CHAPTER 35

PHYSICAL ASPECTS OF WAVE-INDUCED NEARSHORE CURRENT SYSTEM

By

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INTRODUCTION

Since a theoretical approach on rip currents was made by Bowen (1969), our understandings on that system have progressed steadily.

It will be considered that the dynamics of current system are governed by the following equations which indicate the balance among the gradients of radiation stress and of mean water level, and the friction force induced by the current velocity:

$$\left.\begin{aligned}\frac{\partial S_{xx}}{\partial x}+\frac{\partial S_{xy}}{\partial y}+\rho g(h+\zeta)\frac{\partial \zeta}{\partial x}+fU=0\\ \frac{\partial S_{xy}}{\partial x}+\frac{\partial S_{yy}}{\partial y}+\rho g(h+\zeta)\frac{\partial \zeta}{\partial y}+fV=0\end{aligned}\right\}\quad(1)$$

Here radiation stresses such as S_{xx} are given by the local wave height H and wave ray direction θ. The terms ρ, g, ζ, h, and f denote fluid density, acceleration due to gravity, variation of mean water level above still water level, still water depth, and friction factor, respectively. U and V are components of current velocity which satisfy the following continuity equation:

$$\frac{\partial(Ud)}{\partial x}+\frac{\partial(Vd)}{\partial y}=0 \qquad (2)$$

where $d = h + \zeta$. To solve Eqs.(1) and (2), we need one more relation among the three terms stated above.

Hino (1974) treated this problem by the way of assuming that the wave height in a surf zone is proportional to the water depth as follows:

$$H = \gamma d \qquad (3)$$

Iwata (1976) and Mizuguchi (1976) applied the following energy equation in order to close Eqs.(1) and (2):

$$\frac{\partial}{\partial x}\{E(U-c_g)\} + \frac{\partial}{\partial y}(EV) + S_{xx}\frac{\partial U}{\partial x} + S_{yy}\frac{\partial V}{\partial y} = -D \qquad (4)$$

where E, c_g, and D denote wave energy, group velocity, and dissipation, respectively. The axis of x is taken offshoreward, and the wave is assumed to come perpendicular to shoreline.

Another approach has been made to clarify the mechanics of rip current system. This is a way to give a wave height distribution or a radiation stress distribution by something came from the outside of the equation system.

Bowen and Inman (1969) and Harris (1967) suggested that generation of edge wave with the same period of incident waves could make a periodic longshore perturbation of wave height distribution. Sonu (1972) found the distinct correlation between the observed current system and bottom topography. While Noda (1974), Horikawa and Sasaki (1974), and others have tried to simulate the current field by using Eqs.(1) and (2) under the conditions of irregular wave height and ray angle field caused by refraction due to irregular bottom topography, and achieved success to calculate it at least in a qualitative sense. Recently Dalrymple (1975) tried to explain the current system from a view point of two intersecting synchronous waves.

These two kinds of approach to the rip current system suggest us the existence of the following two types of current system. The first one which corresponds to the former formulation can be called " the free type rip current system ", because there is no external force to generate the current system. Mathematically it would be formulated as an eigenvalue problem in spite of using either Eq.(3) or Eq.(4). The treatises by Hino, Iwata, and Mizuguchi are included in this category. But the wave height-depth assumption (Eq.(2)) is not verified well enough to go on forward along this assumption. While the energy coupling assumption (Eq.(4)) has also a deficiency of neglecting the first order dissipation term, which might be important on phenomena in a surf zone.

The second one which corresponds to the latter formulation can be called " the forced type rip current system ", because the external factor such as edge wave or irregular bottom topography plays a crucial part of generating the current system. This forced system is of a zero-th order current system caused by irregular radiation stress distribution in a wave breaking area and could be described enough by Eqs.(1) and (2) by using the radiation stress distribution which is externally given. Equation (4) would only contribute to modify the current system as treated by LeBlond and Tang (1974).

There are still some points which must be settled down in order to understand the dynamics of the rip current system. We have done some laboratory experiments and observed a current system which is similar to that in the field [Sonu (1973)]. Analyzing and discussing the experimental results, we try to make some contribution to clarify the current system.

PRELIMINARY EXPERIMENTS

Experimental set-up and measuring technique are in the following:

a. A fixed impermeable plane beach made of plywood was installed in a ripple wave tank, the size of which was 1.2m wide, 6m long and 0.15m deep. The selected slopes of beach were 1/20, 1/10, and 1/5.

b. The direction of incident waves was always perpendicular to the shoreline.

c. The pattern of current system was observed by a video camera system in tracing the diffusion of dye which was poured into an uprush zone.

d. Wave height distribution in the nearshore zone was obtained by using wave gages which were travelled parallel to the shoreline. Progressive pattern of wave crests was detected by viewing the video camera records.

We show in the following the experimental results in two cases which are the typical ones.

1. CASE 12 is the one where the wave steepness is not very large and the breaker zone is not very wide. In Fig.1 various curves cover the diffusion area by the current at the indicated time in second. Fine solid lines show a wave crest propagation pattern. Figures 1 and 2 give the following information:

    1) The wave crest pattern indicates that the wave propagation is delayed considerably in the region where offshoreward currents (hereafter written offshore currents) exist. We calculated roughly the distortion of the wave crest at the breaker line by using the measured velocity distribution in Fig.5. We get the values of 1.2cm for CASE 12 and 5.2cm for CASE 15 (which will be introduced in the following part) at the breaker line. These results agree well with the observed wave crest pattern.

    2) The results of wave height distribution measured in the nearshore area indicate that the wave reduces its height in the region of offshore currents.

In addition to the above results, we observed that the breaking point in the the region of offshore currents had a tendency to approach the shoreline.

2. CASE 15 is the one where the width of breaker zone is relatively large. In this case the current system is divided into two parts; the first one is the circulation formed in the surf zone which we may call " a closed cell "; and the second one is the two branched feeder currents which join together and finally make an offshore current near the breaker line, thus we may call it " an open cell " (Fig.3). We will name this kind of the current system as a whole a double circulation system.

Another experimental result, which should be mentioned here, is that the beach slope is not important in the qualitative features of the current system except two points stated in the following, at least under the conditions of present experiments:

1) As the beach slope is gentler, the width of breaker zone becomes larger for the same condition of offshore waves.

2) In some cases for 1/5 beach slope, subharmonic resonant edge waves were clearly observed. The edge waves produced a dye diffussion pattern which is different from the others mentioned above as shown in Fig.4 [Horikawa and Mizuguchi (1975a)].

We calculate the offshore current velocity outside the breaker line by using the data of dye diffusion pattern. The results shown in Fig.5 tell us that the offshore current velocity has its maximum around the breaker line.

We measured the rip current spacing just outside the breaker line. In our experiments the spacings are mainly related to the period of incident waves. The results are plotted in Fig.6 where a solid line indicates the relation of $L_r = L_0$ (L_0 is deepwater wave length).

DISCUSSION: PART 1

As mentioned in Introduction, the senior author has developed a theory to treat the rip current system as an eigenvalue problem, where the wave-current interaction was taken into consideration in the equations of wave and energy conservation. The theory is also confined to the cases of relatively steep slope beach, because the long wave approximation is used all over the concerned area. When we neglect a relevant dissipation term in energy equation (Eq.(4)), an eigenvalue problem is formulated to determine the rip current spacing. This problem can be solved by assuming the bottom friction factor in the surf zone as a power of coordinate taking from the shoreline to offshore.

The theory predicts that the first order perturbation of wave energy has exactly the same alongshore phase as the offshore current perturbation. It means that the wave height in the region of offshore current is greater than that in the remained area. This prediction is completely opposite to our experimental result. From this fact we conclude that the observed current system cannot be explained by the theory in which the wave-current energy interaction is considered to be essential.

On the other hand we (1975) described that one possible explanation for the observed current system stated above is to attribute the origin of such current system to the incident wave itself. If we can assume that free oscillations in a uniform depth area of the wave basin would affect the wave height perturbation at the breaker line, the observed fact will be well explained. Horikawa and Maruyama (1976) found that in a rectangular wave basin resonant sychronous cross waves can occur, and pointed out that the

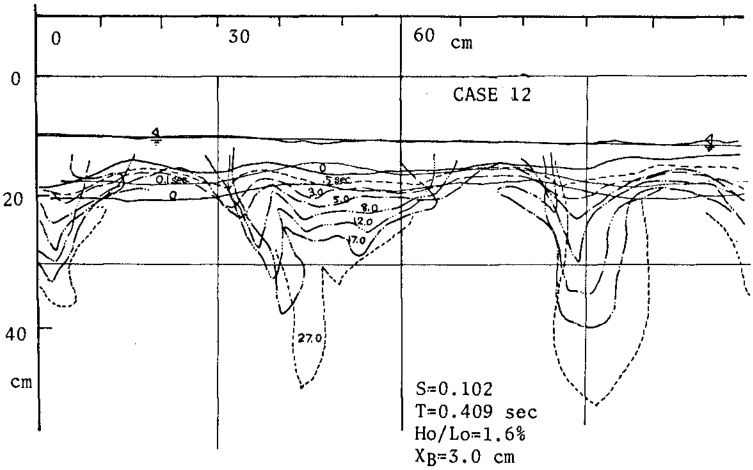

Fig.1. Wave crest propagation and dye diffusion pattern.

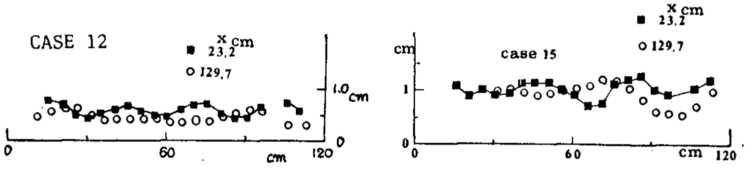

Fig.2. Alongshore wave height distribution.

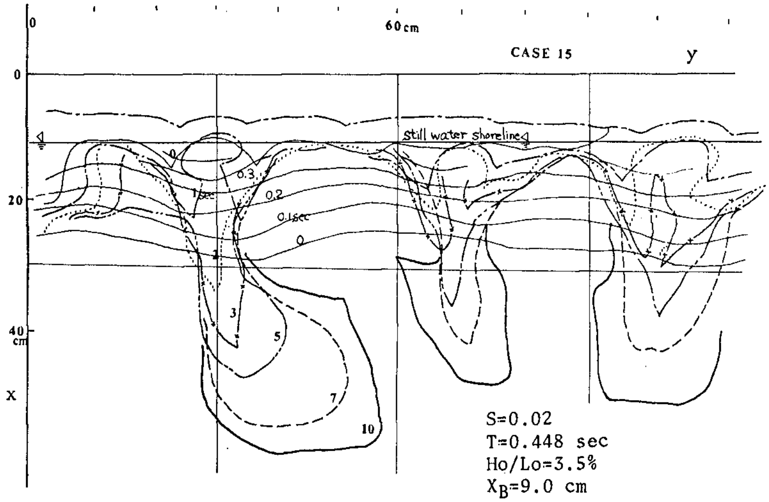

Fig.3. Wave crest propagation and dye diffusion pattern.

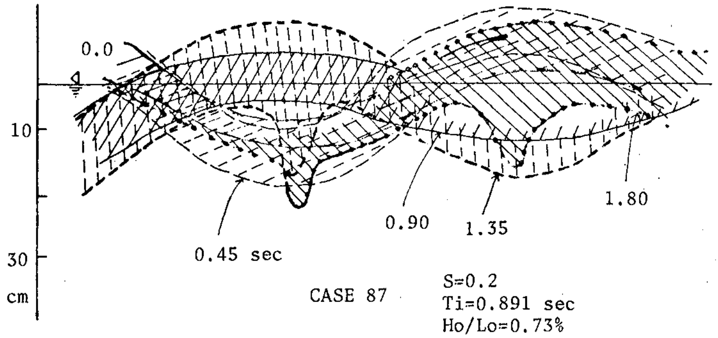

Fig.4. Dye diffusion pattern by subharmonic edge wave.

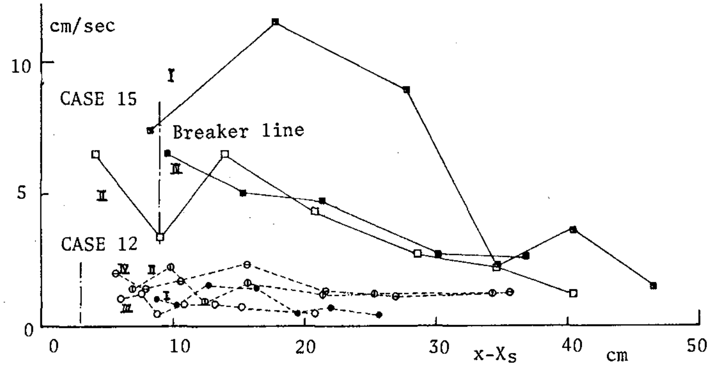

Fig.5. Offshore current velocity profile of rip currents.

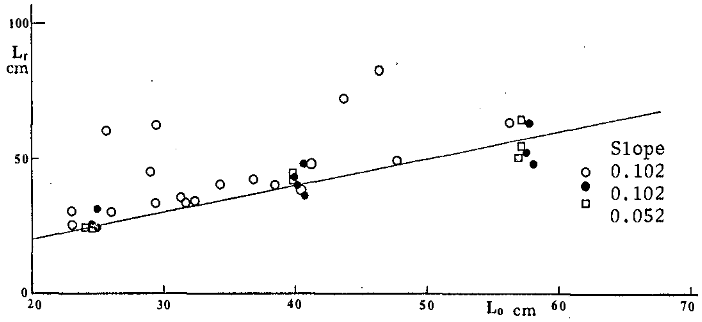

Fig.6. Measured spacings of rip currents.

cross waves generate a wave height perturbation around the breaker line. The wave basin used by them is the same as that we used.

In our experimental set-up with a sloping beach, wave records indicate simple harmonic and steady oscillations at every measuring point. Therefore we interpreted the " cross wave " as follows:

1. The wave maker might generate a little irregular wave component which does travel obliquely to the paddle of wave maker as denoted $\mathbb{k}_c$ in Fig.7.
2. Then the side walls select the component wave which satisfies the following boundary condition along the walls:

   $$N\pi/k_y = b \qquad (5)$$

   where N is a mode number and not greater than kb/π.
3. The selected component travells across the wave basin, reflects at the side walls and finally makes a wave height distribution in the vicinity of the wave breaking area.

When the cross wave is superposed upon the incident waves, the following wave height distribution appears in the basin:

$$a \sim a_i + 2a_{cN}\cos\left(\frac{N\pi y}{b}\right)\cos\left(\int^x (k - k_x)\,dx'\right) \qquad (6)$$

where a_i and a_{cN} are amplitudes of incident wave and of cross wave respectively. A noteworthy characteristic of the cross wave is that the alongshore wave number does not change with refraction.

Considering the fact that the offshore current is always located at the place of lower wave height, we have Fig.8 in which the possible rip current spacings in our experiments are shown. This figure is not in contradiction to the experimental results shown in Fig.6. Reminding the fact that almost every point in Fig.6 is scattering around the relation $L_r = L_0$, we are able to assume that the predominant cross wave is the one that has the largest number of mode in y-direction. Therefore, we can conclude that the phenomena in our experiments show one example of the forced current system, where the cross wave plays an important role to provide an externally given condition.

SECOND SERIES OF EXPERIMENTS (DETAILED OBSERVATIONS)

Based on the above discussions we conducted another series of experiments, paying much attention to the wave height distribution all over the wave basin. Experimental set-up and measuring technique are almost the same as the first series of experiments. We used, this time, static pressure tubes to measure the mean water level in a surf zone, and a wave gage to measure the run-up height distribution.

We selected the following three cases under the condition of the beach slope 1/10 only as shown in Table 1. There d, T, H_i, H_0, and X_B denote

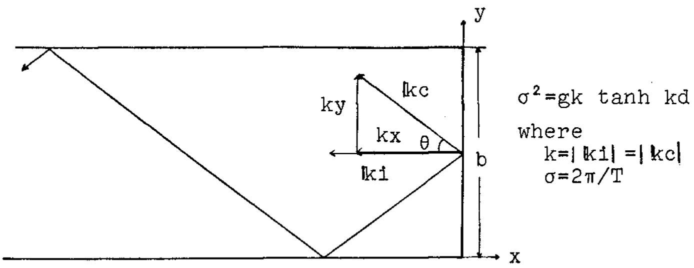

Fig.7. Schematic illustration of " cross wave ".

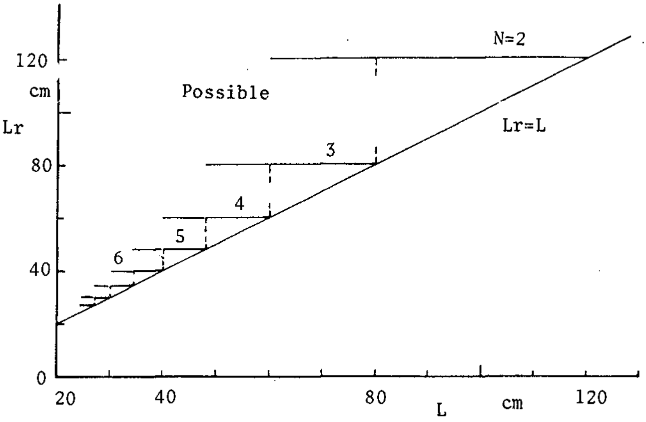

Fig.8. Possible spacings of rip currents by " corss wave ".

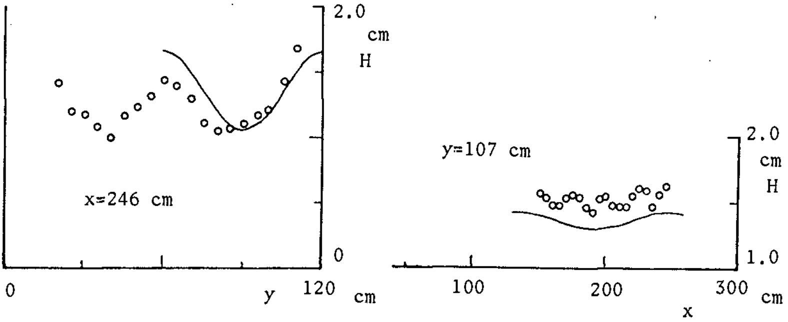

Fig.9. Wave height distribution parallel and perpendicular to the wave maker in uniform depth area (CASE 22B).

water depth in a uniform depth area, period of wave maker, wave height in a uniform depth area, deep water wave height, and width of breaker zone, respectively.

Table 1 Experimental conditions.

CASE	d	T	H_i	H_o/L_o	X_B
22B	11.5cm	0.586sec	1.36cm	2.7%	13cm
26B(=27A)	12.0	0.726	1.70	2.3	12
27B	12.0	0.720	2.60	3.5	21

First we will check the existence of the cross wave in the following:

CASE 22B

Figure 9 shows the wave height distribution at the section of x = 246cm in the uniform depth area. Resonant oscillations in y-direction exist as shown in Fig.9. Calculating the Fourier components, we get H_i (i=0-4) = 1.36, -0.10, 0.28, -0.07, 0.29 cm respectively. Although we can expect the existence of oscillations with mode number N = 2 and 4, we consider only N = 4. The reason is as follows. Figure 9, also, shows the wave height distribution along the section of y = 107.0cm, and Fig.10 shows that at the section of y = 0 for N = 2 and 4. These two figures indicate that N = 2 is not very important in our experiments.

From the above result shown in Fig.9 we will simulate the wave height distribution by the following equation, where N = 2 is neglected and the phase difference in front of wave maker is assumed to be 0 or π.

$$H = 1.36 - 0.30\cos\left(\frac{4\pi y}{B}\right)\cos\left\{\frac{2\pi}{113}(x-417)\right\} \tag{7}$$

Solid lines in Fig.9 give the curves of the above equation.

CASE 26B AND 27B

Following almost the same procedure as in CASE 22B, we get the next equations to express the wave height distribution in a uniform depth area for CASE 26B and 27B respectively.

$$\left.\begin{aligned} H &= 1.70 + 0.60\cos\left(\frac{2\pi y}{B}\right)\cos\left\{\frac{2\pi}{395}(x-295)\right\} \\ H &= 2.60 + 0.54\cos\left(\frac{2\pi y}{B}\right)\cos\left\{\frac{2\pi}{401}(x-270)\right\} \\ &\quad + 0.48\cos\left(\frac{3\pi y}{B}\right)\cos\left\{\frac{2\pi}{152}(x-270)\right\} \end{aligned}\right\} \tag{8}$$

In these cases a screen was inserted in a uniform depth area in order to diffract the incident waves and to get a stable state of the current system. As a result, phase relations between the incident wave and the cross wave are different from that in CASE 22B. Figures 11 and 12 show that these

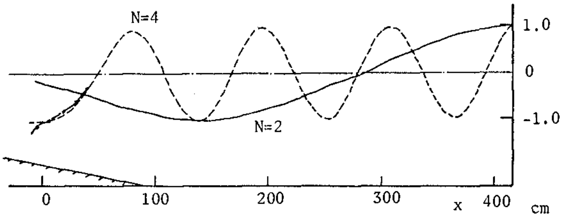

Fig. 10. Caluculated wave height undulation along sidewall (CASE 22B);
—x—x—x—x— with shoaling.

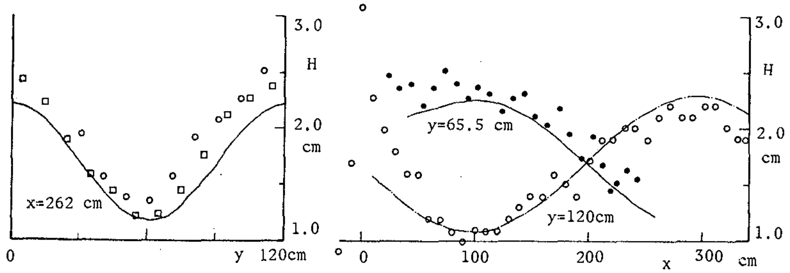

Fig.11. Wave height distribution in uniform depth area (CASE 26B).

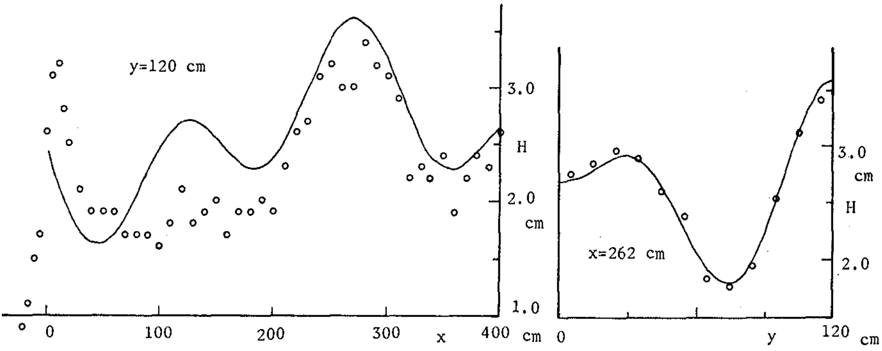

Fig.12. Wave height distribution in uniform depth area (CASE 27B).

equations can explain well the measured wave height distribution.

From the foregoing figures we can conclude that there exist the cross waves and the assumption on the possible alongshore wave number is supported in CASE 22B and 27B, but not in CASE 26B. It is easy to calculate how the above wave height distribution gives its influences on the phenomena in the wave breaking zone. Snell's law tells us that the wave number of the cross wave in y-direction does not change with refraction. Each wave component makes its refraction process independently so far as the linear wave theory is valid.

One of the purposes of the present experiments is to find out the way how to describe the questioned current system which is now clearly classified into the forced type. We measured in detail the wave height distribution, current and wave crest patterns, and mean water level in a surf zone. In the following, three cases will be taken as representative ones.

CASE 22B

Figure 13 shows the current and wave crest pattern recorded by a video camera system. The area bounded by a hatched line shows the region where the poured dye is remained for a long time. Therefore it indicates the location of a closed cell. This pattern gives the same features as the double-circulation type mentioned previously. While Fig.14 shows the wave height distribution in the surf zone in a three dimensional space. The solid smooth line is the predicted curve of the wave height distribution at the section of $x = -1.5$cm based on the offshore wave condition. It agrees well with the experimental result at least in a qualitative sense.

Here we will split the surf zone into two parts; the inner area and the outer area. They are divided by the line where the alongshore wave height perturbation disappears. In this case the line was located at $x = 4.0$cm. In the outer area offshore currents flow out through the region of lower wave height which is predicted by numerical calculations using the wave conditions in the uniform depth area. In the inner area offshore currents flow out also through the region of lower wave height. But the spacing between them is a half of the spacing in the outer area. Alongshore distribution of run-up measured by the wave gage as well as that given in video records show the same periodicity as the offshore current in the inner area. The region where the rup-up height is relatively small corresponds to the place where the offshore current starts. Figure 15 shows the wave height distribution along the section of y = const. in the surf zone. This result confirms also the above observation on the relationship between current and wave height distribution.

The measured static pressure distribtuion is shown in Fig.16. It is out regret to say that the data are not so accurate that anything decisive cannot be concluded. This is because the set-down and set-up are very small in our experiments, hence our hand-made apparatus was not very delicate to detect them.

CASE 26B (=27A)

In this case we made longer the period of wave maker, keeping the wave steepness almost the same as the former one (CASE 22B).

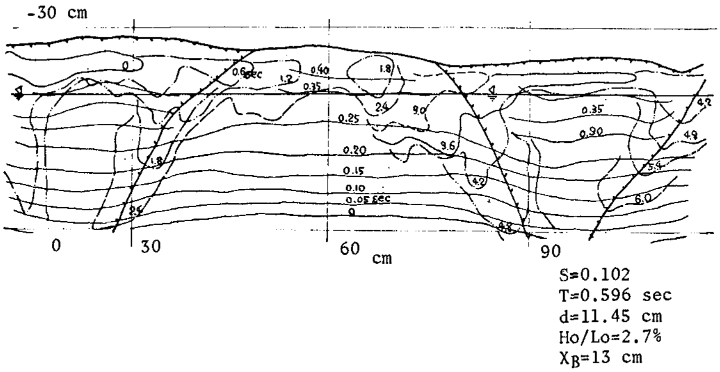

Fig.13. Wave crest propagation and dye diffusion pattern (CASE 22B).

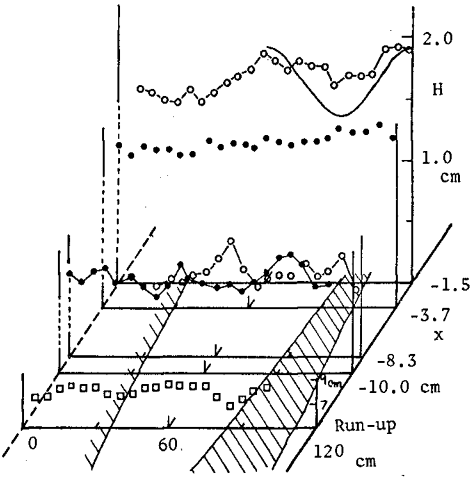

Fig.14. Wave height distribution in surf zone (CASE 22B).

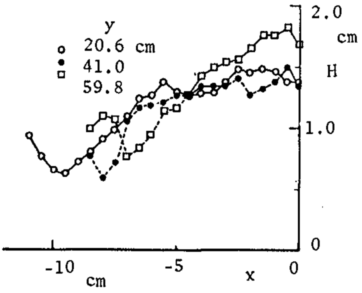

Fig.15. Wave height decreasing in surf zone (CASE 22B).

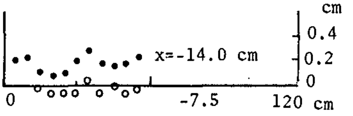

Fig.16. Mean water level variation in surf zone (CASE 22B).

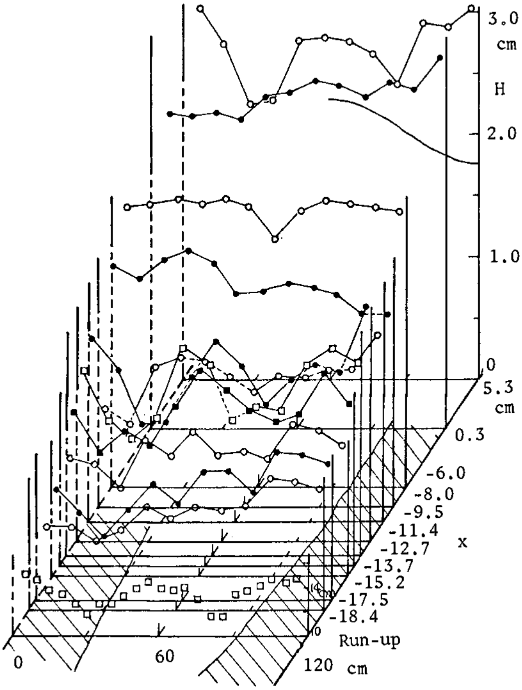

Fig.17. Wave height distribution in surf zone (CASE 26B).

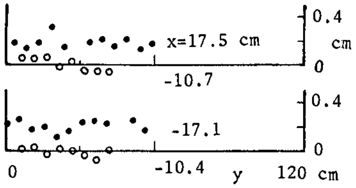

Fig.18. Mean water level variation in surf zone (CASE 26B).

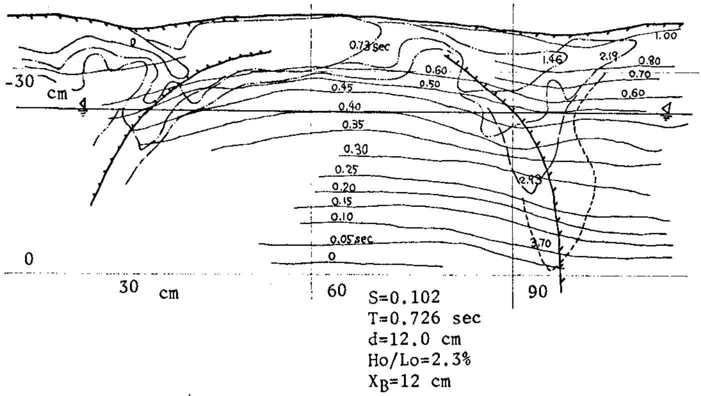

Fig.19. Wave crest propagation and dye diffusion pattern (CASE 26B).

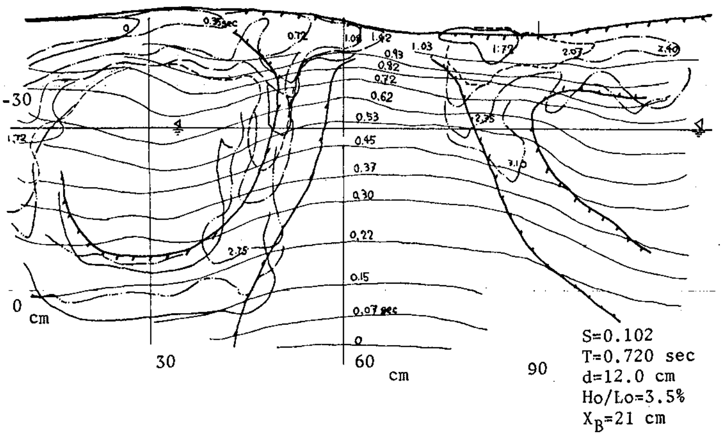

Fig.20. Wave crest propagation and dye diffusion pattern (CASE 27B).

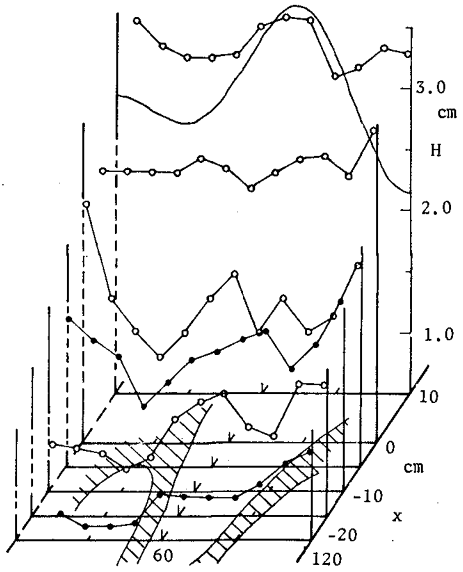

Fig.21. Wave height distribution in surf zone (CASE 27B).

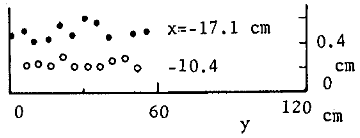

Fig.22. Mean water level variation in surf zone (CASE 27B).

The wave height distribution in this case is shown in Fig.17. Again the smooth solid line in this figure indicates the predicted curve. The measured wave height distribution is different from the predicted one especially near the side walls. The observed current pattern in Fig.19 corresponds well with the measured wave height distribution. The higher wave height region near the wall might be caused partially by the existence of side walls and partially by the wave-current interaction. Another features are the same as that in CASE 22B.

Again in Fig.18 are shown the measured static pressure distributions along the section of x = const.; one is in the inner area and the other in the outer area.

CASE 27B

In this case we made larger the amplitude of wave maker. Experimental results are seen in Figs.20, 21, and 22. New particular feature is that the diffusion pattern induced by the offshore current has a tendency to stay around the breaker line for a while. Therefore the outer area seems to disappear.

Now we have to draw a conclusion about the mean water level. We think that the alongshore variation of mean water level is not so large as that we expect from the measured wave height perturbation based on the wave height-depth assumption.

DISCUSSION: PART 2

Considering the results of the present experiments, we will discuss in the following how the current system can be generated and what kinds of equations can describe its phenomena.

We may say as follows:

1) In the surf zone the wave height distribution given externally would produce the radiation stress distribution, where the assumption $S_{xx} = 3/2E$ etc. and $E = 1/2\rho g a$ are considered to be still valid. At this stage, Bowen's formulation

$$H = \gamma d\,(1 + \varepsilon \cos \lambda y) \qquad (9)$$

would be a proper choice as a first step of approach. This expression is one of the simplest forms which gives an analytical solution and also seems to be a good approximation to the present problem if the wave-current interaction could be neglected as in CASE 12 of the first series of experiments. Outside the breaker line the offshore current velocity decreases monotonically. Therefore it might be reasonable to neglect the radiation stress in the outer area.

2) Continuity and momentum equations can be solved. The solution should give both the current field and the mean water level. Momentum equation

(Eq.(1)) may be rewritten as follows:

$$\frac{\partial \zeta}{\partial x} \sim -\frac{fU}{\rho g h} - \frac{1}{\rho g h}\frac{\partial S_{xx}}{\partial x} \qquad (10)$$

so that the currents have a tendency to reduce alongshore variation of mean water level in a surf zone. This fact does not disagree with the above experimental results.

3) Then the experimental results show that the wave-current interaction should be taken into consideration, especially in the case that the surf zone is wide enough to generate the double circulation pattern. The wave-current interaction has the following two aspects. One is the wave number interaction which distorts the wave crest line, and the other is the energy coupling which contributes to modify the wave height distribution.

In the outer area, the second one plays an important role to modify the wave height perturbation, as seen in the second series of experiments. The energy coupling contributes finally to weaken the offshore current velocity.

The first one holds a key to generate the double circulation system. The wave crest distortion in the outer area means the alongshore variation of the wave ray direction. As a result the wave in the inner area will refract and make a wave height distribution field as shown in Fig.23, where H and L denote a high and low wave region respectively. Thus the double circulation system could be generated.

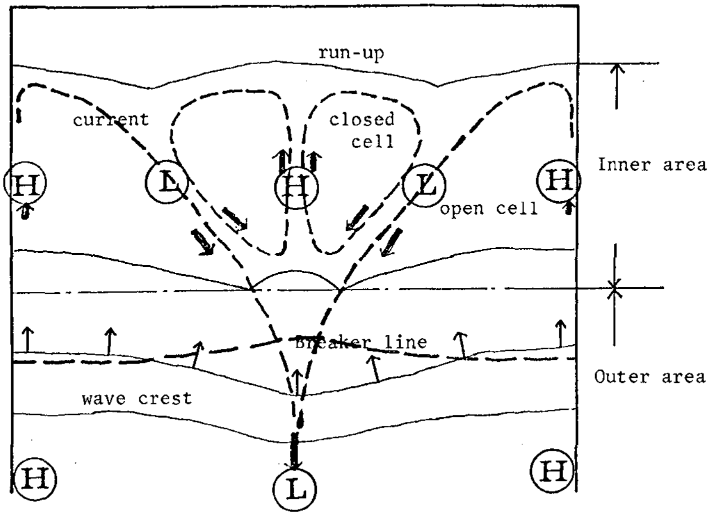

Fig.23. Schematic illustration of a double circulation system.

It is a future problem to formulate the above processes mathematically and to solve and discuss the problem quantitatively

COMMENT ON FIELD OBSERVATIONS

Several papers on the field observations of nearshore current system have been published by Bowen and Inman (1969), Harris (1967), Sonu (1972), Sasaki and Horikawa (1975), Sunamura and Horikawa (1976), Sasaki, Horikawa and Hotta (1976), and others.

The field observations were usually done when the wave condition was not so severe that the change of bottom topography was not rapid even in the surf zone. Moreover wave conditions at the breaker line depend on the bottom topography outside the breaker line, where its change must be very slow and scarce. Therefore we can say that the observed current systems were mainly determined by the bottom topography at least temporarily. Sunamura and Horikawa (1976) reported a case where a distribution of exposed bed rocks near the shoreline determines a current system in that region. The current is very steady in spite of various wave conditions for a long period of time. On the other hand the current system is well simulated by using the refraction method, continuity equation and momentum equation. These facts assure the above idea.

When waves refract both inside and outside of the breaker line, they diverge at depressions and converge at shoals. The high wave region corresponds to the shoals. Applying Bowen's theory, we get outflows at depressions as usually observed.

There are several other explanations. Liu and Mei (1974) calculated radiation stress distribution caused by waves under refraction, and reflection and diffraction at a breakwater. They also calculate a nearshore current pattern as a result. Their idea is essentially the same as the synchronous intersecting wave of Dalrymple (1975). The observed current system in our experiments can be essentially the same kind of them. There is a limitation to apply their idea to the field problem, because monochromatic waves only can make a steady radiation stress distribution.

So far as edge wave is concerned, it creates a very weak current field both in our laboratory experiment (1975a) and that by Bowen and Inman (1969). The current field is completely different from the so-called rip current. Guza and Davis (1974) verified that subharmonic edge wave of Stokes mode is most easily excited under the condition of a standing incident wave. That kinds of edge waves have such a short characteristic length in offshoreward direction that their influence is confined to a region near shoreline.

Hino (1974) energetically approached to this rip current problem by treating it as a time-dependent self generating system on a movable beach. As we stated above, we think that any data obtained so far may not be relevant to compare with his treatment and that the wave height-depth assumtion (Eq.(3)) seems to be incorrect.

Sasaki (1974) presented a hypothesis that " infragravity wave " is an essential factor to control the current system on a gently sloping beach through the bottom perturbation. As a result of the present discussion, it will be suggested to consider that the infragravity wave only modifies the current system which is temporarily controlled by bottom topography. For example the infragravity wave may be related to a pulsation of rip current. The bottom perturbation might be caused by the infragravity wave in a long term.

Finally, there must arise a question how an irregular bottom topography could be formed. We consider at present that the answer could be found in the free type rip current system. But it is still an open question what kinds of equations should be applied.

CONCLUSIONS

The wave-induced nearshore current system can be classified into two types; free type and forced type. In our laboratory experiment, we observed a kind of forced current system which is created by a periodic breaking wave height distribution caused by " cross wave ". Offshoreward currents always flow through the lower wave height region both inside and outside of a breaker line. When the surf zone was rather wide, we observed a double circulation pattern, where wave-current interaction might be important.

According to our experimental results, we propose to consider that the observed current system in fields should be interpreted as the forced type current system where irregular bottom topography plays a crucial part.

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