CHAPTER 53

IRREGULAR WAVE TRANSFORMATION AFFECTED BY OPPOSING CURRENTS

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ABSTRACT

Transformation of irregular waves affected by opposing currents on a sloping sea bed was discussed, experimentally and theoretically. It was found that representative values of wave height, such as a significant wave height, are larger before breaking and the wave height decaying occurs more promptly in a surf zone as opposing currents become dominant, and that characteristics of a irregular wave transformation are determined by the dimensionless unit width discharge q^* and the deep water wave steepness. This means that the effects of opposing currents on irregular wave transformation are qualitatively identical to that on the regular waves.

A transformation model of irregular waves affected by opposing currents was presented. In the model, formulations for a regular wave transformation, in which the effects of opposing currents were taken into account, were applied to individual waves defined by zero-down-cross-method from irregular wave profiles.

Comparisons between experimental results and the prediction by the model showed that the present model gives a good explanation for wave height distributions and the experimental finding that the surf zone is moved offshore by opposing currents.

1. INTRODUCTION

Many studies on the transformation of irregular waves have been conducted, experimentally and theoretically. Goda(1975), Battjes and Janssen(1978), Thornton and Guza(1983) and Iwagaki, Mase and Furumuro(1983) presented transformation models which deal with irregular waves transformation without currents.

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Authors(1984) presented effects of opposing currents on the transformation of regular waves, and Hedge et.al.(1985) investigated an interaction between irregular waves and currents in the deep water.

However, in order to discuss phenomena caused by waves and currents such as the river mouth blocking, it is necessary to take the effects of opposing currents and the irregularity of waves in the shallow water into account.

In this paper, the effects of opposing currents on the transformation of irregular waves are clarified experimentally. Experiments show that the effects of opposing currents on irregular wave transformation are identical to that on regular wave qualitatively. Next, the transformation model of irregular waves affected by opposing currents are presented. In the model, formulations for the transformation of regular waves are applied to individual waves of irregular waves. And, the applicability of the present model is examined by comparing with experimental results, which shows a satisfactory agreement.

2. EXPERIMENTS AND RESULTS

2-1. Experimental Equipment and Procedure

Our experiments were conducted with an experimental setup as shown in Fig.1, which has a length of 35m, a width of 80cm, a depth of 120cm, and a slope of sea bed is 1/30. The water was circulated by a vacuum pump to produce opposing currents. Uniform currents were obtained on a 5m long flat bed located at an onshore end of wave channel, and flowed onto a sloping sea bed as opposing currents. The water depth on the flat bed was about 10cm.

In these experiments, irregular waves had Bretschneider-Mitsuyasu type spectra. Wave profiles were recorded for about 11 minutes, at 20 points with 90cm intervals.

Wave profiles were digitalized with 0.05 second sampling interval, and frequency components over five times of the peak frequency and under one half of the peak frequency were cut off.

Individual waves were defined by applying zero-down-cross-method to filtered irregular wave profiles.

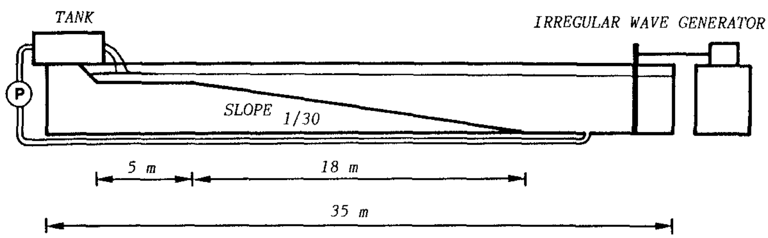


Fig.1 Experimental setup

Table 1 Experimental conditions

Case	q ($cm^3/s/cm$)	Ho' (cm)	To' (s)	Ho'/Lo'	q*
A - 1	0.0	14.9	1.54	0.0402	0.0
A - 2	0.0	14.9	1.55	0.0398	0.0
A - 3	96.4	15.0	1.52	0.0416	2.86×10^{-5}
A - 4	205.5	14.3	1.52	0.0397	6.09×10^{-5}
A - 5	300.0	14.7	1.53	0.0403	8.72×10^{-5}
B - 1	0.0	7.4	1.52	0.0205	0.0
B - 2	0.0	7.4	1.52	0.0204	0.0
B - 3	96.4	7.5	1.51	0.0212	2.92×10^{-5}
B - 4	205.5	6.8	1.51	0.0190	6.21×10^{-5}
B - 5	300.0	7.2	1.48	0.0211	9.64×10^{-5}
C - 1	0.0	11.2	1.30	0.0424	0.0
C - 2	0.0	10.9	1.31	0.0407	0.0
C - 3	96.4	11.3	1.33	0.0411	4.27×10^{-5}
C - 4	205.5	11.3	1.28	0.0443	1.02×10^{-4}
C - 5	300.0	11.0	1.32	0.0406	1.36×10^{-4}

To' : significant wave period in deep water

q* : dimensionless unit width discharge
$q^* = q / g^2 To'^3$

Ho'/Lo' : deep water wave steepness
$Lo' = g\, To'^2 / 2\pi$
(g : gravitational acceleration)

Experimental conditions are shown in Table 1. Capital letters A,B, and C indicate types of irregular wave. Numbers from 1 to 5 mean the condition of opposing currents, and the unit width discharge q was varied from 0 to 300 $cm^3/s/cm$.

Characteristics of irregular waves are defined as follows:
(1) A wave height distribution in the deep water is calculated by adopting a transformation model described in the following section on the individual wave heights at a reference point, which has a largest depth in our experiments. (2) From this wave height distribution, the significant wave height Ho' and period To' are determined.
(3) The deep water wave length Lo' is calculated by To' and the linear wave theory, and the deep water wave steepness is defined as Ho'/Lo'.
(4) q* is a parameter to indicate the magnitude of opposing currents, and is defined by the unit width discharge q and the wave period To'.

Since the deep water wave steepness on Case A is identical to that on Case C, effects of the parameter q* will be examined. And as the deep water wave steepness on Case B is one half of Case A and Case C, the effects of the deep water wave steepness will be able to investigated for cases with a similar value of q*.

2-2. Effects of opposing current on irregular wave transformation

Figure 2 shows a relationship between ratios of the significant wave height to wave height at a reference point and similar ratios with respect to the water depth. Case B has a relatively small deep water wave steepness, and in a region before breaking, wave heights affected by opposing currents are larger than wave heights without currents. It is also seen that the surf zone is moved offshore by opposing currents. In order to examine the effect of currents on wave height decaying in the surf zone, changes of wave heights with a relatively large deep water wave steepness are shown in Fig.3. This figure shows that, in the surf zone, the decaying of wave height with currents takes place more promptly than the decaying without currents.

Therefore it is concluded experimentally that opposing currents increase the shoaling coefficients and cause a prompt wave decaying in the surf zone.

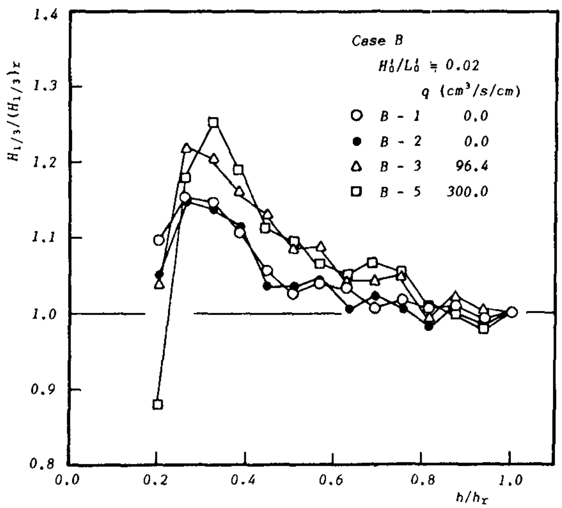


Fig.2 A change of significant wave heights

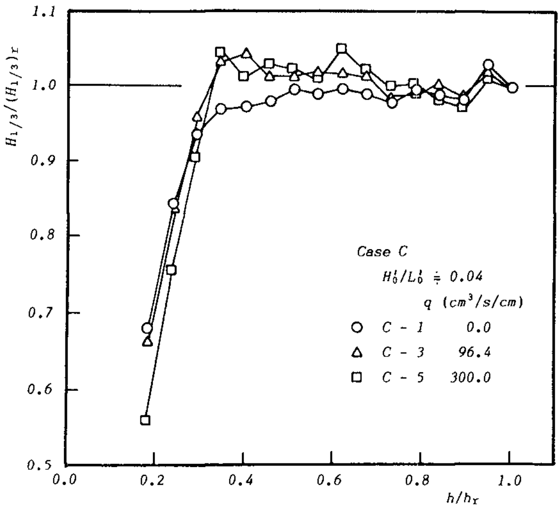


Fig.3 A change of significant wave heights

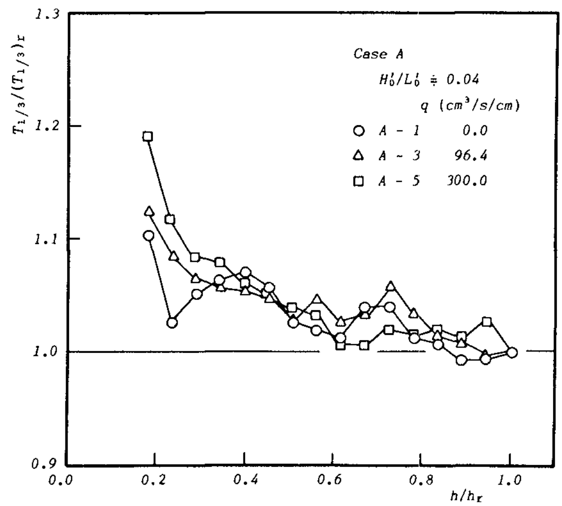


Fig.4 A change of significant wave periods

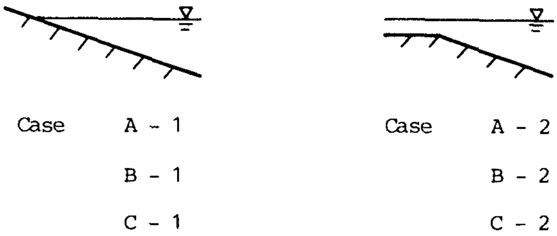


Fig.5 Conditions near the shoreline without currents

Experimental data for the change of the significant wave period, are shown in Fig.4. This figure gives relationships between ratios of the significant wave period to wave period at a reference point and similar ratios with respect to the water depth, and shows that the increase of unit width discharge causes the larger increase rates of the significant wave period especially in the surf zone.

In order to examine the effect of flat bed, which is located onshore of the sloping sea bed, experiments without currents were carried out for two bed configurations. As shown in Fig.5, one condition has a flat bed, and the other condition has an extending slope. The differences due to conditions near the shoreline do not appeared, as shown in Fig.2. Therefore it was regarded that those effects could be ignored in present experiments.

Authors(1984) have indicated the characteristics of regular wave transformation with opposing currents are determined by the dimensionless unit width discharge q^* and the deep water wave steepness, and these parameters will be used to explain the characteristics of irregular wave transformation.

Figure 6 gives a relationship between ratios of significant wave height to the significant wave height in the deep water, and ratios of the water depth to the wave length in the deep water.

If the deep water wave steepness is constant, the shoaling coefficients become larger as the parameter q^* increases.

Further as shown in Fig.7, when q^* is constant, the shoaling coefficient becomes larger and the breaking point is moved offshore as the deep water wave steepness becomes larger.

It was found that the transformation of irregular waves is characterized by g^* and the deep water wave steepness and these two effects are similar to those on regular wave, qualitatively.

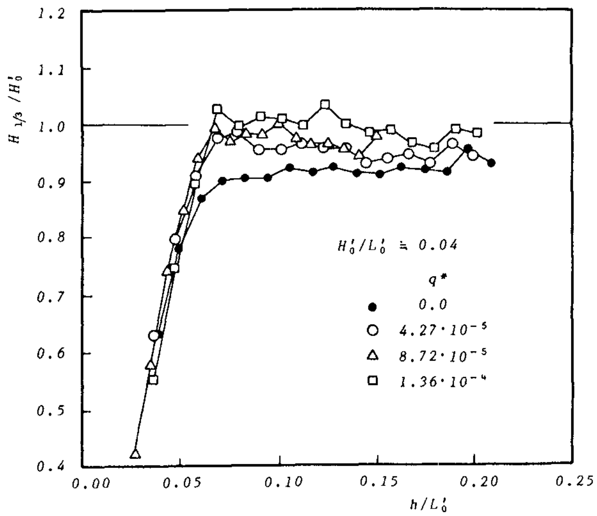


Fig.6 Effects of the dimensionless unit width discharge on irregular wave transformation

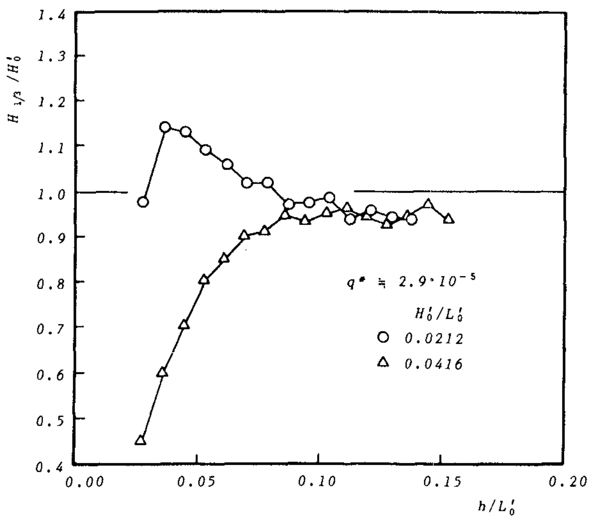


Fig.7 Effects of the deep water wave steepness on irregular wave transformation

3. TRANSFORMATION MODEL FOR IRREGULAR WAVES

In order to examine the effect of opposing currents on transformation of irregular waves quantitatively, a transformation model is proposed. In the present model, to simulate the wave transformation affected by opposing currents, the formulations for a regular wave are applied to individual waves of irregular waves, which have their own wave period and height.

3-1 Shoaling formulation

The formulation for shoaling before breaking is derived from the energy flux conservation law and described, using the linear theory, as follows;

$$E\,(\,Cg_r - U\,)\,\left(\,1 - \frac{U}{C_r}\,\right) = E_0\,Cg_{r0} = const. \qquad \text{------- (Eqn.1)}$$

where Cgr indicates a relative group velocity for the water, Cr gives a relative wave celerity, U means the velocity of opposing current, and subscript o indicates a quantities in the deep water.

3-2 Breaking criteria

Miche(1951) indicated that the breaking criteria is expressed by Eqn.2, and the coefficient α without any currents is 0.142.

$$\left(\frac{H}{L}\right)_b = \alpha\,\tanh\left(\frac{2\pi h}{L}\right)_b \qquad \text{------- (Eqn.2)}$$

Authors(1984) showed that the coefficient with opposing currents is smaller than 0.142. A difference form Miche's coefficient due to the effects of opposing currents is described as $\Delta\alpha$, and a relationship between q* and $\Delta\alpha$ was proposed. However, when the relationship mentioned above was applied to individual waves of irregular wave, the effect of current appeared stronger than what we expected. And after several trials, it was found that the most suitable coefficient α was given by a following equation;

$$\alpha = 0.142 - 0.5\,\Delta\alpha \qquad \text{------- (Eqn.3)}$$

3-3 Wave height decaying formulation

The wave height decay by the wave breaking is calculated by a bore model with opposing currents. Energy balance equation is given as follows;

$$\frac{d}{dx}\left\{\frac{1}{8}\rho g H^2\,(\,\sqrt{gh} - U\,)\right\} + B\,\frac{\rho g}{4}\,\frac{1}{Th}\,\frac{\sqrt{gh}}{(\,\sqrt{gh} - U\,)}\,(\,\beta' H\,)^3 = 0 \qquad \text{------- (Eqn.4)}$$

in which the energy flux is calculated by a linear long wave theory and the dissipation of breaking is approximated with the dissipation of propagating bore.

The fraction of turbulence region to the wave height is assumed as follows; (Battjes,J.A. 1978)

$$\beta' = \frac{H}{\gamma h} \qquad \gamma = H_b/h_b \qquad \text{------- (Eqn.5)}$$

After substituting Eqn.5 into Eqn.4, an integration of Eqn.4 results in a following equation;

$$\tilde{H}^{-4} = \frac{1}{(1-A)^2}\left\{1 - \frac{4K}{9(1-A)}\right\}\cdot \frac{(\tilde{h}^{1.5}-A)^2}{\tilde{h}^2} + \frac{4K}{9\tilde{h}^2(\tilde{h}^{1.5}-A)} \qquad \text{------- (Eqn.6)}$$

where,

$$\tilde{H} = H/H_b \ , \quad \tilde{h} = h/h_b \ , \quad A = q/h_b \,/\, \sqrt{gh_b}$$

$$K = \frac{2B}{S}\left(\frac{H_b}{h_b}\right)\sqrt{h_b/gT^2} \qquad \text{------- (Eqn.7)}$$

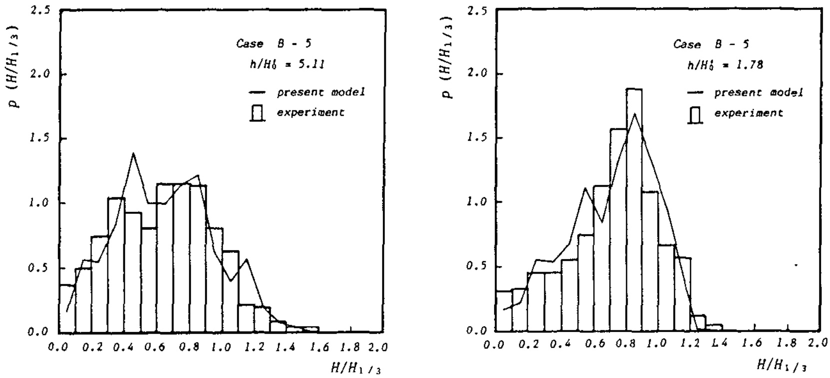
3-4 Procedure of calculation

Wave height is calculated by the shoaling formulation. After a wave height exceeds the breaking criteria, the wave height decay calculation is carried out. These formulations for regular waves are applied to individual waves of the irregular wave. This procedure gives a wave height distribution at each water depth.

4. COMPARISON BETWEEN CALCULATED AND EXPERIMENTAL RESULTS

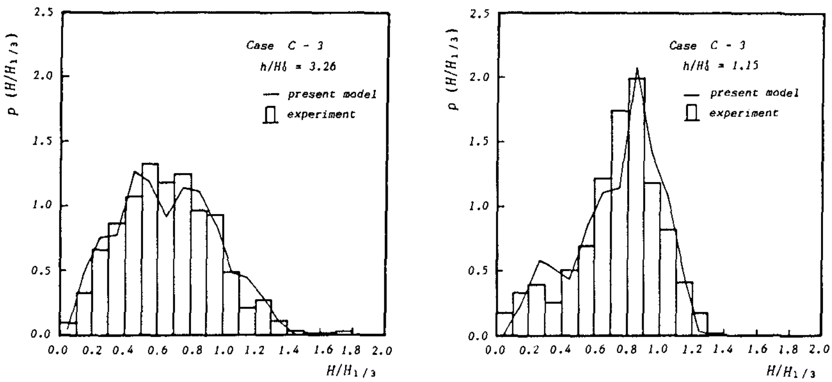
Figure 8(A) and 8(B) show comparisons between calculated results and experimental results for wave height distributions at a point offshore of the surf zone and in the surf zone, respectively. The horizontal axis indicates the ratio of individual wave height to the significant wave height, and the vertical axis indicates the probability density. In this case, waves have a relatively small deep water wave steepness. Calculations gives a good prediction for wave height distributions. And comparisons for a case where waves have a relatively large deep water wave steepness are shown in Fig.9(A) and 9(B). A good agreement is also obtained.

Figure 10 indicates some examples of comparisons between calculated significant wave height and experimental results with a relatively small deep water wave steepness. The experimental findings that the surf zone is moved offshore by opposing currents is explained well by the present model. In the case with relatively large water wave steepness, calculated results are compared with experimental results in Fig.11. Fig.10 and Fig.11 also confirm the applicability of the present model.



(A) offshore (B) in the surf zone

Fig.8 Comparisons between calculated wave height distribution and experiments (Ho'/Lo' = 0.0211)



(A) offshore (B) in the surf zone

Fig.9 Comparisons between calculated wave height distribution and experiments (Ho'/Lo' = 0.0411)

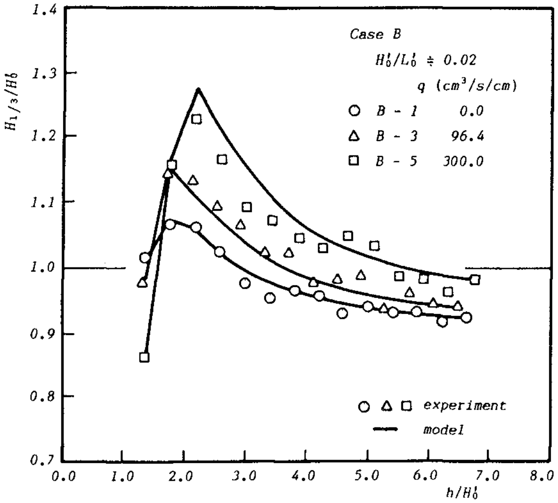


Fig.10 Comparisons between calculated shoaling coefficient and experiments

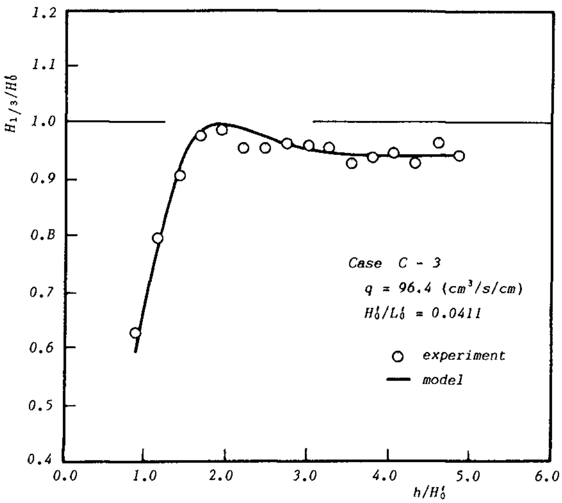


Fig.11 Comparisons between calculated shoaling coefficient and experiments

In order to examine the accuracy of the model for all data, the degree of coincidence between calculated results and experimental results is shown in Fig.12,13 and 14. The horizontal axis indicates calculated results and the vertical axis indicates experimental results, and a 45 degree solid line indicates a perfect coincidence. When the average error is defined by a following equation;

$$E_r = \frac{\sum_{n=1}^{m} \left| \frac{H\ model - H\ exp}{H\ model} \right|}{m} \qquad \text{------- (Eqn.10)}$$

the average error as shown in Fig.12 is 2.8% of the significant wave height.

The root-mean-square of the wave height is shown in Fig.13, the average error is 2.3%. And even if the one-tenth maximum wave height is examined,the average error is only 3.7% as shown in Fig.14.

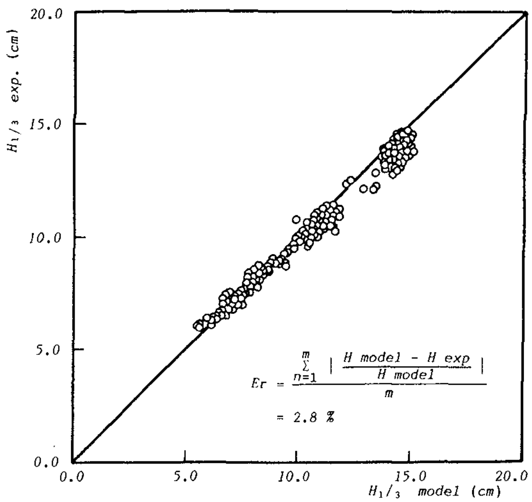


Fig.12 A correlation between calculated $H_{1/3}$ and experimental results

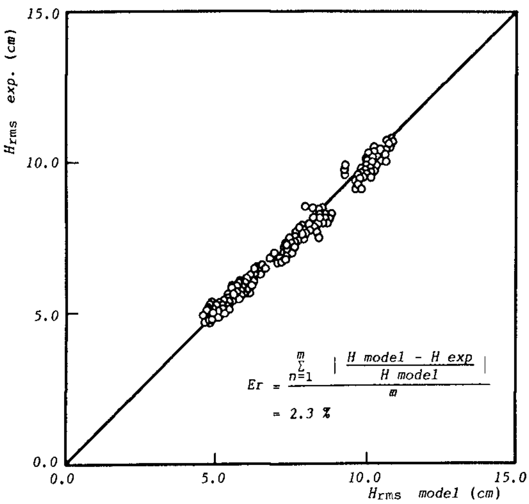


Fig.13 A correlation between calculated Hrms and experimental results

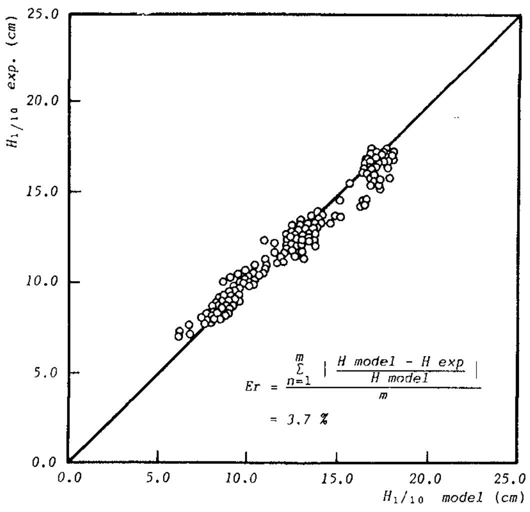


Fig.14 A correlation between calculated $H_{1/10}$ and experimental results

5. CONCLUSIONS

The transformation of irregular waves affected by opposing currents was discussed, experimentally and theoretically. Main conclusions in this paper are as follows:

(1) As opposing currents become dominant, the representative values of wave height, such as the significant wave height, are larger offshore of the surf zone and the wave decaying occurs more promptly after breaking. This tendency is identical to the characteristics of the regular wave affected by opposing currents qualitatively.

(2) The significant wave period also is affected by opposing currents. It was found that the increase of unit width discharge causes the larger increase rates of the significant wave period, and especially this tendency is clear in the surf zone.

(3) The transformation model in which the effects of opposing currents are considered was proposed. In the model, formulations for regular wave affected by opposing currents were applied to individual waves of irregular wave. The comparisons between calculated and experimental results give a satisfactory agreement.

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