# CHAPTER 3

### OBSERVATION OF DIRECTIONAL WAVE SPECTRA

# AND REFLECTION COEFFICIENT OF BREAKWATER IN A HARBOR

by

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#### ABSTRACT

Field investigations were performed in order to show the effect of wave diffraction by breakwaters through directional wave spectra measurements in a harbor, and to estimate the reflection coefficient by resolving the incident and reflected wave energy in front of a composite type breakwater. Combinations of an ultrasonic wave gage (USW) and an electromagnetic current meter (EMC) were used to measure the synchronized data of the water surface elevation and two horizontal velocities. The EMLM (Extended Maximum Likelihood Method) was applied for the calculation of the directional wave spectrum, and the modified EMLM for an incident and reflection wave field was applied for the estimation of the reflection coefficient. Through the estimated directional wave spectra, the effect of wave diffraction by breakwaters were discussed and the reflection coefficient was estimated at about 0.9. As a result, the applicability of the field investigation method and the modified EMLM were verified.

### 1. INTRODUCTION

In the design of maritime structures it is necessary to estimate not only the characteristic height and period parameters but also the random nature of sea waves. To describe the irregularity of sea waves with different frequencies and directions, the concept of directional wave spectrum is of great importance, since the directional wave spectrum employs both the frequency and the wave direction. It is basically possible to determine the directional wave spectrum of random sea waves by use of various methods and instruments. As there have been recent remarkable advances in the theories for estimating the directional wave spectrum, many field investigations have also been performed.

Among the methods for computation of directional spectrum, the Maximum Likelihood Method (MLM) is known to yield the highest directional resolution. However, it is applicable only to wave gage array measurements. So, Isobe, Kondo,

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and Horikawa (1984) extended the MLM to mixed arrays and named it the Extended Maximum Likelihood Method (EMLM). For the estimation of the directional spectrum by the EMLM, a set of data records of various wave properties at one point is sufficient. Moreover, at sites where wave transformation such as that due to refraction and diffraction is significant, the EMLM makes it possible to obtain the local direc-tional wave spectrum. But the EMLM is not applied for the estimation of the directional wave spectrum near the reflection line, because the phase lag between the incident and reflected waves is not random. It is necessary to consider the fixed phase relation of each pair of incident and reflected wave components. So, the EMLM is modified for calculating the directional spectrum in the wave reflection system similar to the relation between the MLM and the MMLM (Isobe and Kondo, 1984). This method is termed the EMLM-2. is possible to estimate the reflection coefficient of a It vertical wall type breakwater by using the EMLM-2. This method to find the reflection coefficient of prototype structures is much easier than the other methods, because of one-point measurement.

The object of this study is to elucidate the diffracting characteristics through the change of the directional wave spectra calculated by the EMLM, and to estimate the reflection coefficient by analyzing the directional wave spectra by the EMLM-2.

#### 2. FIELD INVESTIGATION

#### 2.1 Site Location and Period of Investigation

The field investigations were carried out in the eastern shore of the Japan Sea at Kashiwazaki, Niigata prefecture, Japan, from January through February, 1986. A location map of the investigation site is shown in figure 1. As geographical features, Sado island and Noto peninsula lie north and west of the study area, respectively. So the dominant wave directions during storm are almost limited from northwest to west.

### 2.2 Harbor Layout and Field Investigation Program

Figure 2 explains the harbor layout and positions of the instrument combination of a wave gage and a current meter. The Harbor layout is a complex shape in order to keep the harbor tranquil, prevent retention of coastal sediment, allow free flow of water, and so on. Therefore, the wave transformation due to diffraction in the harbor is fairly intricate.

The field investigation program consisted of :

- measurements of incident waves at location free from the effects of breakwaters (point P0);
- measurements of waves diffracted by breakwaters (point P1, P3, and P4); and
- measurements of diffracted and reflected waves in front of the south breakwater (point P2).



Figure 1





Figure 2 Harbor layout and positions of measuring point

In the third set of measurements, the distance between point P2 and the south breakwater was calculated beforehand, because the accuracy in estimating the directional wave spectra and the reflection coefficient changes depended upon the ratio of distance between the instruments and the breakwater (X) to wave length(L).

Schematic profile of the south breakwater, which is a composite type breakwater without wave energy dissipation, is given in figure 3. This figure also shows the location of point P2 where the instruments were installed at the distance of 32.0 m away from the south breakwater.



Figure 3 Schematic profile of the south breakwater

### 2.3 Measuring Instruments and Data Sampling Mode

Combinations of the ultrasonic wave gage (USW) and the electromagnetic current meter (EMC) were located on the bottom of the sea. The distance between USW and EMC is about 1.0 m and timing is synchronized through an electrical cable link. Therefore this measuring system is considered "one-point measuring" in terms of field scale.

USW acts as a reversed echo sounder to measure the surface elevation and EMC measures the two components of the horizontal water particle velocity at orthogonal angles. Data is measured for approximately 9 minutes every 2 hours, containing 1022 samples with an interval of 0.5 second, and stored on cassette tape inside the instrument.

#### 3. METHOD OF DATA PROCESSING

### 3.1 Statistical Analysis

Both the USW and EMC data sometimes contained more noise spikes than were acceptable for statistical analysis. The data records were therefore semi-automatically corrected on a graphics terminal, which allowed an immediate visual check of corrections. All data were analyzed statistically, including the calculation of significant wave height and period by the zero-up-crossing method, principal wave direction and current velocity, etc.

#### 3.2 Directional Spectrum Analysis

In the analysis of the directional spectrum with no reflected waves, that is, at positions P0, P1, and P3, the EMLM was applied for the calculation of the directional wave spectrum. In the analysis of the directional wave spectrum in the wave reflection system, however, the fixed phase relation of each pair of incident and reflected wave components should be considered. Therefore, the EMLM was modified to estimate the directional wave spectrum and the reflection coefficient in an incident and reflected wave field, according to the relation between the MLM and the MMLM (Isobe and Kondo, 1984). A directional wave spectrum and a reflection coefficient can be estimated as follows:

$$\hat{S}(k,\sigma) = \alpha \left[ \sum_{m,n} \Phi_{mn}^{-1} \cdot \{H_{m}^{\star}(k,\sigma) \exp(-ikx_{m}) + rH_{m}^{\star}(k_{r},\sigma) \exp(-ikx_{mr})\} \times \{H_{n}(k,\sigma) \exp(ikx_{n}) + rH_{n}(k_{r},\sigma) \exp(ikx_{nr})\} \right]^{-1}$$
(1)

$$\frac{\sum \Phi_{m,n}^{-1}[H_{m}^{\star}(\mathbf{k},\sigma)\cdot \mathbf{H}_{n}(\mathbf{k}_{r},\sigma)\cdot \exp\{i\mathbf{k}(\mathbf{x}_{nr}-\mathbf{x}_{m})\} + H_{m}^{\star}(\mathbf{k}_{r},\sigma)\cdot \mathbf{H}_{n}(\mathbf{k},\sigma)\cdot \exp\{i\mathbf{k}(\mathbf{x}_{n}-\mathbf{x}_{mr})\}\}}{2\Sigma \Phi_{m}^{-1}H_{m}^{\star}(\mathbf{k}_{r},\sigma)\cdot \mathbf{H}_{n}(\mathbf{k}_{r},\sigma)\cdot \exp\{i\mathbf{k}(\mathbf{x}_{nr}-\mathbf{x}_{mr})\}}$$

$$2\Sigma \Phi_{m,n}^{-1} H_m^*(k_r, \sigma) \cdot H_n(k_r, \sigma) \cdot \exp\{ik(x_{nr} - x_{mr})\}$$
m<sub>n</sub>n
(2)

where k is the wavenumber vector,  $\sigma$  is the angular frequency.  $\hat{S}(k,\sigma)$  means the estimated wavenumber-frequency spectrum. r denotes the reflection coefficient.  $\Phi$  mm  $(\sigma)$  is the cross-power spectrum of the water surface and horizontal velocity variations at point xm and point xn. H is the transfer function and \* denotes the complex conjugate.  $\alpha$  is a proportionality constant which can be determined from the relationship between the wavenumber-frequency spectrum and the power spectrum. When the reflection coefficient r equals zero, it completely coincides with that for the EMLM. The present method is termed the EMLM-2.

### 3.3 Numerical Simulation of EMLM-2

Applying the MMLM for estimating the directional wave spectrum in an incident and reflected wave field, the resolution power of the directional wave spectrum depends on the number and the arrangement of wave gages. In general, the resolution power increases with increasing number of wave gages, and spurious spectral peaks appear if the nearest wave gage is located farther than about 0.2L from the reflection line (L:wave-length). Therefore, in the analysis of the directional wave spectrum, using the EMLM-2, it is considered that the resolution power of the directional wave spectrum also depends on the number and arrangement of instruments.

Numerical simulations were performed to example the validity of the EMLM-2. The procedure for the numerical simulation is as follows:

1) Specify a functional form for the directional spectrum,

 $S\left(k,\;\sigma\right)$ , and reflection coefficient, r. Here, the Mitsuyasu-type directional distribution expressed by equation (3) was used. The reflection coefficient was assumed constant for every directional component of waves.

$$S(k,\sigma) = \cos^{2s} \{ (\theta - \theta_0) / 2 \}$$
(3)

where  $\theta_0$  is a principal wave direction and s is a parameter respecting the degree of directional energy concentration.

2) Calculate  $\phi$  mn ( $\sigma$ ) for all given components using the relationship between the cross-power spectrum and the directional wave spectrum in an incident and reflected wave field, which is expressed by equation (4).

 $\Phi_{mn}(\sigma) = \int_{k} S(k,\sigma)$ 

(4)

 $\times \{\exp(ikx_m) + r \exp(ikx_mr)\}$  $\times \{\exp(-ikx_n) + r \exp(-ikx_nr)\} dk$ 

 Estimate the directional energy distribution from equation (1) and compare to the given one.

Figure 4 shows the definition sketch of an incident and reflected wave field for numerical simulation. X is the distance between the measuring point and the reflective wall, and  $\theta$  is the wave direction. In this simulation the calculation conditions were set as the typical conditions in this field investigation. For example, the wave period was 8 seconds, the degree of energy concentration was 100, the wave direction was 60 degrees from perpendicular to the breakwater and the given reflection coefficient was 0.90. The number of measuring component was 3 and the distance between USW and EMC was 0.0 m.

Moreover the distance between the reflection line and measuring point, X, is an important parameter to keep the accuracy of estimating the directional wave spectrum and the reflection coefficient. So the three ratio of the distance, X, and wave length, L, that is, X/L=0.2, 0.5, and 1.0 were set for the conditions of numerical simulations.

Figure 5 shows examples of the numerical simulation, and Rs and Rp are the estimated reflection coefficients by use of the methods mentioning in 4.4. When X/L=0.2, the resolution power is highest and the estimated reflection coefficient also agrees with the given one. When X/L=0.5, the estimated reflection coefficient also agrees with the given one, though the resolution power goes down a little and spurious peaks appear around 270 degrees. When X/L=1.0, the resolution power goes down considerably and the













Examples of numerical simulation

estimated reflection coefficient does not agree with the given one.

So, if the measuring point is located far from the reflection line, the resolution power goes down and spurious peaks appear in the estimated spectrum. It is necessary that X/L should be set less than 0.2 in order to keep the accuracy of estimating both the directional wave spectrum and the reflection coefficient, and that X/L should be set less than about 0.5 in order to keep the accuracy of estimating the reflection coefficient.

# 4. RESULTS

### 4.1 Wave Conditions

The wave conditions such as significant wave height, significant wave period and principal wave direction during the observation periods are shown in figure 6. As the significant wave heights were always more than 1.0 m, sometimes reaching 2.0 m to 3.0 m, the wave climate was very rough during the period of investigation. The most prevalent significant wave period was about 6 s to 8 s, though it seems that the wave periods become longer in accordance with the increase of wave height. The wave directions clearly changed from west to north in accordance with the increase of wave height. This change of the wave direction followed a move of a low atmospheric pressure.

### 4.2 Wave Characteristics in a Harbor

Figure 7 shows the relationship between the incident wave direction and the ratio of incident and diffracted wave heights, and compares the diffracted wave direction to the incident wave direction. Symbols are field data and the solid line is the results of numerical simulation in respect of harbor tranquility (Kondo, Shimizu, and Yamada, 1987).

In numerical simulation, the incident directional wave spectrum was considered of a combination of the Bretschneider-Mitsuyasu-type frequency spectrum and the Mitsuyasu-type directional distribution, instead of the observed directional wave spectrum. The other input conditions were typically determined in consideration of mean wave climate during investigations, that is, the significant wave period of 7 s and the degree of energy concentration, Smax, of 25, were chosen.

As regards the rate of significant wave heights, field data exhibits the gradual increase according to the change of incident wave direction from west to northwest because of the shelter of the south breakwater.

Comparing between two wave directions at position P0 and P1, the characteristic of the diffracted wave by the south breakwater is obviously recognized. That is to say, when the incident wave directions are west to northwest, the diffracted wave directions are constantly northwest which is



Figure 6 Wave conditions during the observation periods



(a) Ratio of the incident and diffracted wave height



(b) Comparison of the incident and diffracted wave direction

Figure 7 Wave characteristics in a harbor

a straight line direction from the tip of the south breakwater to the measuring point. When the incident wave directions are northwest to north, the diffracted wave directions change in accordance with the incident one. The results of numerical simulation show good agreement with field data.

# 4.3 Change of Directional Wave spectra due to Diffraction

In order to estimate the effect of wave diffraction due to the south breakwater through the directional wave spectra, the directional wave spectra were computed for three different incident wave direction data sets as shown in table 1.

Table 1 Cases for estimating the directional wave spectrum

CASE NO.	DATE	WAVE DIRECTION	H1/3 (m)	T1/3 (s)
1	1/17 12:00	W (N96°W)	1.31	4.9
2	1/22 12:00	WNW (N64°W)	2.09	5.6
3	1/15 12:00	NNW (N14°W)	1.30	5.0

Examples of the estimated directional wave spectrum are shown in figure 8. Each figure consists of the directional energy distribution contour (central part), the frequency spectra (upper part) and the directional spreading function (righthand part), estimated using the EMLM. The upper three figures are the results at position PO. The lower three figures are the results at position PI.

When the incident wave direction is west, the south breakwater causes a change between the two directional wave spectra as follows.

- The directional peak of incident wave changes to a straight line direction from the tip of the south breakwater in the sheltered area.
- 2) The degree of energy concentration of the directional spreading function in the sheltered area becomes higher than that of the incident wave.
- 3) The frequency power spectrum at sheltered area is different from that at incident area, and the significant wave period changes shorter in the sheltered area. This is because the wave energy included between 0.15 Hz and 0.18 Hz frequency band is more sheltered than that included between 0.21 Hz and 0.24 Hz frequency band.

On the other hand, when the incident wave direction is north-north-west, the two directional wave spectra are almost similar. In this case the south breakwater hardly influences the change of the directional wave spectrum in the sheltered area.

When the incident wave direction is west-north-west that is intermediate direction between the above-mentioned two cases, the change of two directional wave spectra also shows the intermediary characteristics.



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Figure 9 shows the three directional wave spectra at positions, P0, P1, and P3, in order to understand the effect of wave diffraction by breakwaters more than ever. In the incident directional wave spectrum, the swell and wind wave co-exist, but two wave directions are different, that is, the swell direction with 0.12 Hz to 0.15 Hz frequency is north-west, and the wind wave direction with 0.18 Hz to 0.24 Hz frequency is west. The frequency power of the swell is lower than that of the wind wave at position PO. But at position Pl, the frequency power of the swell becomes higher than that of the wind wave. This tendency is more clear at position P3 which is sheltered by both the south breakwater and the north jetty, therefore, the swell only enters into the interior of the harbor.



Examples of the estimated wave spectrum

# 4.4 Reflection Coefficient and Directional Wave Spectra

### (1) Reflection Coefficient

In estimating the reflection coefficient, there are the following two methods. Equation (2) gives an estimation of the reflection coefficient (Rs) for each frequency and for each direction. The second method (Rp) is to adopt the square root of the ratio between the integrated reflected and incident wave energy.

The estimated reflection coefficient by the second method are shown in table 2. In accordance with the results of the numerical simulation, the integrated reflected and incident wave energy between 0.03 Hz and 0.15 Hz was only used for estimating the reflection coefficient, in order to keep the accuracy of estimation. Thus, ten cases including higher wave energy in the frequency range of 0.03 Hz to 0.15 Hz were chosen.

The reflection coefficient shows rather stable values between 0.75 and 0.99 with a mean value of 0.86. Judging from approximate values (0.7-1.0) of the reflection coefficients for a vertical wall as reported in various sources (Goda, 1985), this value is valid. (2) Directional wave spectra in incident and reflected wave field.

Figure 10 shows examples of the estimated directional wave spectrum at position, P2, that is, in front of the south breakwater. The EMLM-2 was applied for estimation. 0 degree means that the wave direction is perpendicular to the south breakwater, and 90 degrees is parallel to the south breakwater. The wave direction is defined anticlockwise. The estimated directional wave spectra have two peaks in symmetrical positions. The direction of the first peak is about 65 degrees, and that of second peak is about 115 degrees.

Judging from the harbor layout, it is understood that the first peak corresponds to the incident wave which come from the tip of the south breakwater, the second peak corresponds to the reflected wave which are set as mirror images of the incident wave at south breakwater. The directional peaks of the incident and reflected waves are sufficiently separated to permit use of the EMLM-2 for estimating the directional wave spectrum.

The peaks between 180 degrees and 360 degrees are, however, regarded as spurious peaks in consideration of the harbor layout and the results of numerical simulation.

Figure 11 shows example of the directional wave spectrum at position, P2, for the same data set with Figure 10, by use of the EMLM. There are also the directional peaks of the incident and reflected wave in this result, whereas the resolution power is lower than the result of the EMLM-2.

#### 5. CONCLUSIONS

The wave measurements were carried out by means of combinations of a wave gage and a current meter. The field data was processed to estimate the directional wave spectra by the EMLM and the EMLM-2, which is the modified EMLM for calculating the directional wave spectrum in an incident and reflected wave system. The effect of diffraction by breakwaters were discussed through the transformation of the directional wave spectra, and the reflection coefficient of the composite type breakwater, without wave energy dissipation, was estimated at a mean value of 0.86. As a result, the applicability of the field investigation method and the EMLM-2 were verified.

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4.71

0.78

NO.	DATE		H1/3	T1/3	REFLECTION
			(m)	(s)	COEFFICIENT
1	1/28	20:00	0.92	4.95	0.84
2	1/28	18:00	0.91	4.34	0.99
3	1/23	6:00	0.87	5.35	0.77
4	1/26	8:00	0.85	4.88	0.96
5	1/24	6:00	0.83	5.29	0.88
6	1/26	2:00	0.82	4.38	0.81
7	1/26	6:00	0.81	4.63	0.89
8	1/24	8:00	0.80	5.14	0.75
9	1/25	8:00	0.80	4.57	0.89

0.78



Figure 10

Example of the estimated direction wave spectrum in front of the south breakwater by EMLM-2



Figure 11 Example of the estimated directional wave spectrum in front of the south breakwater by EMLM

Table 2

10

1/25

4:00

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