the case without a breakwater, as the wave direction may depend, among other factors, on the prevailing wind direction, and the underlying topography. The neglect of this factor may lead to biases, which, under certain circumstances, may be enormous.

Funke and Mansard (1992) stressed the necessities for experiments with directional wave field. It is shown that, this can improve the designs of marine structures, both cost-effectively as well as their safety. The effect of harbour resonance, for example, will be smaller; the loading on fixed structures will generally be less, in a directional wave field.

Mory and Hamm (1997) studied the wave heights, setups and currents around a detached breakwater in both uni- and bi-directional wave fields. The decrease in low frequency waves is significantly higher for directional wave field on an open beach. On the other hand, wave height levels in the lee of the breakwater are found to be slightly higher for directional than for uni-directional waves.

It seems fair to say that, experiments with uni-directional wave field can provide valuable information. However, for a more detailed study, the effect of directionality on the transformation and dissipation of the waves in the spatial domain cannot be neglected.

As a result, modal testing in directional wave fields is to be preferred. Now, since directional spectral analysis consists of determining the energy contains of a wave field in both frequency and spatial domain, it seems, therefore, to be the appropriate tool in dealing with these problems.

The wave field in front of a detached breakwater is mainly composed of the incident and reflected waves. In principle, the reflection coefficients can be obtained when energies of these two parts in the directional spectrum are separated (Frigaard et al., 1997). However, in regions near the breakwater, incident and reflected waves may have become phase-locked. This then leads to spurious peaks in the estimated directional spectra (Elgar et al., 1994; Davidson et al., 1998) and it will then result in erroneous estimates of the reflection coefficients. To take the effect of phase-locking into consideration, some modifications have to be done. Isobe and Kondo (1984); Kondo et al. (1986), for example, used a modified version of the Maximum Likelihood Method (MLM) to estimate the reflection coefficient in front of a reflector. However, in applying this method, the location of an effective reflection line is needed as prerequisite. It should be noted that, for practical conditions, the definition of the reflection line may become ambiguous. This is because the location of this reflection line may vary with different wave conditions, as well as characteristics of structures. On the other hand, for the usual methods that do not consider the effect of phase-locking, the presumption of an effective reflection line is not needed.

In this case, the performance estimating method, the Bayesian Directional Method (Hashimoto et al., 1987) is needed. The method can reduce the effect of phase-locking to the estimation of directional spectrum (Ilic et al., 2001; Huang et al., 2003).

In this paper, we present some of our results on the estimations of reflection and diffraction due to a detached breakwater in a directional wave field. Qualitative experiments and the modal tests of the BDZ fishing harbour were both conducted in the wave basin of the ‘Ocean Engineering Laboratory’ of the Department of Harbour and River Engineering, National Taiwan Ocean University. Measurements have been made both in front of, and behind, a detached breakwater. Furthermore, the characteristics of the wave field around this breakwater were also studied.

2. Mathematical background

The directional spectrum $S(f,\theta)$ describes the distribution of wave energy in both the spatial and frequency domains. Conventionally, a directional spectrum can be expressed as:

$$S(f,\theta) = S(f)G(f,\theta) \tag{1}$$

$S(f)$ is the one-sided frequency spectrum, which can be determined from the record of free-surface elevation from a point measurement. $G(f,\theta)$ is the spreading function that describes the distribution of the wave energy on their propagation directions from 0 to 2π. Even though the wave energy can be distributed in different directions, the total energy of the wave field should remain unchanged. Therefore, $G(f,\theta)$ should have the following property.

$$\int_0^{2\pi} G(f,\theta)\mathrm{d}\theta = 1 \tag{2}$$

It is generally believed that, among all the presently available methods for directional spectrum estimation, the Bayesian Directional Spectrum Estimation Method (BDM, Hashimoto et al., 1987) has the highest resolution. Its drawback lies in that a time-consuming iteration procedure is needed to achieve the correct answer and the acquirement of the specific geometric arrangement of the wave gauges is needed. On the other hand, the EMEP, first proposed by Hashimoto et al. (1993), retains the advantage of the BDM, while reducing the time of iteration refinements. Possible errors contained in the cross-spectra were taken into account. In this study, the Newton’s technique of iteration was applied to minimize them. Furthermore, it is suitable for estimating directional spectra from the wave data measured by the arbitrary geometry of the wave gauge array.

The formulation of $G(f,\theta)$ estimated by the EMEP is characterized by an exponential function that can be expressed as:

$$G(f,\theta) = \frac{\exp\left[\sum_{n=1}^{M}\{a_n(f)\cos n\theta + b_n(f)\sin n\theta\}\right]}{\int_0^{2\pi}\exp\left[\sum_{n=1}^{M}\{a_n(f)\cos n\theta + b_n(f)\sin n\theta\}\right]\,\mathrm{d}\theta} \tag{3}$$

where $a_n(f)$ and $b_n(f)$ are the unknown parameters and M is the order of the model. More detailed expressions of this model, as well as discussions concerning procedures of the iteration, can be found in Hashimoto et al. (1993); Hashimoto (1997).

When incident and reflected waves coexist in a wave field, the estimated directional spectrum will be bimodal. Separating the wave field in front of a breakwater into the incident and reflected parts, hereafter denoted as respectively $S_I(f,\theta_I)$ and $S_R(f,\theta_R)$, the reflection coefficient K_R can be defined as (Frigaard et al., 1997):

$$K_R(f,\theta) = \sqrt{\frac{S_R(f,\theta_R)}{S_I(f,\theta_I)}} \tag{4}$$

In a laboratory wave basin, waves that are generated by the wave generator, and propagate toward the test model can be considered as incident waves. On the other hand, waves that travel in directions toward the wave generator are considered as reflected waves. These waves are reflected by the test model or from the dissipating beach on the other end of the basin. Integrating the directional spectrum in the separated directional bands, i.e. the direction of incident and reflected domain, the reflection coefficient as a function of frequency can be summarized as:

$$K_R(f) = \sqrt{S_R(f)/S_I(f)} \tag{5}$$

where

$$S_I(f) = \int_{180°}^{360°} S(f,\theta)\,\mathrm{d}\theta \tag{6}$$

$$S_R(f) = \int_{0°}^{180°} S(f,\theta)\mathrm{d}\theta \tag{7}$$

are, respectively, the incident and the reflected wave energies.

The separated incident and reflected spectra in Eqs. (5) and (6) can be integrated further in the frequency space. This then leads to a single valued reflection coefficient for general purposes (Eq. (7)).

$$K_R = \sqrt{\frac{\int_0^F S_R(f)\mathrm{d}f}{\int_0^F S_I(f)\mathrm{d}f}} = \sqrt{\frac{\int_0^F \int_{0°}^{180°} S(f,\theta)\mathrm{d}\theta\,\mathrm{d}f}{\int_0^F \int_{180°}^{360°} S(f,\theta)\mathrm{d}\theta\,\mathrm{d}f}} \tag{8}$$

F is the cut off frequency.

3. Experimental setups

Two kinds of experiments were conducted. The first one is qualitative experiments with an empty basin, the second one uses fishing harbour BDZ as a model. The layouts are shown in Figs. 1 and 2, respectively. All the experiments were carried out in a multi-directional wave basin which has a dimension of 50×50×1 (width×length×depth, in meters).

A serpentine wave generator of the piston type, consisting of 56 paddles is located at one side of the wave basin. A 1:6 gravel beach is paved on the opposite side of the wave generator. Furthermore, mesh sheet wave absorbers are used for the surrounding sidewalls of the basin. Preliminary tests conducted without the detached breakwater have shown that

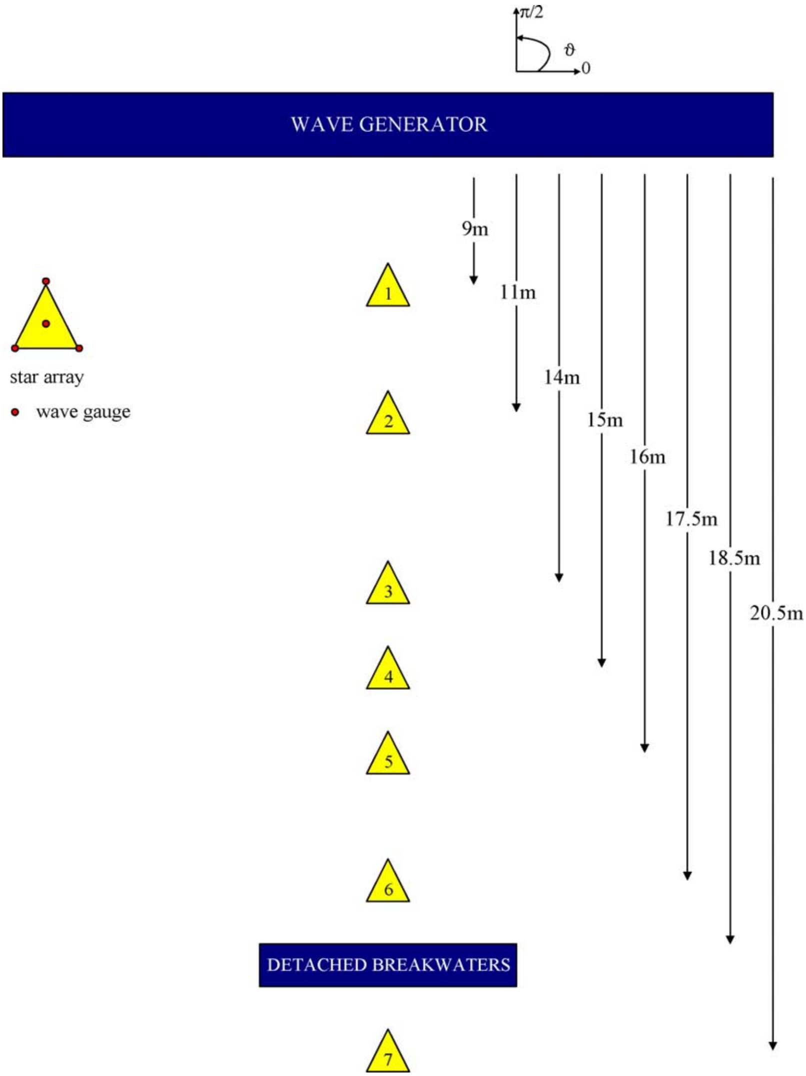

Fig. 1. The setup of the qualitative experiments (Huang et al., 2003).

the reflected energies were never more than 5% those of the incident waves. It is believed that, experiments with the breakwater were only slightly affected by re-reflection from the sidewalls of the basin. The sampling rate, recording length of the surface elevations, and the wave conditions were summarized in Table 1.

Throughout the experiments, the target spectra are of the JONSWAP type:

$$S(f) = \alpha(2\pi)^{-4} g^2 f^{-5} \exp\left[-\frac{5}{4}\left(\frac{f}{f_p}\right)^{-4}\right] \gamma^{\exp[-(f/f_p-1)^2/2\sigma^2]} \tag{9}$$

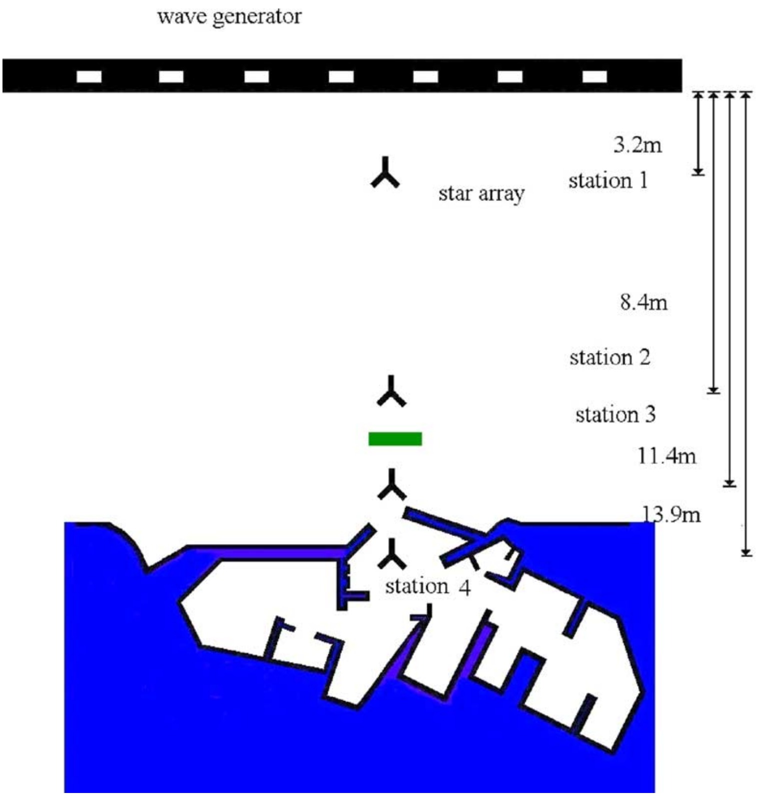

Fig. 2. The setup of the BDZ fishing harbour experiments.

where

α the Phillips constant, ($\approx$0.081)
f_p the peak frequency;
γ the peak enhancement factor, (mean$\approx$3.3)

$$\sigma = 0.07 : f \leq f_p = 0.09 : f > f_p \tag{10}$$

Table 1
The experimental condition

Experiment	Qualitative experiment	BDZ experiment
Target spectrum	JONSWAP	JONSWAP
Peak frequency	0.6, 0.8, 1.0, 1.2 (Hz)	0.7, 0.9, 1.1 (Hz)
$H_{1/3}$	5, 8 (cm)	7 (cm)
Main wave direction	270°	270, 292.5°
Spreading index S_{max}	10, 25, 50, ∞	10, 25, 50, ∞
Sampling rate	20 Hz	50 Hz
Record length	8192 s	122.88 s

In generating multidirectional waves, a spreading function of the Mitsuyasu type was used (Goda, 2000). It can be written as follows:

$$G(f,\theta) = G_0 \cos^{2s}\left(\frac{\theta}{2}\right) \tag{11}$$

where θ is the azimuth measured counterclockwise from the principal wave direction. G_0 is a constant which satisfies Eq. (2) as:

$$G_0 = \left[\int_{-\pi}^{\pi} \cos^{2s}\left(\frac{\theta}{2}\right) \mathrm{d}\theta\right]^{-1} \tag{12}$$

where s can be modified as:

$$s = \begin{cases} S_{\max}(f/f_p)^{-2.5} : f > f_p \\ S_{\max}(f/f_p)^{5} : f \le f_p \end{cases} \tag{13}$$

where $S_{\max}$ is the spreading index which represent the peak value of s.

During the qualitative experiments, a constant water depth of 0.6 m is used. This means that, the only factor that can affect the wave field is through the presence of the detached breakwater. It is hoped that, in this way complicated wave phenomena, such as those due to the underlying topography, can be avoided. The detached breakwater is 4 m in length, 0.6 m in width, and has a height of 0.9 m. It is a model of a standard perpendicular caisson and is located at 18.5 m away from the wave generator. No wave-dissipating blocks were used in the foot of the detached breakwater. The surface of the detached breakwater is smooth and impermeable. The height of the detached breakwater is higher than usual scale so that no overtopping will occur. Experiments were conducted for cases both with and without it. Measurements were conducted using wave gauges in the form of so-called star array. A total of six star arrays were used, with five of them located in front of, and one behind, the detached breakwater.

The BDZ modal experiments were also conducted to test and verify the feasibility of some empirical results derived from the qualitative experiments. The BDZ harbour is near Keelung in the northern part of Taiwan; where in winter strong northeast monsoon winds prevail. To improve the tranquillity inside the harbour, a detached breakwater was proposed. The detached breakwater should have a total length of 150 m. To test the feasibility of the proposal, experiments were conducted for cases both with and without the proposed breakwater. A scale of 1/81 was used for the experiments. During the experiments, the model was located 10 m away from the wave generator. Four star arrays were located at, respectively, 3.2, 8.4, 11.4, and 13.9 m away from the wave generator, where the water depths are 60, 47.5, 36.5 and 29 cm.

4. Results and discussions

The procedures of the present evaluations are as follows. At first, we have derived empirical relations for both reflection and diffraction due to the breakwater from

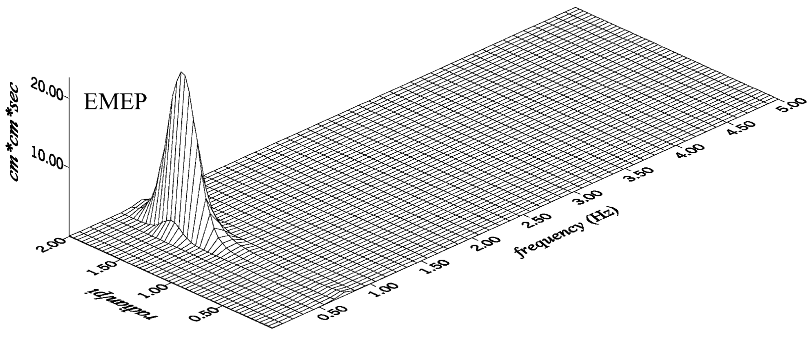

Fig. 3. The directional spectrum of station 4 without the detached breakwater.

the qualitative experiments. Using these equations, the distributions of wave energies around the detached breakwater of BDZ are then estimated. These results are then compared with those measured by the wave gauge arrays. In this way, the feasibility of the equations can be assessed.

4.1. The qualitative experiments

Estimated directional spectra are shown in Figs 3 and 4. While Fig. 3 is for the case without the detached breakwater, the result of with the breakwater is shown in Fig. 4. The measuring star array is station 4 (of Fig. 1), which located at 3.5 m in front of the detached breakwater. The incident significant wave height and period are 8.0 cm and 1.5 s, respectively. The directional spreading index, $S_{\max}$, is 50 and the principal wave direction is 270°. It should be noticed that in these two figures, the abscissas are the directions of wave propagation, which are normalized with the factor π. The reflected waves are located in the region from 0 to 1 (0–180°) of the dimensionless axis, whereas the incident waves are located from 1 to 2 (180–360°). In Fig. 3, the estimated peak of the directional spectrum is located at 1.5 (270°), which is the main direction of the incident waves. As Fig. 4 clearly shows, the construction of the breakwater changes the characteristics of the wave field drastically. Reflected waves now have a concentrated energy that peaks at 0.5

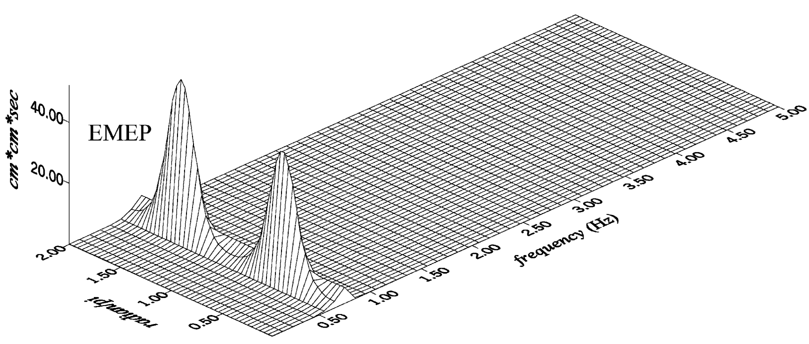

Fig. 4. The directional spectrum of station 4 with the detached breakwater.

(90°) of the abscissa, is just opposite to the principal direction of incident waves. Using Eq. (7), we have estimated the reflection coefficient to be 0.89.

There are altogether six measuring stations that are located in front of the detached breakwater. The different locations of these stations serve to study the reflecting behaviors of the breakwater. We have plotted the estimated reflection coefficients for all the wave conditions as a function of the ratio of *D*/*L* in Fig. 5, where *D* is the measuring distance, and *L* the dominant wavelength. The latter is calculated from the dispersion relationship using the peak frequency of the spectrum. For the cases with directional waves, it can be seen that the reflection coefficients decrease rapidly within four wavelengths away from the detached breakwater, and tend to reach a constant value after this. It is also seen that the reflection coefficients decrease more rapidly when the spreading index $S_{\max}$ is small. That is to say, when the incident waves become more and more short-crested, the reflected waves will disperse faster in the spatial domain away from the detached breakwater. On the other hand, when the incident waves are unidirectional, the reflection coefficients do not seem to vary with the ratio of *D*/*L*. For these cases, the reflected waves travel in only one direction, which is opposite to that of the incident waves, and they do not disperse in the spatial domain while propagating away from the detached breakwater.

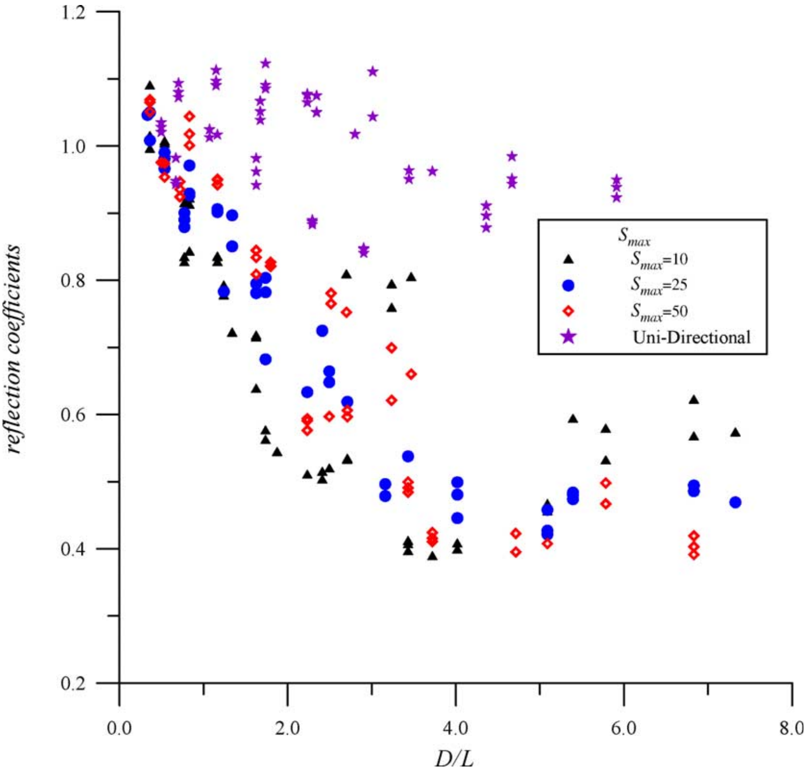

Fig. 5. The reflection coefficients estimated by the directional spectra (Huang et al., 2003).

Goda (2000) has pointed out that the length of the reflector limits the length of the crest lines of the reflected waves. As a result, the reflected waves disperse while propagating away from the source of reflection in a way similar to the phenomenon of wave diffraction. Since the length of the detached breakwater is fixed, the length of the crested lines of reflected waves varies with the spreading parameter. When the waves became more and more short crested, reflected waves will disperse wider, and, therefore, reflected energies pass the measurement points will be less.

When the measuring distance (D) is less than one wavelength (of the dominant wave), there are cases where estimated reflection coefficients may have values larger than 1. It is unrealistic that energies of the reflected waves should have values larger than that of the incident waves. It is because for a wave field in front of the reflector, standing waves are formed and there are nodes and antinodes. It is because of some of the wave gauges are located near those points. When this is the case, measured surface elevations would have been contaminated. As a result, the vital phase information between wave gauges, which are needed for the estimation of directional spectrum, are then obscured. Under these circumstances, the directional spectra estimated by the EMEP method will no longer be valid, since the wave energies will then be scattered in all directional bands.

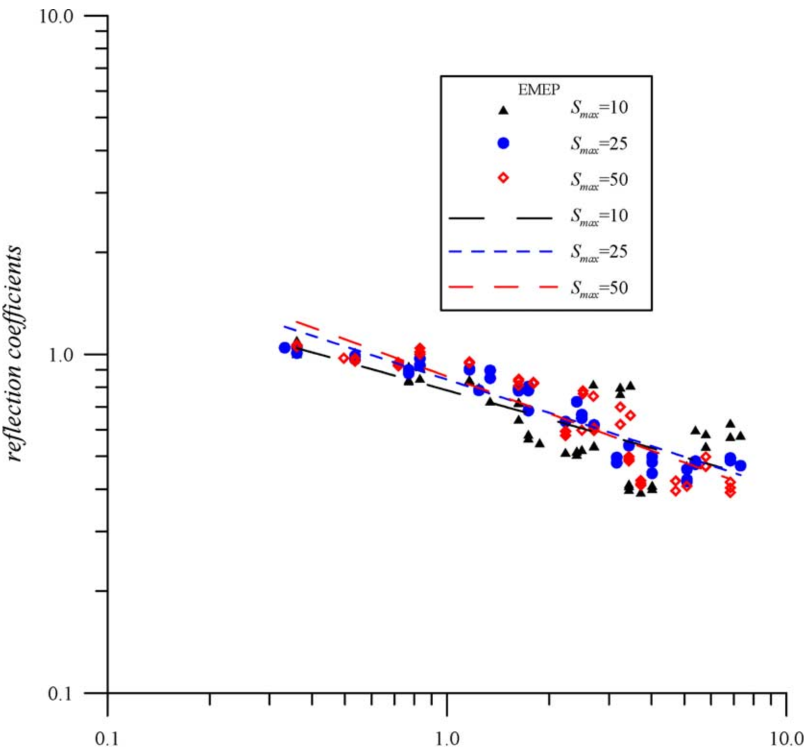

Fig. 6. The regression results of the reflection coefficients according to *D*/*L*.

In Fig. 6 we have draw three regression lines according to different values of S_{max}. It should be mentioned that, the results for the cases with unidirectional waves are not included in this figure. This is because, as mentioned earlier, for these cases litter variations of the reflection coefficients in relation with the ratio of D/L were found. The relations between the reflection coefficients and the ratios of D/L can be approximated as:

$$K_R = \alpha\left(\frac{D}{L}\right)^{\beta} \tag{14}$$

where

$$\begin{cases} 0.7766 \le \alpha \le 0.8513 \\ -0.2757 \le \beta \le -0.3787 \end{cases} \tag{15}$$

It can be seen from the figure that the three regression lines are very close. This seems to suggest that, a single empirical equation using the mean values of the coefficients can be used instead of three. In the following, we will use the mean values of, respectively, 0.84 and −0.34 for the coefficients α and β of Eq. (13).

The wave field behind a detached breakwater is mainly due to diffracted and oblique incident waves. In Fig. 7 we show the estimated directional spectra for the cases where

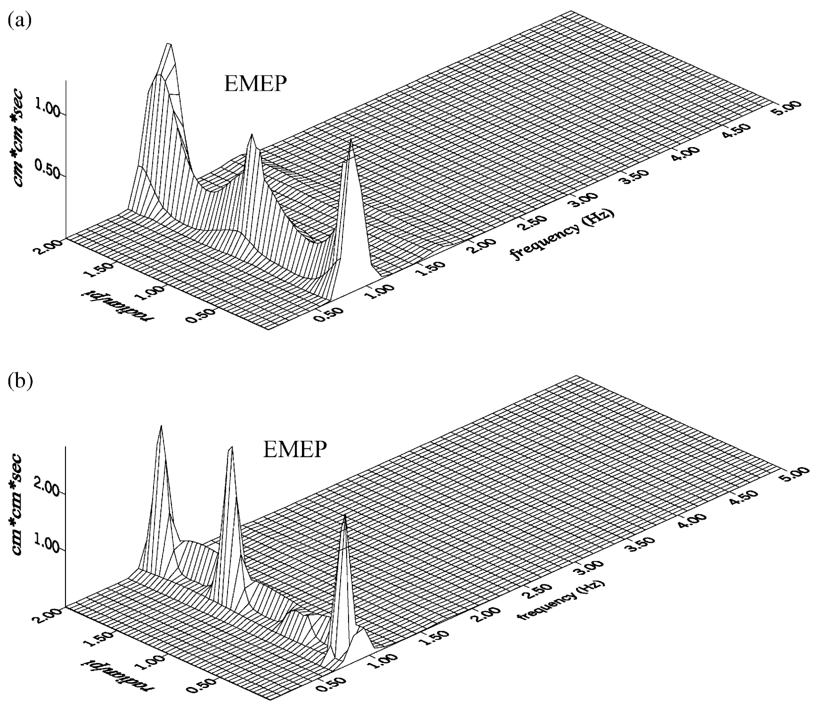

Fig. 7. The directional spectrum behind of the detached breakwater with S_{max} are 10(a) and 50(b).

have the same significant wave period (1.1 s) with different spreading index which equals to 10 (Fig. 7a), and 50 (Fig. 7b), respectively.

It can be seen from Fig. 7 that both of these two directional spectra have three peaks, which are all located at approximately, 0, 1, and 2, of the normalized abscissas. However, it should be noted that, since the abscissa is an unwrapping of the period of 2π, the two peaks at 0 and 2 should be seen as one. Thus there are only two peak values for the both cases that located at 1.13 and 1.87. The diffracted waves propagate from the breakwater ends with an included angle 23.4° with symmetry. From this it is clear that, the principal direction of diffracted waves is not affected by the directionality of the incident waves. On the other hand, the directionality of the incident waves is retained at the lee of the detached breakwater. With increasing $S_{\max}$, diffracted energies will become more and more concentrated in the spatial domain.

A sheltering coefficient, *KD*, defined as the ratio of significant wave height with the breakwater to that without, is computed from the measurements behind the detached breakwater through Eq. (15):

$$KD = \frac{H_{1/3,(\text{with detached breakwater})}}{H_{1/3,(\text{without detached breakwater})}} \tag{16}$$

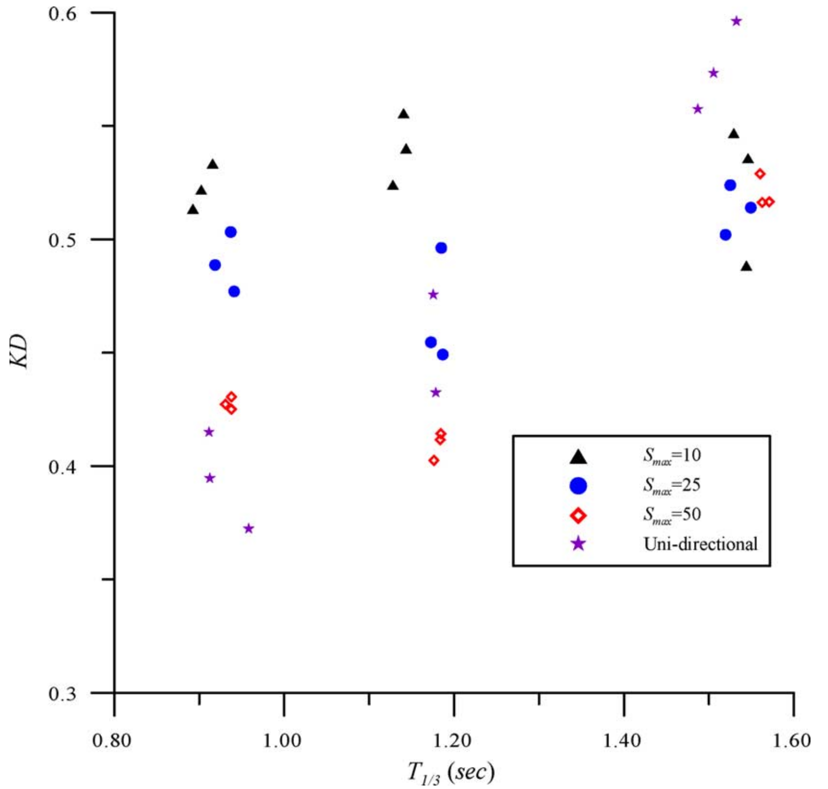

Fig. 8. The sheltering coefficients according to the wave period.

A large value of the sheltering coefficient means that, more energy will be diffracted into the lee of the detached breakwater. With other words, less incident energy would be detained by the breakwater.

Fig. 8 shows the distribution of the sheltering coefficients as related to the wave periods. It can be seen from Fig. 8 that, for cases with $S_{max}=10$ and 25, the values of *KD* seem to have no relation to the wave period. Briggs et al. (1995) have also shown that, it is the wave directionality, rather than wave period, that plays an important role in governing the extent of wave diffraction in the lee of a detached breakwater. However, when the incident waves become more and more long-crested, the effect of the wave period on the diffraction becomes apparent. For the uni-directional cases, there is a noticeably relation of the values of *KD* with wave period. For longer wave periods, the diffraction is more pronounced.

Fig. 9 shows *KD* values as a possible function of wave directionality. The larger symbols in the graph represent the mean values of the sheltering coefficients for the respective S_{max}. It is seen that directional spreads have a direct relation to wave diffraction. With increasing directional spread, more energy will be diffracted into the lee of the detached breakwater. Silvester (1986) has pointed out that oblique incident wave energies are more easily diffracted. Judging from the fact that, the reflection coefficients was found to decrease for smaller spreading index, we find that the argument of Silvester is

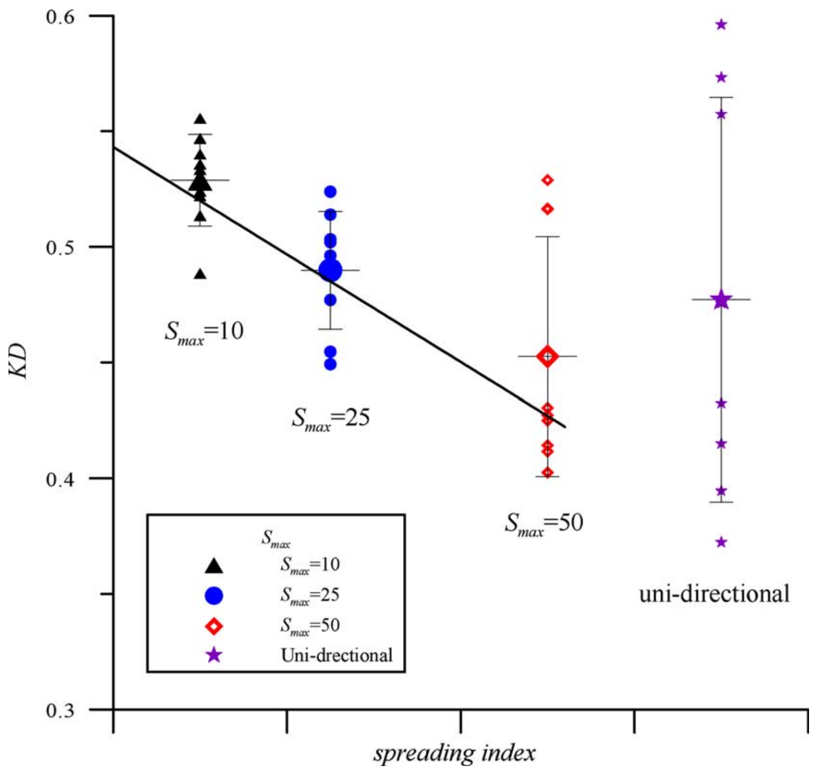

Fig. 9. The sheltering coefficients according to the wave directionality.

reasonable. This is to say that, the more spread is a directional wave field, the more oblique incident waves will be diffracted into the lee of a detached breakwater. The relationship between S_{max} and the sheltering coefficients can be expressed as:

$$KD = -0.00186S_{max} + 0.5432 \quad (17)$$

4.2. Modal tests of fishing harbour BDZ

To test the applicability of the empirical equations, Eqs (13) and (16), they were then used for the comparison with the measured results of BDZ. Measured and predicted reflection coefficients are shown in Fig. 10. In this figure, the prediction based upon Eq. (13) is represented as a curve, whereas measured results are shown as symbols. The incident waves propagate with a direction of 270° to the detached breakwater. It can be seen that, as the significant wave period of the incident waves becomes larger, the predicted results deviate from those measured. There is a simple explanation for this. The distance between the measuring station and the detached breakwater, D, remain unchanged. When the incident wave periods become larger, the wavelengths, L, will become longer. And, this causes a decrease of the ratio of D/L. As was pointed out earlier, for small ratios of D/L,

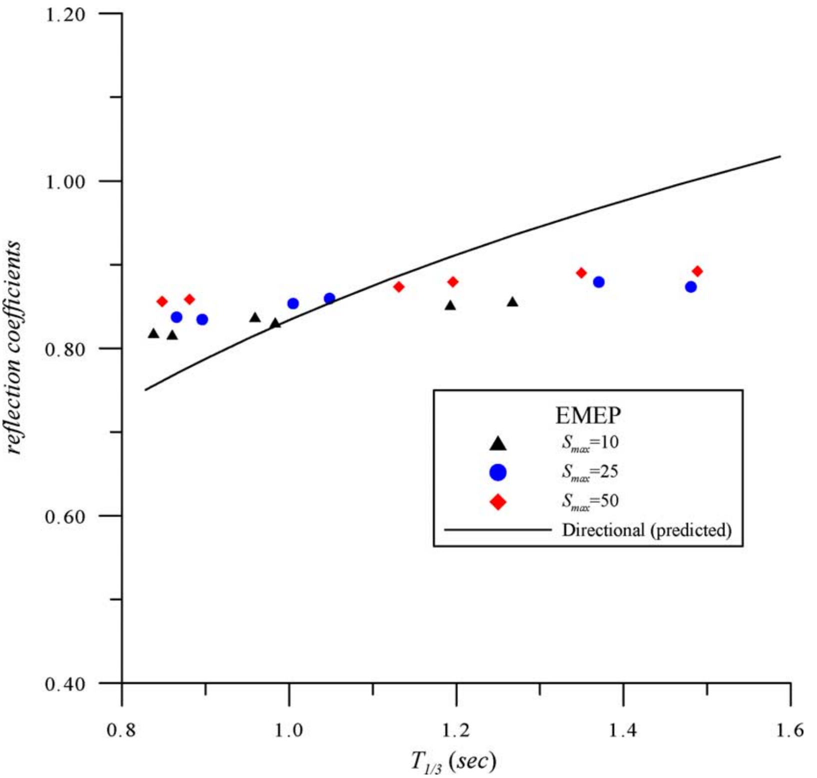

Fig. 10. The predicted and measured reflection coefficients of the BDZ (270°).

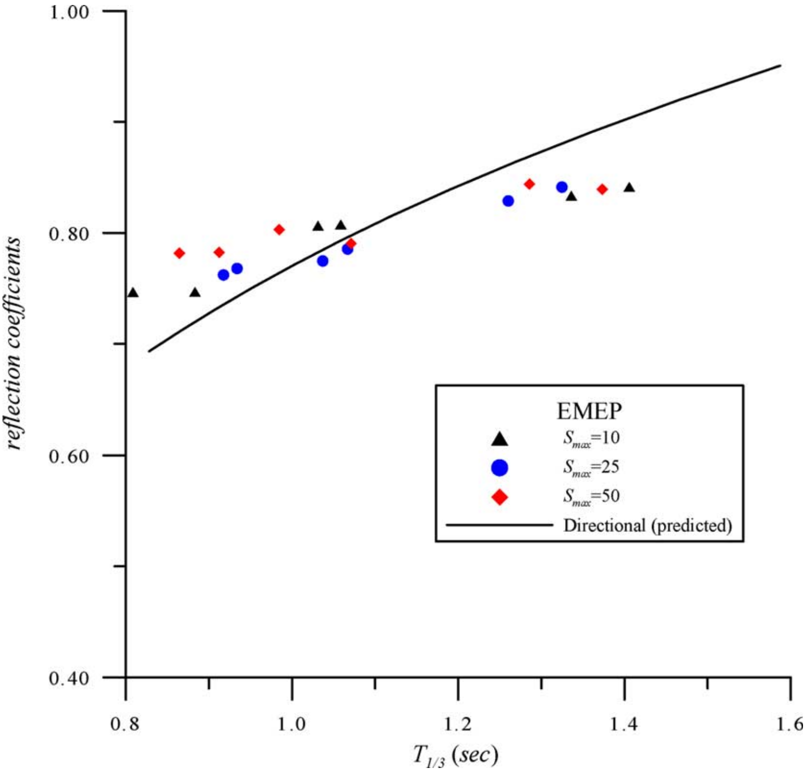

Fig. 11. The predicted and measured reflection coefficients of the BDZ (292.5°).

phase-locking becomes more pronounced, and estimated directional spectra become less accurate. Furthermore, since the effect of topography is not considered in the empirical equation, it is conjectured that this could cause further bias in the estimate.

Fig. 11 shows the results when the incident waves propagate with a principal direction which has an angle of 292.5° to the detached breakwater. Since our Eq. (13) was derived for cases where the waves were normal to the breakwater, it is modified as follows. Here, we transfer the oblique incident energy into the normal one by multiplying the cosine functions (Eq. (17)), following the method proposed by Dickson et al. (1995), we can multiply Eq. (17) with a cosine function.

$$K_R = 0.8427\left(\frac{D}{L}\right)^{-0.3409}\cos(\Theta) \tag{18}$$

where Θ is the angle between the normal of the breakwater and the principal direction of the incident waves.

Fig. 12 is the relative errors between the measured and predicted results. The larger symbols are the mean values of the relative errors. The solid and the empty symbols represent the relative errors for the cases when the principal wave directions are, respectively, 270 and 292.5°. When the incident waves are normal to the breakwater,

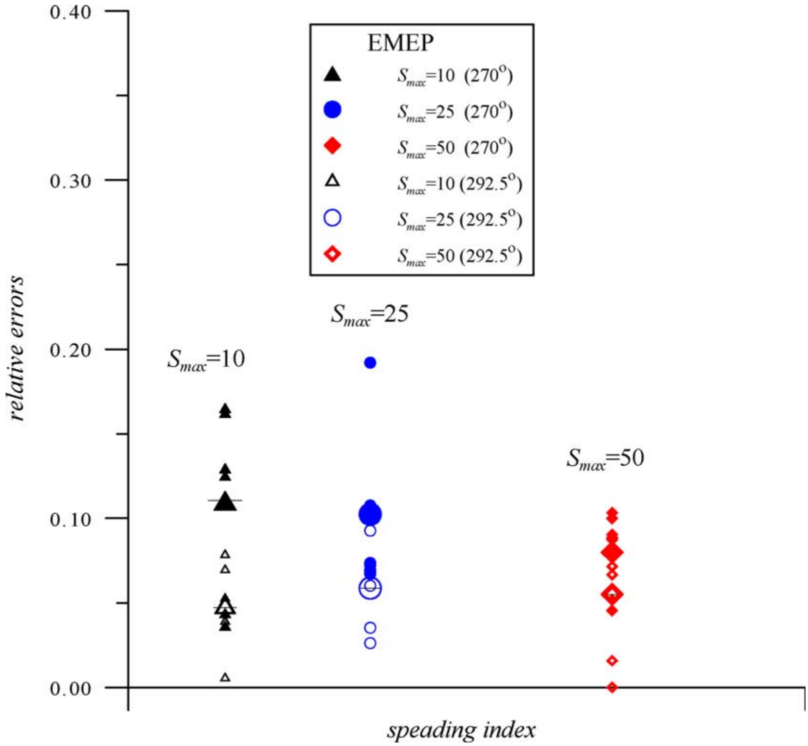

Fig. 12. The relative errors between the predicted and measured reflection coefficients.

the mean values of the relative errors are 0.11, 0.10 and 0.08, for $S_{\max}=10$, 25, and 50, respectively. On the other hand, for the cases with oblique incident waves, the mean relative errors are 0.05, 0.06 and 0.05 for the same $S_{\max}$ values. These results seem to indicate that our proposed empirical equation is applicable.

Fig. 13 compares the sheltering coefficients measured at station 3 of the BDZ experiments and those predicted using Eq. (16) (solid line). The dashed line, Eq. (18), is a least square fit of the measured results of BDZ as a function of the spreading index It can be seen that these two lines are parallel to each other, and have the similar trend, i.e. they all show a decrease of the sheltering coefficients with the increasing $S_{\max}$. This clearly shows that, irrespective of the existence of any surrounding structures, so long as the waves tend to be more long-crested, less wave energies will be diffracted. The *KD* values of the BDZ are all larger than those of the qualitative experiments. This can be explained as follows. In the qualitative experiments, the wave field behind the detached breakwater is composed of diffracted and oblique incident waves. On the other hand, in the wave field in the lee of the detached breakwater of BDZ there are also waves reflected by the breakwaters of BDZ those behind of the detached breakwater (Fig. 2). As a result, the significant wave heights, as well as the values of *KD*, are larger.

$$KD = -0.00183S_{\max} + 0.5917 \tag{19}$$

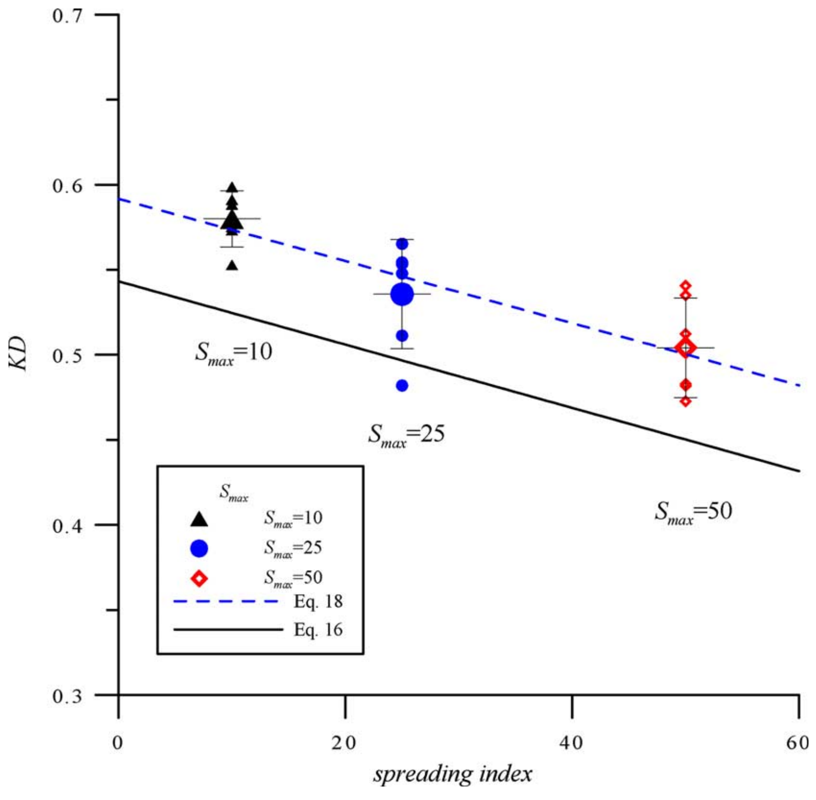

Fig. 13. The sheltering coefficients of BDZ.

5. Conclusions

Wave reflection and diffraction due to the presence of a detached breakwater is considered here in this paper. Two empirical relations were derived from the results of qualitative experiments. The effect of wave field directionality is considered in these two equations. In the following, we summarize our present findings.

The present results indicate that, within a distance of four dominant wavelengths from the breakwater, reflections tend to decrease for short-crested waves. In the meantime, the reflection coefficient will decrease with increasing distance away from the breakwater. On the other hand, for distances more than four dominant wavelengths away from the breakwater, the reflection coefficient seems to approach to a constant value. An empirical equation that relates reflection and the distance away from the breakwater has been derived. Applying this equation to the BDZ experiments, the relative errors between the estimates and measured results were found to be less than 0.10.

A relation between the wave diffraction and directionality has also been derived. The predicted and the measured results of BDZ have the same slope of the regression lines. Estimated and the measured results of BDZ show similar trends. They all show that, diffracted wave energies in the lee of the breakwater increase with increasing directional spread. However, measured results are found to be lager than estimated. It is believed that, this is due to the fact that reflections from the surrounding breakwater of BDZ are not considered in the empirical equation.

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